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Rebuilding Education

STEM Education Practices and Research during the Post-COVID-19 Era

Edited by
Noora J. Al-Thani and Zubair Ahmad

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Rebuilding Education: STEM Education Practices and Research during the Post-COVID-19 Era

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Editors

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Editorial

Rebuilding Education—Contributions to STEM Education Practices and Research during the Post-COVID-19 Era

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COVID-19 resulted in an unprecedented transformation in the context of learning and teaching, wherein a significant shift in the different realms of educational attainment was observed [1]. This Special Issue in *Sustainability*, titled "Rebuilding Education—Contributions to STEM education practices and Research during the post-COVID-19 Era", comprises 12 contributions. These contributions demonstrate the diverse approaches adopted in different developing and developed countries to remediate the analogous challenges, which prompt us to explore the variant underlying factors. Delving into the uncertainties posed by integrated teaching practices, specifically across STEM education, it was observed that the teaching community faced diverse challenges in both learning areas and improving learners' cognitive behavior [2]. Gaining clarity to nullify inherent uncertainties is quintessential when dissecting the teaching and learning processes.

As cases of COVID-19 were initially reported in China, educators in China pioneered methods of overcoming most classroom drawbacks by initiating flexible learning with enhanced accessibility and implementing open educational practices and resources. However, significant concerns were raised by STEM educational researchers from diverse communities in implementing multidisciplinary education, which was, at that time, acquiring augmented responses from diverse audiences. To sustain and nurture multidisciplinary learning, researchers developed an innovative STEAM education model supported by collaborative teaching employing project-based learning and collaborative learning, successfully promoting a multidisciplinary approach (contribution 4). Meanwhile, in Korea, convergence education was introduced into STEAM education to enhance multidisciplinary education. STEAM-integrated convergence education solves the problem of the lack of knowledge associated with segmented academic paradigms resulting from rapidly disproportionate digital transformation (contribution 6). It is also interesting to observe the findings from a study associated with a Qatar-based university course that adopted a multi-course project-based learning (MPL) approach in which educators observed effective achievement of student outcomes, promoting multidisciplinary research (contribution 11). Studies from Spain introduced a STEM-driven multidisciplinary approach by blending pedagogic and architectural backgrounds with substantial experience in instruction, organizational management, and ICT applied to education. The key highlights were, however, limited to the relationship between the setting/learning space (bedroom and facilities) as a moderator and students' effective learning outcomes (contribution 9).

Researchers also explored more direct challenges that were faced in formal settings, such as in school or university classrooms. For example, researchers studied the challenges faced during the online regime by most computer education professionals in understanding students' programming processes (contribution 8). They employed visual representations to clarify the evolution of source-code contents, thereby serving as a reference for future real-time implementation in class. Meanwhile, two student-centered instructional strategies (problem-based learning (PBL) and just-in-time teaching (JiTT)) were adopted across multiple disciplines to encourage a non-conducive online learning climate, with technical problems being the main implementation challenges (contribution 7). Researchers also delved into exploring the impact of different teaching styles adopted during online lessons, specifically, experimental classes, by approaching the experiments with activities that could be conducted at home by employing daily-use materials (contribution 12). Meanwhile, it was reported that online ICT implementation using flipped classrooms in Physics and Chemistry teaching to university students gained popularity with the initiation of lockdown (contribution 10).

On the behavioral front, it was also observed that university students' responses during a vulnerable situation, as in the case of a pandemic, adversely affected their emotions, as researchers explored the impact on students' cognitive responses to adaptability and the resultant emotional development (contribution 5). The researchers also reported that this emotional behavior influenced the degree of engagement and investment in school-related activities. Meanwhile, a study based in the United States and Mexico explored the effects of taking online classes on students' sense of belonging in engineering, whereby students had uncertainties about successful learning in the domain, including deficits in peer collaboration and faculty support (contribution 1). While re-conceptualizing education to incorporate STEM education practices with utmost efficiency in the post-COVID era, the key highlights were limited to innovative research that demonstrated students' knowledge or capabilities in multi-disciplinary settings.

However, further studies need to be performed to expand the scope of these research findings beyond the COVID pandemic with concise and conclusive directions for educators in engaging students for sustainable impact. The evolution of teaching practices from the pre-COVID era to the post-COVID era with sustainable takeaways needs to be elaborately explored so as to create models that can be replicated or built upon to attain meaningful and productive student learning gains. It would also be interesting for STEM educators to explore the possibilities of effective implementation of digital tools in the post-COVID era with the escalated digital presence in students' lives.

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2. Al-Thani, N.J.; Santhosh, M.E.; Bhadra, J.; Ahmad, Z.J.S. The Prominent Roles of Undergraduate Mentors in an Online Near-Peer Mentoring Model. *Sustainability* **2023**, *15*, 3020. [CrossRef]

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Article

Compilation of Chemistry Experiments for an Online Laboratory Course: Student's Perception and Learning Outcomes in the Context of COVID-19

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Abstract: The COVID-19 pandemic forced a quick change of the teaching styles to online lessons; specifically, experimental classes had to be redesigned to achieve the best possible academic performance within the imposed limitations. This work describes three different approaches: adaptation of a laboratory chemistry course to an online mode, learning proficiency, and students' perception. First, a compilation of experiments that cover topics from general chemistry at an undergraduate level was included, with activities that can be conducted employing daily-use materials and substances. Next, the learning achieved was estimated, and the grades were related to a domain level of competency acquisition. The results indicated that at least 68% accomplished the highest level. Finally, the perception of the participants about the activities was inquired. The statistical analysis showed a generalized positive attitude towards the mode proposed, an appreciation of having earned meaningful knowledge, and most of the students stated they would recommend the course.

Keywords: educational innovation; COVID-19; higher education; professional education; remote learning; online teaching; chemistry laboratory; hands-on experiments; competencies; students' perception

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1. Introduction

The health contingency originated by the COVID-19 pandemic posed a worldwide challenge, as emerging strategies had to be sought to continue with essential activities safely [1]. In academia, it raised the need to redesign the classes. Moreover, it led to a sudden shift from in-person to online sessions or e-teaching [2] through interactive platforms, such as Zoom (zoom.us (accessed on 2 December 2021)) [3], Skype™ calls, or Microsoft® Teams; incorporating new technological resources to avoid affecting academic performance [4], while trying to keep a motivating and encouraging environment [5].

Teaching during a disruption requires creativity, flexibility, and resilience; and learning during this time requires similar skills [6]. While the students should want to learn, the teacher must not be limited to communicating information in a traditional way but should take risks to guide them to the production of knowledge [7], for instance, by creating new situations that stimulate their learning and give meaning to the knowledge acquired [8–10]. It has been proven that if leaders show a positive attitude towards the usefulness of online teaching, they may constructively influence the students' behavior and perception [11].

The relevance of experimental work in chemistry is undeniable [12]. In general, laboratory experiences have the following goals: understanding scientific concepts, developing practical skills and problem-solving abilities, stimulating scientific thinking, and motivating a general academic interest, among others [13]. These objectives correspond to the cognitive, affective, and psychomotor domains that are founded on meaningful learning [14,15].

In this field, whereas for theoretical subjects, it was complicated to integrate students and leaders into an e-teaching system [16], it represented an even greater challenge for experimental disciplines [17]. Some of the major concerns that emerged were how to incorporate experiments without compromising the educational goals and how to stimulate the acceptance towards this mode [13,18]. One more focal point was how to digitally maintain student–student and student—instructor interactions since these are crucial components of the learning process.

In this transition, simulators, remote-controlled laboratories, video-based experiments, and other digital tools have been integrated into these online courses [19,20]. Although these resources may be excellent complements, effective learning needs to be strengthened through authentic and research-based experiences [21].

In the literature, there are several original cases regarding the adaptation and innovation of in-person experimental sessions towards an online mode. Selco [22] proposed a virtual chemistry course during the pandemic using food, household substances, and chemicals available in stores (such as baking soda, antacid, and aspirin) to cover acid–base, precipitation reactions and crystal growth, and exothermic and endothermic processes. The author reported that in the change from face-to-face to distance classes, it was essential to be flexible with the resources that were easily available to carry out experiments at home. This is consistent with other publications that state that good online practices depend heavily on the organization and that the instructor should stimulate a friendly environment, provide clear guidelines, and find ways to connect with students despite the remote connection [11,23].

Al-Soufi et al. [24] described the design and construction of a double-beam photometer using smartphones and domestic materials for Applied Thermodynamics, using wine as dye and kitchen paper as filter paper. Another proposal, which started a few months before the lockdown, was the "The Chemical Kitchen" (TCK) initiative at Imperial College London [25], where a domestic kitchen serves as a scientific laboratory, and the project aims to develop practical skills and competencies, such as collaborative teamwork and scientific thinking. A different example is presented by Bruce et al. [26], in which chemistry kits were assembled by a faculty team and distributed through a rental program at the university bookstore, providing access to the experiment.

Schultz et al. [27] reported hands-on experiences about colligative properties and acid-base reactions conducted in a kitchen; the authors mentioned that the at-home activities added situations that only take place in the laboratory (such as spills and cleanup) and that may not be imitated by any virtual tool. A similar conclusion was reported in Kelley's study [21], where it is stressed that scholars prefer running hands-on experiments over video assignments. Moreover, it is concluded that the interest and morale seemed to be higher with these implementations, and the learning process is similar to the techniques in in-person sessions.

After pondering on the educational needs and how to provide continuity to the curricular plan, appropriate conditions to create an online laboratory were settled. Accordingly, the present work describes a selection of experiments related to a laboratory of general chemistry at an undergraduate level. While the core is non-dangerous procedures using several substances and materials of daily use; it also incorporates free interactive simulators and demonstration videos. Not having the equipment, materials, and reagents that are normally available in a laboratory was not viewed as a limit but an opportunity to look for other ways to meet the learning objectives and to develop skills and abilities. Furthermore, the situation promoted creativity since the only restriction was the domestic nature of the materials. These actions are meant to encourage interest in chemical experimentation, despite social isolation.

To genuinely consider the impact of chemistry lessons, the effectiveness of the proposal was analyzed in terms of competency acquisition, which is related to the gain of knowledge. The execution of this task does not follow a specific method, and it becomes a complicated exercise; however, this can be successfully accomplished by performing a continuous assessment of activities (e.g., bibliographic research, problem-solving, at-home experiments, quizzes involving real cases solved through argumentative thinking) focused on promoting distinctive skills. The present work agrees with the recent research published by Mínguez-Aroca [28], where the connection of the activities performed and the competencies to be achieved are discussed.

Despite the virtual chemistry courses that have already been organized [24,25,29,30], little research has been published related to what is more valuable for the students, what are their format preferences, and what is their general perception after taking these online classes. Therefore, this study is based on the following research questions:

RQ1. *How to adapt a competency-based chemistry laboratory course to an online mode?*

RQ2. *How is the students' learning favored after completing an online laboratory course?*

RQ3. *What are students' perceptions after performing chemistry laboratory experiments with daily-use materials and substances?*

2. Materials and Methods

2.1. Overview

The present study consists of two parts. In the first one, a selection and implementation of an adequate sequence of at-home experiments that may be conducted with safe materials that are easy to collect is described. This was assembled to fulfill the competencies specified in the academic programs of two experimental chemistry courses (Chemical Experimentation and Statistical Thinking I & II, identified as Q1021 and Q1023, respectively) of the curriculum map of some engineering degrees at the Tecnologico de Monterrey in Mexico. Additionally, the proposal was designed to generate an authentic experimental work environment, where the activities were not limited to a typical theoretical or purely demonstrative format.

The second part describes the analysis of the learning outcomes and the perspective of the students. Regarding the educational aspect, the final grade of the course was related to a domain level of competency acquisition, as reported in [31]; also, the improvement of the students' performance after completing the programs was assessed. Then, the perception related to the experiments was explored by applying surveys monitoring the learners' previous background with online laboratories, their expectations, and their sense of accomplishment at the end of all the sessions. The answers provided were statistically treated and analyzed, considering the evidence of associations between the learning quality and the perceptions described by the CEQ (Course Experience Questionnaire) scales [32–34].

2.2. Participants

This research was conducted using a quasi-experimental design with conventional non-probability sampling [35]. It involved 194 students between 18 and 21 years old, 57% male and 43% female, and they all agreed to be part of this work. They were enrolled in the second semester of different engineering degrees at two different campuses of the Tecnologico de Monterrey. From this population, 150 attended Q1021 and were separated into 7 groups from 12 to 29 members; and 44 were registered in Q1023 and distributed into 2 groups of 21 and 23 elements, respectively, where each group was supervised by one teacher.

The students' distribution by degree is summarized in Table 1. It should be noted that Q1021 is a course for all engineering degrees, but Q1023 is just mandatory for degrees that have a chemistry approach.

Table 1. Distribution of students' population by engineering degree in the courses Q1021 and Q1023.

Course	Degree	%
Q1021	Biomedical Engineer	1
	Biotechnology Engineer *	23
	Chemical Engineer *	9
	Civil Engineer	3
	Electronic Engineer	1
	Food Engineer *	1
	Industrial and Systems Engineer	23
	Industrial Physical Engineer	5
	Innovation and Development Engineer	6
	Mechanical Engineer	8
	Mechatronics Engineer	8
	Nanotechnology Engineer *	5
	Sustainable Development Engineer *	7
Q1023	Biotechnology Engineer *	48
	Chemical Engineer *	23
	Nanotechnology Engineer *	20
	Sustainable Development Engineer *	9

* Engineering degrees with a chemistry approach.

2.3. Course Description

The implementation was made in two sequential chemistry laboratory courses, "Chemical Experimentation and Statistical Thinking I (Q1021)" and "Chemical Experimentation and Statistical Thinking II (Q1023)" [36,37]. Each is taught in five-week periods, according to the educational model Tec21 of Tecnologico de Monterrey [38], which has a competency-based learning approach. This system has shown to be effective in different formats, such as "i-Semester" [31]; several science subjects [39,40]; and in the challenge-based learning methodology [41–43], which is a key collaborative transversal strategy in this program.

Both courses may be equivalent to a one-semester program of general chemistry laboratory; and consist not only of conceptual topics, specified in Table 2, but also, of procedural and attitudinal aspects. Among the procedural aspects, there are carrying out experiments, applying principles, and building arguments to explain the behavior of natural phenomena, and effectively communicating results and conclusions. Some of the most noticeable attitudinal contents are demonstrating proactivity in the search for new knowledge, understanding the relevance of the scientific method to prove or disprove explanations of natural phenomena, and identifying the importance of chemistry to understand daily-life situations.

Table 2. Academic content of the courses Q1021 and Q1023.

Q1021	Q1023
• Safety standards and laboratory equipment • Statistical analysis • Experimental determination of properties of matter, according to its chemical nature and physical state • Chemical bonds • Polarity of molecules and their relationship with solubility and conductivity • Solutions and colligative properties • Basic concepts of reaction rate and implementation of oxidation-reduction reactions in the construction of batteries (electrochemistry)	Statistical analysis of experimental data Stoichiometry Introduction to chemical equilibrium Acid–base equilibrium Kinetic control of chemical reactions

Based on the information published by the Tecnologico de Monterrey [34,35], the aim of the curriculum objectives is to develop the following institutional competencies (IC):

IC1. Explain and demonstrate the behavior of natural phenomena through argumentations based on concepts, theories, and principles.

IC2. Assess the components that integrate a case study; make decisions to solve them; and implement actions, applying current standards and considering environmental care, to solve real engineering and science problems.

IC3. Apply fundamental chemistry concepts of the structure and function of matter through procedural competencies and analyze statistical data obtained from experiments.

3. Experimental Sessions

The role of the teacher is fully reflected in RQ1, which refers to the adaptation of a competency-based chemistry laboratory course to an online mode. Specifically, the actions involved in the design started by reviewing the official curriculum goals and the intended learning outcomes; looking for activities related to the relevant topics that could be performed using daily-use substances and materials; and then preparing guidelines to conduct the experiments listed in Table 3.

Table 3. Experimental sessions for the courses Q1021 and Q1023.

Course	Topic
Q1021	3.1. Chemistry Laboratory Safety 3.2. Common Laboratory Equipment and Experimental Measurements 3.3. Separation of Mixtures 3.4. Preparation of Solutions and Dilutions 3.5. Redox Reactions 3.6. Electrochemical Cells
Q1023	3.7. Stoichiometry by Precipitation Reactions 3.8. Chemical Kinetics 3.9. Chemical Equilibrium 3.10. Acid–base Titration

Each session was 2 h long and was held twice a week. During this time, the teacher was in charge of briefly explaining the procedures and supervising the performance. The students were separated into virtual rooms where each team carried out the assigned activities in real-time, and they could ask for advice at any moment. In case someone had Internet connection issues or was not able to gather the necessary materials, it was enough if only one team member performed the experiment and the rest of the classmates would participate by giving instructions, recording the measurements, and writing the observations among others. Afterward, they had one week to prepare a report that contained a concise literature review regarding the state-of-the-art, the description and discussion of the trials and results, and conclusions. The instructor was able to assess the understanding of the concepts by analyzing the work and providing formative feedback.

3.1. Chemistry Laboratory Safety

To prevent accidents in a laboratory, it is necessary to know the safety measures, for example, recognizing warning signs and emergency exits; identifying the code color for each supporting service; and locating emergency showers, eyewashes, and safety equipment. The Official Mexican Standard NOM-018-STPS-2015 establishes the requirements of the Global Harmonized System or GHS for the identification and communication of dangers and risks due to chemical substances [44].

To reinforce the safety measures, labels according to GHS standards for two chemicals provided were schemed; these included H-phrase codes on health hazards and P-phrases indicating precautionary advice [45]. Then, each team wrote a guideline of good practices, including ten basic safety measures for a chemistry laboratory (Figure 1); and looked for the meaning of 10 different pictograms related to safety and chemicals management. Finally, they were asked to (1) identify the code color used for gas, water, and vacuum pipes according to Mexican Standards; (2) research the conditions to use fire extinguishers, safety showers, and eyewash stations; and (3) investigate the characteristics of a proper ventilation system.

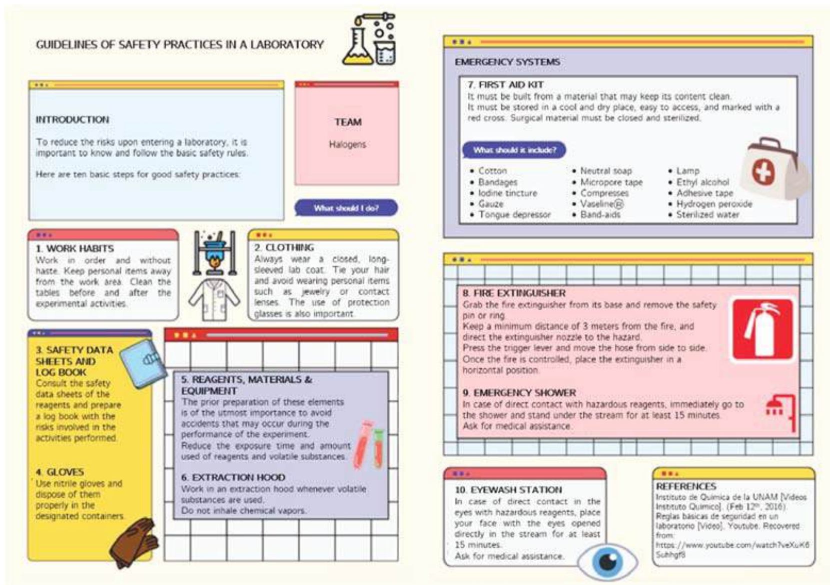

Figure 1. Example of a guideline of safety practices in a laboratory (Image translated from a students' report).

3.2. Common Laboratory Equipment and Experimental Measurements

Experimental work is an excellent activity to introduce scientific concepts and promote procedural skills. One of the first steps may be the identification of common equipment and its proper use. Although in distance learning, there is no actual manipulation of laboratory devices, it is relevant to become familiar with the common instruments. A demonstration video [46] with a brief explanation about the use of some instruments was presented. In addition, an interactive website was used to reinforce the identification of common equipment [47]. Several instruments shown were classified according to their use with the information provided and by conducting bibliographic research.

Next, learners estimated the uncertainty of the measurement of different instruments used at home, such as spoons and cups, by applying the concept of error equal to minimum scale/2. As a complement, on an interactive page [48], the determination of uncertainties in volume measurements was exercised. Finally, a teamwork task was carried out (Figure 2), where the number of drops contained in one milliliter of water measured with a syringe was counted [45]. The data collected was used to estimate basic statistical parameters (mean and standard deviation) of a set of direct measurements and concepts, such as accuracy, precision, and experimental error were applied and discussed.

Figure 2. Drop counting activity using a syringe (Image extracted from a students' report).

3.3. Separation of Mixtures

The separation of mixtures is a common technique used in general chemistry to isolate the components; the procedure applied is based on the physicochemical properties of substances. A mixture of ethanol, sugar, and oil (mixture A) and a second one formed by table salt, sand, and screws (mixture B) were separated, considering the characteristics of each component [45]. This trial was similar to the one described by Schultz et al. [27].

The separation procedures are outlined below (Figure 3):

- Mixture A: ethanol and oil were separated from the sugar by filtrating the sample using a funnel (or a homemade funnel built with the top part of a plastic bottle) and a coffee filter. Subsequently, the ethanol was separated from the oil by decantation.
- Mixture B: screws were removed from the mixture of table salt and sand with the help of a magnet. Then, water was added to the mixture to dissolve the table salt so that filtration could be ulteriorly used to separate the sand from the dissolved table salt. Finally, the solution was heated to evaporate the water and recover the table salt.

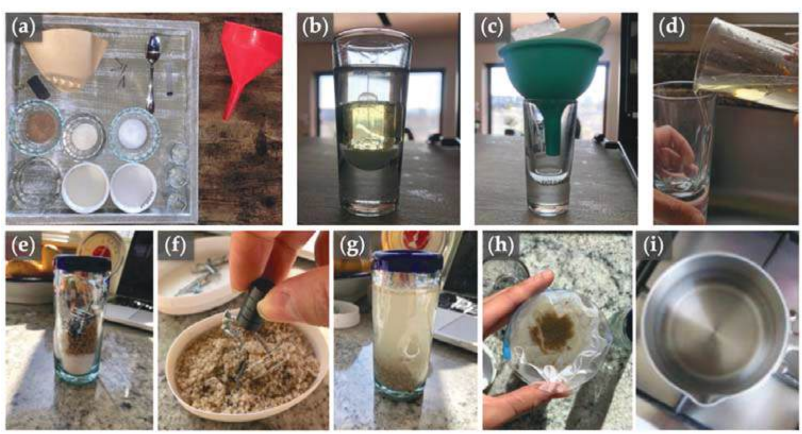

Figure 3. (**a**) Components of mixtures A and B and materials used, (**b**) mixture A, (**c**) separation of sugar from ethanol and oil by filtration, (**d**) separation of ethanol and oil by decantation, (**e**) mixture B, (**f**) separation of the screws by magnetization, (**g**) dissolution of table salt, (**h**) filtration of sand to recover the saline solution, and (**i**) evaporation of water to recover the table salt (Images extracted from a students' report).

3.4. Preparation of Solutions and Dilutions

The preparation of a solution of known concentration is perhaps the most common activity in a laboratory. While pipettes and volumetric flasks are the preferred materials when the concentration needs to be accurate, to teach how to prepare aqueous solutions and dilutions, syringes, kitchen scales, measuring cups, and spoons were employed. The following solutions were prepared:

- A 0.025 molal dilution of table salt in 0.25 kg of water was prepared using a measuring cup as a container. Considering the solute was only sodium chloride (NaCl), 0.36 g or 2 teaspoons of NaCl were dissolved in 250 mL of tap water (assuming 1 teaspoon weighs approximately 0.2 g).
- A cup of coffee was prepared with 0.4 g of instant coffee and 1.2 g of common sugar, assuming it was sucrose ($C_{12}H_{22}O_{11}$), and 250 mL of tap water. This solution was furtherly diluted 1000 times, taking into account only the sucrose concentration since the coffee was used just to add color to the sample [49]. This process was performed in 3 steps (Figure 4).

Figure 4. Sucrose solutions diluted 1000 times using coffee as colorant (Image extracted from a students' report).

Finally, a virtual simulator [50] was used to practice the procedure and the calculations to prepare 5 different solutions of molar concentration.

3.5. Redox Reactions

Oxidation and reduction procedures are very common in many daily activities and biochemical processes; as examples, two sequential redox reactions were executed [51]. The first part consisted of the oxidation of galvanized nails with zinc coating by adding iodine tincture; this substance was directly purchased at the pharmacy. First, a handful of small nails was placed inside a container, and enough iodine tincture was added to cover them; at least one nail was kept in its original form to use as a reference. As a water bath, enough tap water was poured into a metal vessel to at least cover the height of the container with the nails and the iodine tincture. The sample was moderately heated for around 15 min to speed up the reaction process but without boiling it. Because the iodine tincture contains alcohol, it was important to avoid direct contact with the fire, and the container was covered to prevent the alcohol from evaporating. When discoloration in the solution due to iodide formation was observed, the heating was stopped, and the solution was left to cool for a few minutes. Afterward, with the help of a cloth or gloves, the container was removed from the water bath and the iodide solution was transferred to another glass container to observe the final oxidized material (Figure 5).

In the second part, the colorless iodide solution obtained in the previous procedure was oxidized. To this end, about 5 mL of laundry bleach (5–6% NaOCl) were poured with the help of a syringe (or dropper), and then 5 mL of vinegar (5% CH_3COOH) were added, which led to the original color of the iodine solution after the oxidation.

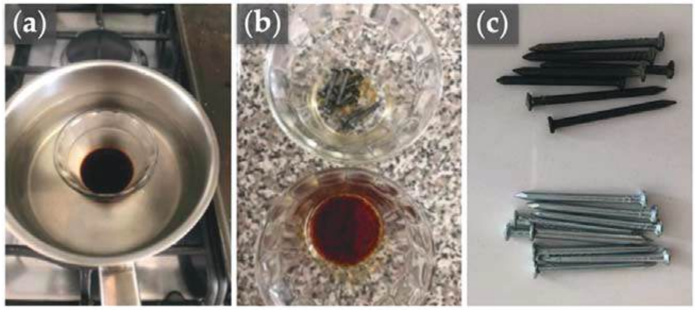

Figure 5. (**a**) Heating the mixture of nails and iodine tincture in a water bath. (**b**) Separation of the iodine tincture and nails after the reaction. (**c**) Comparison of the nails before and after the oxidation reaction (Images extracted from a students' report).

3.6. Electrochemical Cells

During the lockdown, homemade materials to create and measure electrochemical cells [52] were difficult to collect; the teacher made a demonstrative assembly of two galvanic cells, Zn–Cu and Mg–Cu, and recorded a series of potential measurements analyzed with statistical calculations. Students were asked to compare the calculations with the theoretical values obtained using a simulator [53]. From this information, it was established whether the device represented a galvanic or an electrolytic cell, and the spontaneity of different redox reactions was concluded. Alternatively, everyone who had access to a voltmeter and either alligator clips or copper wire was able to build a cell using an aluminum can, graphite from a pencil as electrodes, and a saturated saline solution as electrolyte [54] (Figure 6).

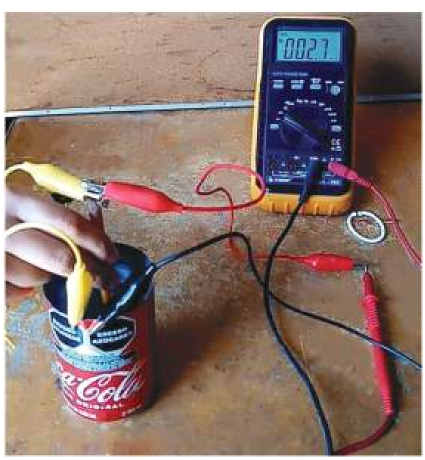

Figure 6. Image of an electrochemical cell built using an aluminum can and saline solution (Image extracted from a students' report).

3.7. Stoichiometry by Precipitation Reactions

Precipitation reactions can be perfectly used to introduce stoichiometric calculations, such as yield percent since the nature of the reaction products allows them to be easily recognized and recovered. Three precipitation reactions were studied. The first one consisted of the precipitation of the casein from milk in an acid medium, which may be achieved with a sample of whole milk and vinegar [55] (Figure 7). Due to the complexity of the corresponding chemical reaction for an introductory chemistry course, this activity was just used as an illustrative example.

Figure 7. Filtration of casein precipitated from a sample of milk (Images extracted from a students' report).

The other two experiments dealt with the precipitation of phosphates in acid medium using magnesium hydroxide (milk of magnesia) from cola soda ($3Mg(OH)_{2\ (aq)} + 2H_3PO_{4\ (aq)} \rightarrow Mg_3(PO_4)_{2\ (s)} + H_2O_{\ (l)}$) and detergent ($Mg(OH)_{2\ (aq)} + NH_4Cl_{\ (aq)} + \frac{1}{2}Na_2HPO_4\ (aq) \rightarrow MgNH_4PO_{4\ (s)} + NaCl_{\ (aq)} + H_2O_{\ (l)}$) [56]. The reactions were easily carried out, and the corresponding solid was recovered by simple filtration (for example, using a common funnel or the top part of a bottle and coffee filter paper or a paper napkin). After letting the samples dry for a few hours exposed to the sunlight, the solid was weighed using a kitchen scale, and the yield percentage was estimated.

3.8. Chemical Kinetics

Some chemical reactions show a sudden change in a property due to an increase or decrease in the concentration of a substance involved. These types of reactions are often compared to a clock alarm since there is no evidence of the reaction until an alert or abrupt change is triggered [57]. Such modification may be appreciated, for example, as a color modification, and, in turn, this may be an indication of the concentration of the reagent at a specific period; hence, their study may provide important information related to the kinetics of the reaction, especially the reaction order.

In this experiment, a redox reaction between a blue food coloring and hydrogen peroxide (H_2O_2) was carried out, and the concentration of the dye was estimated by tracking the *R*-index of the RGB scale throughout the reaction process [58,59]. First, a teaspoon of baking soda (sodium hydrogencarbonate ($NaHCO_3$)) was mixed with 10 mL of drinking water and, subsequently, 10 mL of H_2O_2 were added. Then, the solution was poured into a clear container and placed on a red background. A smartphone with an RGB analyzer app was set over the reaction container, focusing the camera on a top view of the center of the vessel. Before starting, the initial *R*-index was recorded as the blank (R_{blank}). Next, 1 or 2 drops of blue food coloring were added and mixed; immediately, the timer was started, and the following *R*-index values were registered every 15 s. The reaction finished when the blue color had faded, and the mixture had turned red (Figure 8).

The results obtained were analyzed according to Beer-Lambert's Law, $A = \varepsilon cx$ [60], where A is the absorbance of the substance, ε the absorption coefficient, c the molar concentration, and x the path length. Since the concentration of a substance is directly proportional to the absorbance, by estimating this amount, it was possible to qualitatively establish the behavior of the concentration throughout the reaction, and, therefore, determine a reaction order. The calculations performed were as follows: first, the transmittance T of the dye was estimated as the ratio R/R_{blank}; then, the corresponding absorbance was calculated as $A = -logT$; lastly, the following plots were sketched: (a) zero-order: A vs. time, (b) first-order: $ln\ A$ vs. time, and (c) second-order: A^{-1} vs. time. The graph that better adjusted to a linear fit was the one that indicated the reaction order.

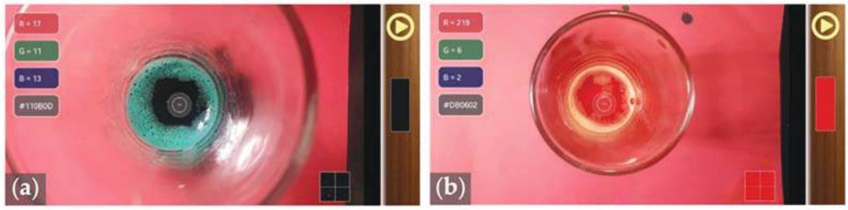

Figure 8. Image of the chemical reaction performed and record of the *R*-index using ColorMeter Free app. (**a**) Addition of blue food dye at the beginning of the reaction. (**b**) View of the system once the reaction was completed.

3.9. Chemical Equilibrium

Natural pH indicators are organic substances that show distinctive colors depending on the acidity or basicity of the medium; for example, red cabbage contains anthocyanin that shows red tones in acid medium, blue-violet in neutral medium, and yellow-green in basic medium, respectively [61]. This is the result of an acid–base reaction between a compound in the medium and the pH indicators acting as weak acids. Therefore, according to Le Châtelier's Principle, a change in the concentration of hydronium ions will result in reversible reactions to restore equilibrium, where the chemical structure of the corresponding conjugate base can be macroscopically identified by a specific shade [62].

A challenge to prepare several natural pH indicators by common extraction procedures was presented and, first, mix them with an acid substance and then, with a basic substance to observe a change in the equilibrium. Moreover, a qualitative colorimetric pH scale was built, where the equilibrium reactions were explained based on Le Châtelier's Principle (Figure 9).

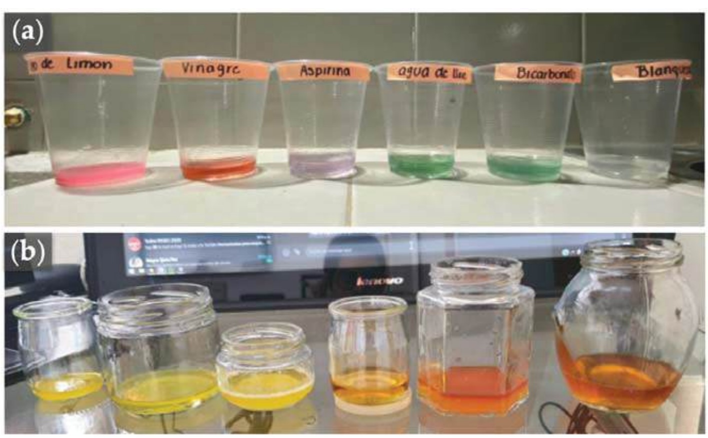

Figure 9. Observed pH colors for different substances (from left to right: lemon juice, vinegar, acetylsalicylic acid, water, baking soda, and bleach) with (**a**) red cabbage and (**b**) turmeric indicators (Images extracted from a students' report).

Additionally, a video in which the equilibrium reaction

$$4Cl^{-}{}_{(aq)} + Co(H_2O)_6{}^{2+}{}_{(aq)} \rightleftharpoons CoCl_4{}^{2-}{}_{(aq)} + 6H_2O_{(l)}$$

takes place was analyzed to explain the equilibrium changes caused by the addition of water, concentrated hydrochloric acid, and sodium chloride and the increase and decrease of temperature.

3.10. Acid–Base Titration

Titration is the classical analytical method used in quantitative determinations of the concentration of a substance. In the food industry, the acid content has an impact on the taste, color, microbial stability, and quality of preservation, among others, of food and may be estimated by an acid–base titration. For instance, the determination of acetic acid content (CH_3COOH) in vinegar samples may be easily performed as an at-home experiment [63] with baking soda solution ($NaHCO_3$), according to the following reaction:

$$CH_3COOH_{\,(aq)} + NaHCO_{3\,(aq)} \rightleftharpoons CH_3COONa_{\,(aq)} + H_2O_{\,(l)} + CO_{2\,(g)}.$$

A ~1 *M* baking soda solution (using kitchen scales and drinking water) and a natural pH indicator (previously tested in the chemical equilibrium experiment Section 3.9) were prepared. With a measuring cup, around 5 mL of vinegar were transferred into a clear vessel, mixed with some drinking water and a few drops of the pH indicator to be able to qualitatively identify the equivalence point by the color change. The baking soda solution was placed in a graduated syringe (which replaced a burette), and the dropwise addition to the vinegar sample began, mixing every drop with a spoon until the color of the system was the one corresponding to the neutral pH (Figure 10). Finally, the molarity (*M*) of the acid was calculated as

$$M_{acid} = (M \times V)_{baking\ soda} / V_{acid},$$

where $V_{baking\ soda}$ stands for the total volume spent of the baking soda solution. The total acidity content was then reported as percent mass (% m/m) and compared with the theoretical content published.

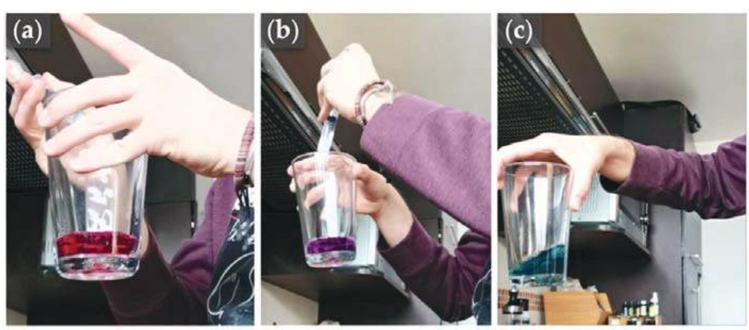

Figure 10. Titration of vinegar with baking soda solution, using red cabbage as the pH indicator. (**a**) Initial view of the reaction system (acid medium). (**b**) Equivalence point of the titration. (**c**) View of the reaction system after the equivalence point (basic medium) (Images extracted from a students' report).

Additionally, an acid–base titration simulator was used [64], wherein different indicators were selected, and a titration curve was generated.

4. Research Design

4.1. Evaluation and Competencies Achievement

The following activities aimed to respond to RQ2, which is related to the learning outcomes after completing this online laboratory course. Students were asked to complete a diagnostic questionnaire at the beginning of the academic period (pre-test) and to take it again once it ended (post-test). It consisted of thirteen questions of several formats (multiple choice, match columns, complete sentences, etc.) and was applied on Canvas (a Learning Management System LMS platform). The rating scale ranged from 0 to 100 points, with 70 being the minimum passing mark accepted by the Tecnologico de Monterrey. The improvement of knowledge was divided into five percentiles of 20% each, which were assigned as the following examples explain. If in the pre-test someone scored 60 points and in the post-test 100 points, this would mean that he/she was able to get the 40 points missing to have a perfect mark; hence, this case will be in percentile I (100%). An alternative example is if another person obtained 35 in the pre-test, to be in the highest percentile, he/she would need 65 points in the post-test; however, if the final grade achieved was 75 points (i.e., only 40 points more), this case will fall in percentile III (60%).

The core topics were equitably distributed in the questionnaires. For Q1021, the topics covered were laboratory reports, safety, material and instruments, volume measuring, basic statistical calculations, mixtures separation, preparation of solution and dilutions, redox reactions, cells potential, electrochemical cells, electrolytes, and colligative properties. The topics addressed in Q1023 were stoichiometry, limiting reagent, chemical equations of double substitution reactions, reaction rate, and basic statistical calculations.

The learning activities were graded according to an evaluation system outlined in Table 4; using the same scale as in the questionnaire described above. These included individual quizzes focused on the key concepts involved in the experiment to be performed (Q_{pre}) and others intended to assess procedural skills and the application of the topics in real contexts (Q_{post} and FE). Moreover, reports (R) from the experimental sessions and a solution of a project based on a real case referred to as problem situation (PS) were submitted in teams. The teacher provided constant feedback to the teams when they were experimenting (ED) and by assessing their reports; also, personal observations were shared considering the results from exams.

Table 4. Evaluation system of the courses Q1021 and Q1023.

Criterium	%
$\boldsymbol{ED}$ = Experimental performance	8
$\boldsymbol{Q_{pre}}$ = Pre-experimental quizzes	5
$\boldsymbol{Q_{post}}$ = Post-experimental quizzes	8
$\boldsymbol{R}$ = Reports	26
$\boldsymbol{FE}$ = Final exam	30
$\boldsymbol{PS}$ = Solution to problem situation	23
$\boldsymbol{FG} =$ Final grade $\left(\boldsymbol{ED} + \boldsymbol{Q_{pre}} + \boldsymbol{Q_{post}} + \boldsymbol{R} + \boldsymbol{FE} + \boldsymbol{PS}\right)$	100

Then, the final grade (FG) obtained was related to a domain level of competencies achievement as follows [31]:

- **Domain level 3** (score: $90 \leq FG \leq 100$) stands for an excellent accomplishment of competencies. The learner outstandingly completed all the activities and demonstrated distinctive knowledge.
- **Domain level 2** (score: $80 \leq FG \leq 89$) was reached when the competencies were satisfactorily gained, and all the grading activities were completed. The acquired knowledge was acceptable, but some concepts needed to be clarified.
- **Domain level 1** (score: $70 \leq FG \leq 79$) refers to the minimum passing execution. Competencies were regularly fulfilled, and activities were partially delivered and needed improvement. The learning outcomes showed confusion in the main topics.
- **Domain level 0** (score: $FG \leq 69$) was assigned when most of the competencies were not achieved, and there were significant deficiencies in the comprehension of the theoretical background.

4.2. Surveys of Perceptions

RQ3, regarding the students' perceptions after completing these courses, was cleared up with initial and final survey instruments (the English translation of the surveys is incorporated as Supplementary Materials S1 for publication purposes). The first survey included five multiple-choice items, three referring to the participants' background with other virtual laboratories; one related to the formats they considered to work better as learning tools (i.e., simulators, lectures, scientific article review); and the last one about the expectations of the class. The second survey had 26 items, 14 of which measured the point of view about experiments with daily-use materials, videos, and simulators; 10 items referred to the sense of competencies' accomplishment; and the last 2 items addressed the satisfaction after taking the courses. All items were assessed with a 5-point Likert scale [65]: Strongly Disagree (SD), Disagree (D), Neutral (N), Agree (A), and Strongly Agree (SA). Finally, there were two open-ended questions to discuss the positive and negative impressions.

Based on the curricular objectives [36,37], five common competencies were intended to be developed during both Q1021 and Q1023: conduct experiments considering the general safety standards in the laboratory (C1), handle correctly the chemicals considering the corresponding risks and precautions (C2), use properly the most common laboratory instruments (C3), express a measurement with the corresponding error (C4), and perform statistical analysis of a set of experimental data (C5).

There were five other competencies specific to each of the courses outlined ahead:

- Q1021. Identify the physicochemical properties of substances and use them to separate the different components of a mixture (C6A), prepare solutions of a defined concentration (C7A), plan a sequence of dilutions from a stock solution (C8A), explain a phenomenon involving oxidation-reduction reactions (C9A), and build a galvanic cell with all its components (C10A).
- Q1023. Calculate the yield of a chemical reaction from its balanced equation (C6B), experimentally demonstrate the order of the chemical reaction related to kinetics (C7B), predict the direction of a chemical reaction as a result of a change in the reaction conditions (C8B), relate chemical equilibrium with a pH scale built using a natural acid–base indicator (C9B), and calculate the unknown concentration of a sample from a reagent of known concentration in acid–base reactions (C10B).

4.3. Data Statistical Analysis

The replies provided were treated using descriptive statistics to determine the frequency and percentage of each survey item. The data collected were examined using IBM SPSS Statistics version 26 and Microsoft Excel v. 16.55. Qualitative data from both open-ended questions were categorized by analyzing the content to have an insight into the perceptions. To sort out the responses, a coding system was applied to logically pool them by their frequency and assign them into an adequate classification labeled with a specific number [66].

For Q1021, the answers received were initially divided considering the chemistry and non-chemistry approach of the degrees (refer to Table 1 for more detail). However, the Student's *t*-test statistical analysis determined there were no significant differences in the perception of these groups.

5. Results and Discussion

The reliability of the results concerning the acceptance of the distance teaching format was assessed using Cronbach's alpha values. According to Cortina [67], a minimum acceptable α coefficient should be between 0.65 and 0.8 (or more) and values less than 0.5 are inadmissible. This test was applied, keeping all the items intact from the answers of both final surveys, Q1021 and Q1023; and the results displayed $\alpha = 0.95$ and $\alpha = 0.94$, respectively, which demonstrated excellent internal consistency of the instruments. The corresponding findings are discussed in the following sections.

5.1. Preferred Class Format

According to the results of the Q1021 initial survey, undergraduates who had already been involved in virtual laboratories accounted for 80% of the respondents, and 49% were not satisfied with the previous experience. From these, 12% worked with real-time experiments conducted by the teacher, 21% used demonstration videos, 54% performed at-home experiments, and 13% practiced with simulators.

Figure 11 shows the results obtained from the question: "*Which format from the online experimental chemistry course do you think can contribute the most to your learning of the topics?*". The answers were ranked in order of preference from 1 to 5, where the number 1 was assigned to the top choice. In Q1021, the first place was real-time demonstrations done by the teacher with 65%; the second option was for videos held in a laboratory with 17%; followed closely by experiments with simple materials available at home with 14%. In Q1023, the item corresponding to real-time demonstrations conducted by the teacher had a much lower percentage (43%), and the experiments carried out with simple materials available at home increased (43%); the next option chosen, with 12%, was videos of experiments in the laboratory; and simulators were the fourth option for both, with 5% for Q1021 and 2% for Q1023.

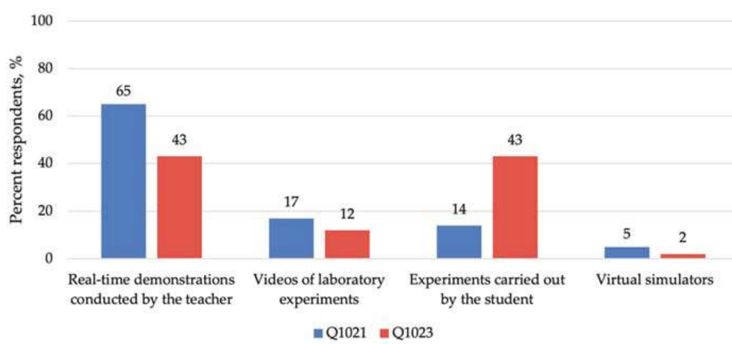

Figure 11. Students' distribution (%) of their preferred teaching formats before taking the courses Q1021 (blue) and Q1023 (red).

A clear difference can be observed in the item "Real-time demonstrations conducted by the teacher" between Q1021 and Q1023. In the first one, it may be assumed that students wanted the instructor to execute the demonstrations due to previous bad experiences in other virtual laboratories. Fortunately, this perception changed in the second course, where the preference leaned towards carrying out experiments with materials available at home.

A central part of the final survey was based on the opinions regarding different attributes of the formats used. Table 5 shows the percentages of students that classified each item using a Likert scale; for analysis purposes, answers were pooled as SA/A for "Strongly agree" and "Agree", N for "Neutral", and SD/D for "Strongly disagree" and "Disagree". Items were assorted as homemade experiments (E1–E11), simulators (S1–S2), and demonstration videos (D1). The highest percentages of SA/A in Q1021 were for items related to the indications with 91% (E9) and the benefit that the at-home experiments provided to understand the concepts (E10), also with 91%. In Q1023, the highest percentages for SA/A were for E2 (finding an adequate space to work), E6 (length of experiments), E9 (instructions), and S2 (simulators as a complement to understand the concepts), all with 95%. Contrastingly, in Q1021, the lowest percentage of SA/A was for the item related to the replacement of laboratory volumetric equipment (E3), ending in 61%; followed by E4 (replacement of non-volumetric material equipment) with 76%; and E11 (at-home experiments allow to apply chemistry in everyday life) with 77%. In contrast, in Q1023, the lower percentage belonged to E3 (64%), followed by E11 (77%). In the SD/D responses, except for E3, which was 18% for Q1021 and 16% for Q1023, the rest of the items were below 10%. It is interesting that in 9 of the 14 items of Q1023 no one selected SD/D.

Table 5. Results of opinions regarding the teaching formats used: experiments carried out at home (E), virtual simulators (S), and demonstration videos (D), for the online courses "Chemical Experimentation and Statistical Thinking I (Q1021) & II (Q1023)"; where the numbers represent the percentage of students that selected that qualification.

Item	Description	Course	SA/A	N	SD/D
Homemade Experiments	E1. The requested material was easy to gather.	I	88	7	5
		II	91	9	0
	E2. By the nature of the experiment, it was easy to find an adequate space at home to perform it.	I	81	13	7
		II	95	2	2
	E3. Household utensils adequately replaced specialized laboratory volumetric equipment.	I	61	21	18
		II	64	20	16
	E4. Household utensils adequately replaced specialized non-volumetric laboratory equipment.	I	76	15	9
		II	84	11	5
	E5. The procedure performed was easy to execute.	I	89	8	3
		II	91	9	0
	E6. The length of the experiments was adequate.	I	88	9	3
		II	95	5	0
	E7. I felt safe while I performed the experiments.	I	89	7	4
		II	91	9	0
	E8. After experimenting, it was easy for me to clean the materials and remove any residues.	I	85	7	7
		II	93	7	0
	E9. The instructions were clear and I felt I received appropriate guidance.	I	91	5	4
		II	95	2	2
	E10. The experiments helped me to understand the concepts of the class.	I	91	5	3
		II	93	7	0
	E11. Unlike laboratory tasks, experiments performed at home allow me to apply the fundamentals of chemistry in everyday life.	I	77	15	7
		II	77	20	2
Simulators	S1. The chosen simulators are intuitive and user-friendly.	I	87	11	3
		II	91	9	0
	S2. The simulators served as a complement to understand the concepts of the class.	I	83	13	4
		II	95	5	0
Demonstration Videos	D1. The demonstration videos served as a complement to understand the concepts of the class.	I	87	10	3
		II	86	14	0

It was expected that the learners would feel it was not easy to substitute both volumetric and non-volumetric materials with ordinary goods; hence, E3 and E4 received the lowest percentage of SA/A and the highest of SD/D.

The positive percentages for E11 were also relatively low when compared with the other attributes of the teaching formats. It stated that at-home experiments allow the implementation of chemistry in everyday life, and the results indicate that less than a quarter considered activities in an actual laboratory could be more valuable.

In Q1023, participants affirmed it was easy to find an adequate space at home to work; also, they expressed that the length of the experiment was appropriate. This remarkably supports the relevance of designing an adequate sequence of experiments and that the selection was suitable to be performed remotely. The impact of the resources used as facilitators and means of reinforcement to understand the concepts was also underlined; in this context, the use of simulators proved to be an excellent complement for the learning process [17,19].

Finally, the importance of giving clear and precise instructions is highlighted and is consistent with other publications regarding the relevance of the teacher's role [6,11,68].

5.2. Perception of Knowledge and Skills Achievement

The survey explored self-perception about the competencies achieved after attending the online laboratories. Figure 12 shows the impressions on the five common competencies. In Q1021, the percentage of members who agreed (SA/A) on having achieved these competencies is between 79% and 91%, where C2 got the lowest percentage and C1 the highest. In the case of Q1023, the interval is between 84% and 93%, with the smaller percentage being for C3 and the biggest for C4. In both courses, the group who considered they did not achieve the competencies was between 0% and 6%, and the neutral answers ranged between 6% and 15%. Competency C2 presented the highest percentage of SD/D in terms of the achievement of the competency (6% in Q1021 and 5% in Q1023).

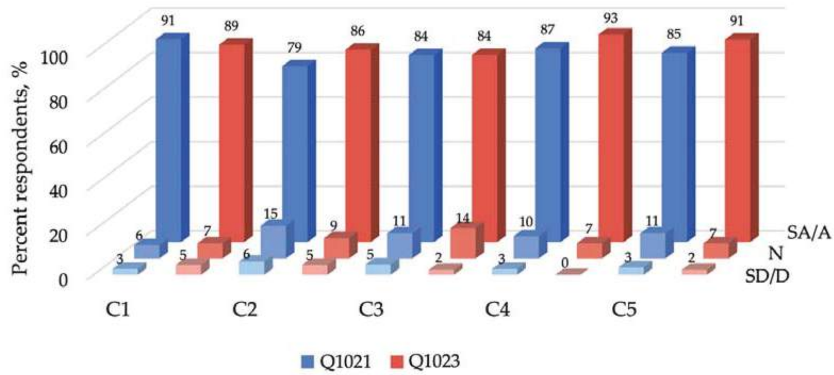

Figure 12. Students' distribution (%) of their perception about common competencies achievement in both courses Q1021 (blue) and Q1023 (red) (C1: conduct experiments considering the general safety standards in the laboratory, C2: handle correctly the chemicals considering the corresponding risks and precautions, C3: use properly the most common laboratory instruments, C4: express a measurement with the corresponding error, C5: perform statistical analysis of a set of experimental data, SA/A: strongly agree/agree, N: neutral, SD/D: strongly disagree/disagree).

Attendants of Q1021 believed they learned about safety measures for experimental work (C1). This could have been favored by having encouraged them throughout the activities to use safety and protection equipment, such as goggles, lab coats (or aprons in its absence), kitchen gloves, and shoes with closed-toes and heels. Competency C2, which refers to the handling of chemical substances, had the lowest percentage in Q1021, possibly because no chemical reagents requiring special handling were used; although an increase in the percentage was observed in Q1023, the score is still low in comparison to other competencies. In Q1023, C3 was the competency with the lowest numbers, which may be explained since common laboratory glassware (such as pipettes, burettes, volumetric flasks) were not available and were replaced by commonly used instruments.

The greatest percentages of acceptance for competencies C4 and C5 were obtained in Q1023, reporting a significant increase in comparison with Q1021. This is probably because in Q1021 the topics related to the expression of the error in measurements and statistical analysis of data were addressed for the first time, but they were reinforced in the second period (consult Table 2 for the complete list of topics).

Figure 13 shows the perception of the procedural competencies specific for Q1021. The highest percentage of SA/A responses is found in C9A (94%), followed by C8A (92%), C6A (90%), and C7A (88%); whereas the lowest value was obtained in C10A (81%). Neutral responses ranged from 5% to 13% of respondents, while those who felt that they did not develop these competencies (SD/D) ranged from 1% to 6%.

Given the large percentage of acceptance in C4, it may be assumed that the redox experiment (Section 3.5) was adequate. The lowest values in C10A may be justified since it was not easy to build a homemade galvanic cell due to the lack of materials, and this topic was mainly reviewed with videos and simulators. This observation reinforces the initial idea that at-home experiments help them to achieve procedural skills.

Figure 13 shows the point of view about the development of specific Q1023 competencies. In general, the SA/A of students' replies for each competency were very similar, with values between 91% and 95%, being the lowest for C10B and the highest for C8B. Between 5% and 9% opted for a neutral answer, and no one chose SD/D.

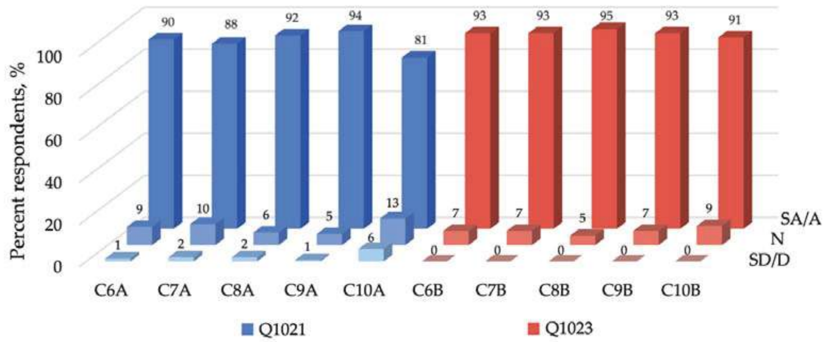

Figure 13. Students' distribution (%) of their perception about specific competencies achievement in the courses Q1021 (blue-A) and Q1023 (red-B) (C6A: identify the physicochemical properties of substances and use them to separate the different components of a mixture, C7A: prepare solutions of a defined concentration, C8A: plan a sequence of dilutions from a stock solution, C9A: explain a phenomenon involving oxidation–reduction reactions, C10A: build a galvanic cell with all its components, C6B: calculate the yield of a chemical reaction from its balanced equation, C7B: experimentally demonstrate the order of the chemical reaction related to kinetics, C8B: predict the direction of a chemical reaction as a result of a change in the reaction conditions, C9B: relate chemical equilibrium with a pH scale built using a natural acid–base indicator, C10B: calculate the unknown concentration of a sample from a reagent of known concentration in acid–base reactions, SA/A: strongly agree/agree, N: neutral, SD/D: strongly disagree/disagree).

Broadly speaking, there is an increase in the percentage of favorable responses obtained in comparison with the results from Q1021. One possible reason is that the design, in terms of distribution and extension of each activity, of the sessions in Q1023 was improved. In addition, the thematic content of the second course favored proposing more attractive experiments with a greater intellectual challenge.

5.3. Evaluation of Competencies Achievement

The learning outcomes provided good insight into the knowledge and competencies domain level acquired as a result of completing these courses. The analysis had two different approaches, estimating an improvement based on the grades of diagnostic tests and assigning a domain level of competencies' achievement.

In Q1021, the average grade on the initial questionnaire was 58 points, and the final was 73 points. By comparing the scores obtained in both tests, a general increase of 15% in the final marks within the ranges of 100 to 90 points and from 89 to 80 points was reported, an increase of 22% was found from 79 to 70 points, and the number of failing scores reduced to 33%. In Q1023, the initial average score was 42 points, and the final was 73 points; wherein 98% of the students started with failing scores and, after taking the lessons, this group reduced to 39%; the scores of the rest were distributed 27% in the range between 100 and 90 points, 34% between 89 and 80 points and also 34% from 79 to 70 points.

Figure 14 shows a chart with the scores' distribution in percentiles where each one represents a range of improvement: (I) 100–80%, (II) 80–60%, (III) 60–40%, (IV) 40–20%, and (V) <20%. In Q1021, 32% of the students showed a recovery of 20% or less in their scores, and only 12% upgraded their marks to the top percentile. In contrast, for Q1023, 30% fell into percentile (I), and only 13% exhibited progress of 20% or less.

Overall, the grades' increase was more noticeable in Q1023. This may be because it was a second online chemistry laboratory; consequently, students were already familiar with this teaching format and might feel encouraged to keep a positive attitude.

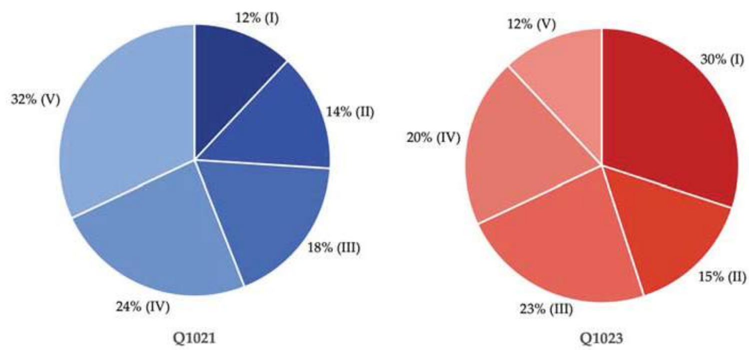

Figure 14. Students' distribution (%) in the ranges of scores' improvement (I: 100–80%, II: 80–60%, III: 60–40%, IV: 40–20%, and V: <20%) as a result of completing the courses Q1021 (blue) and Q1023 (red).

Moreover, the grade obtained was associated with a domain level of competency achievement. Figure 15 contains a scheme that illustrates these results, where both courses showed a similar distribution. That is, 68% of the students reached the maximum domain level (DL 3); 26% from Q1021 and 23% from Q1023 fell in the domain level 2 (DL 2); and 5% and 9% from Q1021 and Q1023, respectively, were in domain level 1 (DL 1). While in Q1023, everyone gained some competency domain level, in Q1021, only 1% failed to reach a certified level (DL 0).

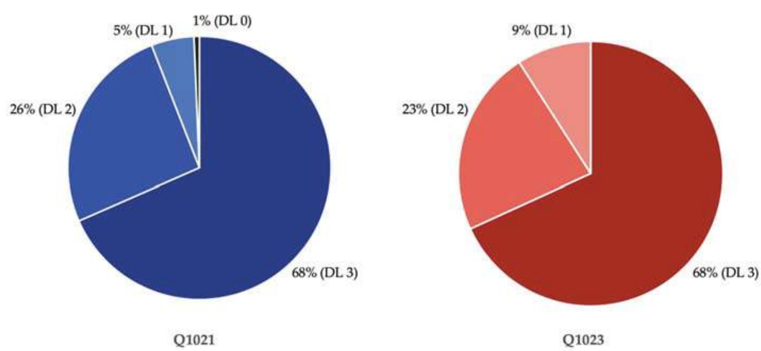

Figure 15. Students' distribution (%) of final grades (FG) in the domain levels (DL) of competencies achieved (DL 3: $90 \leq FG \leq 100$, DL 2: $80 \leq FG \leq 89$, DL 1: $70 \leq FG \leq 79$, DL 0: $FG \leq 69$) as a result of completing the courses Q1021 (blue) and Q1023 (red).

The expertise of the three institutional competencies stated in Section 2.3. was corroborated through the course evaluation instruments (Table 4), and, in turn, the learners stated their standpoint about their acquisition of skills C1–C10 (Figures 12 and 13). The results of the reports and quizzes were associated with the first competency (IC1) centered on being able to explain and demonstrate the behavior of observed phenomena through the application of the concepts learned (pertinent to C1, C2, C6A, C9A, C8B, and C9B). The experimental performance, the final exam, and the solution to the problem situation addressed the second (IC2), focusing on problem-solving, which includes a deep analysis of the case, taking decisions, and implementing actions that meet with the suitable standards (connected with C1, C2, C4, C5, C6B, C8B, and C10B). The experimental performance was further used to assess the third competency (IC3), which was mainly focused on the laboratory activities and statistical results management (linked to C1, C2, C3, C4, C5, C7A, C8A, C10A, and C7B).

The continuous evaluation promoted the mastery of the competencies. For instance, after each report was submitted by the students, the teacher provided formative feedback, which was ultimately reflected in an improvement in their grades and a better development of the procedural (IC3) and intellectual skills (IC1 and IC2). Specifically, by the end of the period, a better organization within the teams and a more accurate execution of the experiments were observed; likewise, an enhancement of critical thinking was appreciated in the discussions of the reports, the argumentation of the exams, and the elucidation of the problem situation.

The overall results were analyzed based on the learners' scores. From both courses, the average range of improvement fell in percentile III; i.e., Q1021 showed an upgrade of 41% (58 to 73 points) and Q1023 an advance of 55% (42 to 73 points). Since these marks were based on the diagnostic questionnaires that included the most important topics (safety, use of laboratory materials, basic operations, electrochemistry, stoichiometric calculations, kinetics, chemical equilibrium, acid–base titration, and statistical data analysis), this means that most of the students were able to achieve IC1 and IC2. The final average of both classes was 92 points; this mark is contemplated in DL 3, which stands for an excellent accomplishment of all institutional competencies.

The general impression of the students was that the laboratory could not be entirely substituted; this is supported by a low percentage of achievement of competencies C2, C3, and C10A. However, they not only believed they had gained the corresponding competencies (Figures 12 and 13), but the numbers prove the vast majority indeed reached an acceptable domain level (Figures 14 and 15). This is consistent with the idea of significant learning because the grades showed it was possible to assimilate concepts through at-home experiments supported with virtual tools (simulators and videos) [19,22,25,69].

5.4. Online Laboratory Course Experience

This section addresses a discussion regarding the sense of accomplishment after finishing the programs. This analysis involves two open-ended questions, and two items ranked with a Likert scale.

The feedback of the open-ended question "What were the two best aspects of your experience in this online laboratory course?", for both classes, showed responses confirming the participants were satisfied when they performed the experiments adapted for the remote sessions (27%) and when they used simple and accessible materials (15%). Other replies indicated that the activities helped them, whether to integrate knowledge (11%) or to achieve effective learning (15%); also, there were declarations referring to the relevance of the teacher's help and advice (11%). Additionally, a few students (7%) mentioned that the lessons were amusing and dynamic. Finally, a lower percentage (4%) considered that the class was challenging and motivating and that they rather use simulators and videos (3%). The remaining responses were random ideas that could not be categorized (7%). Figure 16 shows a word cloud with the most frequent responses.

Figure 16. Word cloud of the best aspects of the students' experience with the courses Q1021 and Q1023.

The students enjoyed experimenting because of the intellectual challenge, and they found the activities to be an adequate complement to the theoretical content. The fact that the materials were readily available also received good rates and, naturally, the role of the teacher was a medullar topic [11,19,20]. These results are comparable with the percentages shown in Table 5, where items E9 (clear instructions and appropriate guidance) and E10 (experimental activities contributed to understanding the concepts) had notably high percentages of SA/A scores. Likewise, this is supported by other studies published, where authors highlight the relevance of homemade experiments in learning achievement [13,14,21,22]. A small percentage of students mentioned the use of simulators as the best aspect (S2); specifically, in Q1023, the item related to this matter had the leading percentage (along with items E2, E6, and E9).

Concerning the second open-ended question of the survey "Could you mention two areas of opportunity (for improvement) that you have identified in this online laboratory course?", for both programs, 16% requested more accessible materials. Another 16% asked to improve the content in terms of workload; that is, to summarize the theoretical information before carrying out the experiments, in addition, to reducing the amount of homework, and other percentages (8%) mooted to minimize the content of the reports. Moreover, 13% pointed out it would be better to assign more time to each experiment. Further, there were criticisms related to the tutoring and demanded clearer instructions in each activity (12%), along with better guidance during the performance. The lowest percentages suggested limiting the use of simulators (5%) and enhancing teamwork dynamics (3%). Furthermore, 4% wrote responses related to improving their learning in a personal way and 15% just included general positive remarks. From all the commentaries, 8% were random and could not be categorized. The most frequent responses to this question are schematized in a word cloud presented in Figure 17.

Figure 17. Word cloud of the areas of opportunity according to students' experience with the courses Q1021 and Q1023.

In the first question, some students reported they were satisfied with at-home experiments using phrases such as *"the experiments were easily developed"* and *"the best experiences were the experiments done at home"*; the other group requested to review and better organize the classes and the necessary materials. Moreover, some of the phrases used were: *"the syllabus content is too long"*, *"ask for materials easier to get"*, and *"enhance the length of the sessions"* as improvement aspects. Accordingly, in Table 5, item E6 (related to the length of the experiments) was better ranked in Q1023 than in Q1021. Therefore, it is consistent with the recurrent recommendation about increasing the time designated to finish the trials.

An issue that resulted in divided opinions referred to the assistance. Examples of positive answers include: *"excellent teacher and guidance"* and *"I liked the explanation before the experiments"*; but some declared *"the teacher should provide more support"* and *"more detailed explanations"*. Despite several comments describing areas of opportunity, there were more opinions expressing approval of the design, the experiments, and the teachers' role.

The results of the surveys concerning the students' expectations about the contribution of the online laboratory to their learning process and their feeling of accomplishment at the end are compared in Figure 18. The percentages of SA/A in Q1021 were 77% before and 92% after the course, respectively, which represents a 15% increment of fulfillment. In Q1023, initial and final percentages of SA/A were similar (93% and 91%, respectively); however, there was a slight decrease in the number of pleased participants. The percentage of neutral opinions in Q1021 decreased from 18% to 5%; unlike in Q1023, where an increment from 5% to 9% was appreciated. In Q1021, only 5% presumed this class would not contribute to their learning (SD/D), but this value decreased even more after the lessons (to 2%). In Q1023, this criterion decreased from 2% in the initial survey to 0% in the final inquire. The positive reception at the end surpassed the expectation, and the learners who initially felt they would not be part of a valuable experience changed their perspectives.

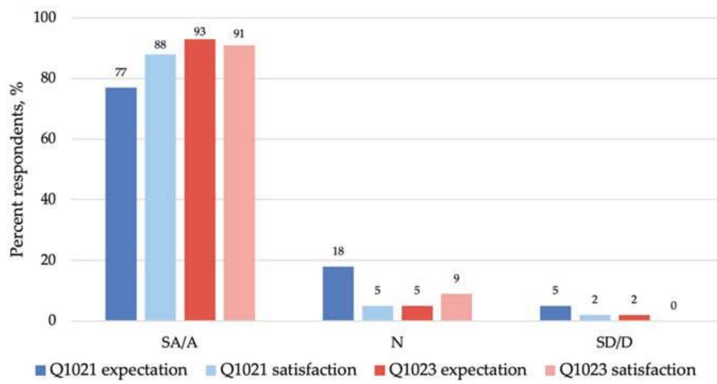

Figure 18. Students' distribution (%) of their perception before (expectation) and after (satisfaction) the courses Q1021 (blue) and Q1023 (red) (SA/A: strongly agree/agree, N: neutral, SD/D: strongly disagree/disagree).

One decisive parameter of the effectiveness of this adaptation was whether the students would recommend this online mode or not. In Q1021, 88% selected SA/A, 7% N, and 5% SD/D; and in Q1023 81% chose SA/A, 14% N, and 5% SD/D. Although around 5% would not recommend this remote laboratory, a much higher percentage (i.e., about 85%) of the participants from both courses would strongly recommend this class format (with at-home experiments, videos, and simulators).

6. Conclusions and General Recommendations

This paper presents a brief description of simple experiments that cover the topics of an introductory chemistry course at an undergraduate level. The idea arose from a worldwide necessity where the COVID-19 pandemic demanded distance teaching. The proposed activities can be carried out safely at home since they are planned to be conducted with materials and substances of daily use; nonetheless, the supervision of an expert is imperative.

Regarding the first question proposed in this work: RQ1. "*How to adapt a competency-based chemistry laboratory course to an online mode?*", a homemade chemistry laboratory was effectively remodeled with ten experiments. The implementation triggered the development of the institutional competencies and this was reflected in the results of the evaluation system.

The second research question, RQ2. "*How is the students' learning favored after completing an online laboratory course?*", was discussed according to the academic performance. There was a general increase in the scores of the diagnostic tests, detecting more than 60% of improvement in a quarter of the learners in the first period and half of the students in the second. In conjunction, about 70% of the applicants reached the highest domain level of competencies. These outcomes confirm a successful learning process.

In the last question, RQ3. *"What are students' perceptions after performing chemistry laboratory experiments with daily-use materials and substances?"*, the students believed their development of competencies was adequate. They felt more confident with competencies related to safety measures, explanation of redox reactions, expression of measurements, statistical data management, and prediction of chemical equilibrium shifts. The aspects more appreciated were: at-home experiments carried out with materials easy to gather, direct application of the topics, and the guidance provided by the teacher. On the other hand, optimal management of the content and workload were suggested as possible amendments. The general feeling after completing the courses was that these activities contributed to their training.

Altogether, this research showed that students can accomplish the learning goals and that although some participants had reservations about the format and were reluctant to be involved in this mode, after finishing the tasks, a feeling of general satisfaction predominated. Moreover, most of the class members declared they will indeed recommend this approach. Despite the great efforts, there will always be limitations related to the lack of actual laboratory facilities; for example, the skills to handle real laboratory glassware and specialized equipment may not be attained. The competencies supported in these courses were evaluated within the online conditions; however, the real acquisition of these skills might only be corroborated when students have access to an actual laboratory experience.

The instructor's role was revealed to be a key factor. This involves preparing and organizing the program, giving clear lectures, supervision, and the general assistance provided, such as being available out of hours to work out doubts or to offer supplementary explanations. In addition, the leadership shown promoted a friendly and motivating environment, not only from the perspective of the members' interaction, but also it made the student more willing to learn, to gather the materials, and to get involved in the lessons; collectively, this aroused their scientific awareness. The most important value transmitted by the teacher was to keep a positive attitude and an open mind since skills and knowledge can eventually be gained.

This study shows that even though there may be restrictions in a remote laboratory, there are also many alternatives that could be implemented without compromising the educational quality. It also opened an opportunity to research for new best practices for the following times that may further be applied in other contexts, such as hybrid formats, international groups, lectures where the presence is not mandatory, hands-on workshops, in low-income areas, or at-home review exercises. This work intends to encourage students and teachers to get involved in new activities with the available resources to achieve an enriched understanding and enjoy the experience.

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Case Study of Multi-Course Project-Based Learning and Online Assessment in Electrical Engineering Courses during COVID-19 Pandemic

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Abstract: Due to the COVID-19 pandemic, there was an urgent need to move to online teaching and develop innovative teaching techniques to ensure that student learning outcomes (SOs) were fulfilled. This paper tries to answer the important question of whether an established teaching strategy through a multi-course project-based learning (MPL) approach, along with online assessment techniques, helps in the effective achievement of SOs in a senior-level electrical engineering (EE) course. The authors have developed a course project for attaining the objectives of a senior and a capstone course, where students are registered at the same time. In addition, the course conducts assessments online. The paper reports the effect of the two approaches on the attainment of the SOs of the two courses, along with testing the programming and problem-solving abilities of the students. It is known that the MPL approach enhances the critical thinking capacity of students, which is also a major outcome of Sustainable Development Education (ESD). It was ensured that the project that was used to test the fulfillment of a series of SOs were concentrated on soft engineering and project management skills. The difficulty of adopting the MPL method for the senior-level courses is in the scheduling of the course materials to help the student advance to the final project while also aligning the project towards fulfilling the learning outcomes of the individual course. The study also provides the students with feedback on online assessment techniques incorporated within the MPL. Besides this, the effect of the innovative teaching approaches was compared with the same senior course taught using conventional methods in an earlier semester. Based on the feedback from teachers and students from a previously conducted case study, it was concluded that the MPL approach had supported the student learning. The results of the statistical analysis (Chi-square, two-tailed T statistics and hypothesis testing using a z-test) show that an MPL approach and online assessment improved the attainment of the SOs despite the constraints posed by the pandemic.

Keywords: engineering education; online assessments; COVID-19; multi-course project-based learning (MPL); Sustainable Development Education (ESD)

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1. Introduction

To develop a sustainable, environment-friendly, and conscious society, it is advisable to use technology, innovation, and especially the active participation of student learners in university courses. The application of the above approaches involves a wide range of abilities, such as the creative resolution of problems and collective decision-making [1,2]. The traditional curriculum approaches need to be changed [3], and several creative instructional methods need to be implemented for making the students active observers and prepared with Education for Sustainable Development (ESD) skill sets, which are currently highly demanded [4–9]. Petousi and Sifaki in [10] conclude that new grounds for building trust and confidence in science are needed for sustainable development and to avoid harm in the form of normative dissonance for scientists and loss of trust in science. In a recent publication [11], the authors have highlighted an improvement in the learning outcomes as a result of the inclusion of ESD in the curriculum in the form of multi-course project-based learning (MPL), which is used as a guideline for the study discussed in this article. In their previous work [11], they stressed the applicability of MPL, i.e., a project which was used in the assessment of different courses. The main motivation of this approach was the students not being able to create a successful working prototype using the ideas provided in each course separately. Moreover, due to the workload of multiple projects in different courses, the students have a hard time dedicating time to each of the projects and thus do not get enough time to produce quality output. An MPL experience was shared in [12], where MPL was utilized in a software development assignment. In a recent work, researchers stressed the notion that realistic multi-course lessons in the form of a project would help to encourage students in understanding and applying their technical expertise to an engineering project [13,14]; this demonstrates how capability set deficiencies in traditional curricula were resolved by using the proposed approach of having a project span over multiple semesters. These studies do not report how the projects were planned and executed, and do not include a comprehensive comparative study in terms of efficacy. This paper gives a detailed overview of how, in a series of steps, the authors introduced an MPL (Figure 1). In addition to modifying the standard curriculum to integrate ESD, one of the main reasons for this case study was to affirm the success of a multi-course initiative in achieving student learning outcomes and promoting project-based learning (PBL). PBL aims to improve study methods while studying real-world problems and is appealing to learners as well [15]. A similar MPL was implemented by the authors in [11], where they used two junior level undergraduate Electrical Engineering courses and showed that such an implementation is appreciated by the students, while also successfully achieving the Student Learning Outcomes (SOs) for the courses involved. The authors have also shown via a step-by-step approach how such an implementation can be done for undergraduate level university courses. This approach could be further verified in the new education paradigm, i.e., online learning, due to the pandemic.

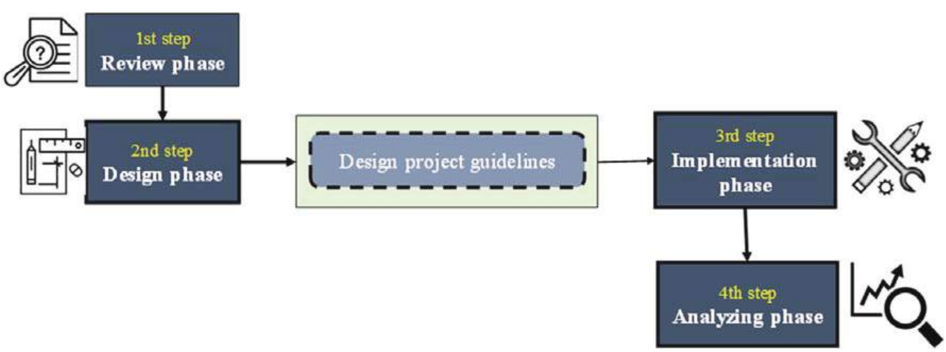

Figure 1. Important phases of the research.

When the coronavirus disease 2019 (COVID-19) outbreak was declared as a global pandemic by the World Health Organization (WHO), education at all levels was significantly affected, and much research was carried out into innovative teaching methods to reduce the loss. Many articles discussed the approaches adopted to tackle the hindrances caused by the COVID-19 pandemic to medical studies [16–20]. The articles discussed flipped classrooms, online practice questions, teleconferences instead of in-person seminars, engaging residents in telemedicine clinics, procedural modeling, and the use of video surgeries as a creative alternative. Although there is no replacement for realistic learning from direct patient care, these alternative ways reduced the limitations of learning during the pandemic. Wei Bao, in [21], conducted a case analysis on online education at Peking University and presented six unique instructional techniques to outline the existing online education experience for university instructors. The study concludes with five high-impact online learning principles: (a) high relevance between online teaching design and student learning, (b) efficient provision of online teaching knowledge, (c) adequate support given to students by faculty and teaching assistants, (d) high-quality engagement to expand the scope and depth of learning for students, and (e) a contingency plan to deal with unforeseen online education network accidents. Laskaris et al. in [22] centered on the evaluation of an online course conceived and built for the University of Athens's Department of Communication and Media in the framework of blended learning. The course was designed around the ideas of distant learning, and it was implemented as an action research project across three semesters using the open-source learning management system Moodle (2014–2016). The research findings indicated elements connected to expression of interest, encouragement for participation, and the motivation of students to infiltrate, assess, and contribute to the redesign of the e-educational course's material as a case study. The same set of authors have, in [23], extended their research to investigate the management of e-courses through the implementation of a prototype model of digital learning called 'Interactive Evaluation', which has laid some initial foundation for the current framework that is proposed in this paper.

Academic program accreditation is highly demandable all over the world among university students, and there have been studies where universities have tried initiatives to have their courses aligned to course learning outcomes (CLOs), which are then mapped to Program learning outcomes (PLOs). Aziz and Hashem have, in [24], iterated the importance of ABET accreditation and have used a fuzzy logic based assessment to have a fair, unbiased grading system and to improve the grading system to prepare for ABET accreditation. Another similar approach was reported by Alhakami et al. in [25], where they performed an analysis of students' performance and accomplishments regarding ABET course files learning using data mining approaches such as Naïve Bayes and a decision tree. In [26], Sarker and Ketkar discussed the importance of assessment and improvement in ABET accredited programs. They have stressed the importance of obtaining student feedback their continuous improvement, along with the design of some assessment tools for their effective use in the process of the continuous improvement of programs. In [27], Saeed et al. discussed the importance for all education programs of designing an appropriate program assessment approach to ensure a sustainable process to foster better learning among students using the case study of the ABET accreditation performed at the universities of the Kingdom of Saudi Arabia. The same authors have published another article where they have stated the unique aspect of institutes in certain regions consisting of segregated male and female students to respect the cultural norms of the society and how that is addressed for ABET accreditation. Recently, many studies discussed the effect of the Pandemic on the Accreditation Board for Engineering and Technology's (ABET) accredited programs. Hussain et al. [28] have proposed a novel remote evaluator module that enables successful virtual ABET accreditation audits during the pandemic. Detailed results and discussions of the paper show how the various phases of their framework help to qualify the context, construct, causal links, processes, technology, data collection, and outcomes of comprehensive Continuous Quality Improvement (CQI) efforts. The same group of authors presented an assessment model in [29] that used web-based software and embedded assessment technology to collect and report accurate cohort outcomes for credible multi-term evaluations. This model could also identify trends in student outcomes and evaluate the impact for three engineering programs using regression analysis. In [30], Supernak conducted an online survey to discuss the impact of COVID-19 on students' learning and concluded that COVID-19 did not alter their positive perception about the student outcome (SO) coverage in their courses. They also concluded that courses and SOs that were significantly negatively affected by the COVID-19 restrictions were the ones that had to rely on lab experimentations and student teamwork. Similarly, in [31] Szopinski and Bachnik have discussed the student evaluation of online learning during the COVID-19 pandemic and highlighted the obvious fact that regarding student engagement, nationality determines the frequency of participation in online courses.

Despite the recent growth in the innovative teaching strategies adopted by engineering courses, there is a need for empirical studies demonstrating education for sustainable development. Thus, this paper contributes by showcasing the use of MPL, online teaching and assessment, and a detailed framework. The implication of the MPL approach is investigated based on student feedback and performance.

To develop the programming and problem-solving abilities of undergraduate Electrical Engineering (EE) students at Qatar University, two senior-level courses were selected in Spring (January to May) 2020. The first one was an elective course, entitled 'Wireless Network and Application' (ELEC 472), and the second one was the 'Senior Design Project II' (ELEC 499), a capstone course. To integrate ESD in the courses and to meet the criteria set by the industry, and also to raise the level of participation of students in problem-solving and independent study, the curriculum as well as the instructional approach of the elective course were changed. The students were asked to focus on an MPL, and the instructions were structured to enable collaboration on a project involving the knowledge and skills learned in both courses. The project-grading rubric was structured to fulfil the requirements of the learning outcomes of both courses. The paper also used the study reported by Petousi and Sifaki in [10] in taking special care of the ethical issue.

Thus, the contributions of the paper can be highlighted as:

i. Developing a novel MPL framework for a senior level Electrical Engineering Course and Capstone course,
ii. Investigating the impact of the MPL framework on student performance using surveys and comparison of student assessments,
iii. Analyzing the effect of online teaching along with other innovative approaches for engineering courses, with suggestions that can be added for future implementation.

Based on the scope and contribution stated above, the research questions addressed by this paper are:

1. How can we design and conduct a multi-course project-based learning?
2. What are the students' perceptions towards the MPL implementation activities and online assessment technique?

The questions are unfolded in the article as follows: Section 2 describes the MPL approach applied in this study. Section 3 presents the research methodology for both the implementation and analysis of the implementation, covering both the research questions. Section 4 presents the results of the analysis and an assessment of the impact of MPL study in terms of how well the students have attained the learning outcomes. Section 5 discusses the findings and recommendations for the changes based on input from the instructors and students, along with the proposed MPL framework that can be replicated in other engineering courses. Finally, Section 5 proposes an appropriate conclusion for the study.

2. Theoretical Background

Project-based learning (PBL) is the fundamental framework for MPL and PBL, and helps students to implement projects with self-learning and minimal mentoring [11,32]. PBL depends on an involved, interconnected, and positive learning process, informed by social and contextual influences, which is necessary for learners to develop skills for an improved sustainable future [33–35]. The PBL methodology should provide the following features: student-centered learning limited to a group of students, an instructor as a tutor or guide, and challenges being posed to help the student self- learn the course-related advanced knowledge that can be used to overcome them [9,35]. The successful introduction of PBL in engineering education at the University of Aalborg, Denmark can always be used as a reference [35–37].

In MPL, explicit project rules/instructions stating the deliverables and a detailed rubric to a grade are key parameters [11,32]. The instructions will prevent any misunderstanding among the students about how to present the project and illustrate the specifications of each course. It is also important that the project-grading rubric should follow the learning outcomes of the involved courses. The MPL requires specific and concise guidance, including coordination and adaptation to the previous experience of the students [38]. MPL believes in engaging in groups to solve challenges together with their creative thinking, where the teacher is just a facilitator in collective learning [33–35,39]. These methods help students to be prepared for the competitive market that is always seeking people with skills for a sustainable solution and also can communicate it intuitively to an audience [40]. Studies involving surveys on the effects of PBL on ESD teaching in European institutions of higher education have been conducted in [41] and in a technical university in Malaysia in [42] with positive results providing confidence to the study. In Germany and Vietnam, similar studies were also performed in [43] and [44], respectively. As stated earlier, all the studies did not provide a step-by-step approach demonstrating how such MPL can be implemented, and its effect analyzed. This study is trying to fill this gap.

3. Research Methodology

This case study explores the context of integrating two senior courses (mandatory and elective) with the same project-based assessment. This study redesigns and tests an MPL case in four phases: a review phase, a design phase, an implementation phase, and an analysis phase (Figure 1).

The methodological approach was discussed in detail in the authors' previous work [11]. This can be considered similar to the process groups of a project (according to Project Management Book of Knowledge PMBOK [45,46])—Initiation, Planning, Execution, Monitoring and Control and Closing, with the difference being that Monitoring and Controlling and Closing phase is combined as analyzing phase. As in any project, the planning phase is the most crucial and it is the review and design phase where the planning is done. The first phase of preparation entails the teacher planning the activities to be performed in the course, in the form of relating the learning methods of the two courses. The concept of the project and its evaluation schedule are conducted in the second phase. In the third phase, the execution of the action plan is carried out in accordance with what was designed/planned. The fourth stage is an observation and reflection phase, in which actions are documented during the research. At the end of the analysis, the reflection process is carried out with the data collected to criticize the method and recommend the appropriate changes, i.e., the proposed replicable framework in this paper. In the following sections, the details (study participants and the details of the phases) are presented.

3.1. Study Participants

As stated earlier, this study was conducted at the Department of Electrical Engineering, Qatar University, Doha, Qatar, similar to ample studies that were conducted relying on the student perception by means of survey to show the effect of an applied pedagogical approach [47]. In the Spring 2020 semester, the thirty-three students of the Elective Course entitled ELEC472: Wireless Network and Applications and ELEC 499: Senior Design Project II were involved in this study. There were 19 male students and 14 female students who participated in this study, which was reasonable for the study conducted for a senior level course [48,49].

3.2. Review Phase

The Electrical Engineering Department of Qatar University is an Accreditation Board for Engineering and Technology (ABET) accredited units of higher education. All the courses have Course Learning Outcomes (CLOs), which have to be linked to the ABET student learning outcomes (SO's)—i.e., (a). Thus, the course instructors evaluated the learning outcomes of the senior course (ELEC 472) and tested if there was any chance of designing a project that could be used to test courses' learning outcomes and at the same time help in fulfilling some of the course learning outcomes of the capstone course (ELEC 499).

An MPL was finalized as an assessment method to fulfill most of the course learning outcomes for the two courses (ELEC 472 and 499) after close analysis of CLOs with the SOs for the courses. A project for the design concept was allocated to analyze the cumulative CLOs for these courses. The project was to develop a mobile application that could be used to present the results of their capstone project (ELEC 499) using the concepts students were learning in their ELEC 472 course. The project guidelines can be found in Figure A1 in the Appendix A. Online exams were used as an assessment approach to avoid the students coming to the campus physically due to the pandemic. The periodic quizzes in the ELEC 472 course and progress reports were used as formative assessments, and the final project submitted as part of the courses was used as a summative assessment.

3.3. Design Phase

Once the CLOs wee mapped to the SOs, and the SO that was to be assessed was determined, detailed project guidelines and a respective grading rubric needed to be designed. This would provide details to the student concerning the implementation of the project and how they were to be evaluated. According to the course-learning outcome of the two courses, project grading rubrics and weights were defined. Sample Project guidelines (Figure A1) for ELEC 472 can be found in the Appendix A. A detailed orientation was conducted to introduce the MPL concept to the students. The orientation included discussing the flow of the course throughout the semester and what was expected from them. The orientation is highly important in allowing the students develop confidence in the approach, or else they will not enjoy and learn from the process. The orientation is followed with the course syllabus, which is a form of legal agreement between the students and the instructors. In addition, the students were also provided with training sessions with tools that could help in the efficient implementation of the project The trainings included lab tutorials on the use of the application that could be used by the different team members, how to manage their time effectively with the help of periodic meetings, meeting minutes, task assignments, and follow-up.

3.4. Implementation Phase

This process is involved in tracking and assessing the success of the study during the project and concludes with the fulfillment of project activities. The students are supported in executing their assignments using the comprehensive training session. Before the specific due date, the instructors have set deadlines to check the student's development to provide practical insights to help them progress. The students are made aware that the project involves a self learning approach.

The opportunity of self-learning in projects can help in increasing creativity. It can also enhance the practical application of the concepts that students are learning in the course, i.e., a mobile application development to enhance their implementation in the capstone course. It also helps the students in understanding more than what was discussed in the lectures through self-learning techniques. Three or four students who are working together in the capstone course form a team. With the conceptual phase of the project, this simple multi-course process begins, then verifies the structure in the simulation phase, and then tests it by integrating it with their capstone prototype.

3.5. Analysis Phase

The design of the learning activities and students' perceptions are investigated using the survey designed in the define stage, and the impact is investigated based on the project grades. The participants were advised that the purpose of the research was to see the students' views on the efficacy of MPL in the Electrical Engineering courses described above. The question was specifically crafted so that no redundant questions were asked, and the experience of the authors was used to prepare surveys that gathered the information that could be tested for relevant conclusions [50,51]. Strict steps were taken to protect the privacy of the participants and the secrecy of answers by preventing the identification of the participants. Besides this, the cumulative evaluation and disclosure of the data prohibited participants from being identified. The survey questionnaire was conducted to acquire students' feedback and questionnaire reviews as seen in Table 1. From the prior experience of the authors, who were the instructors of these courses, and feedback from students who took the course earlier, a successful and effective learning experience from the project approach was expected. Gender-based responses have been analyzed to further verify if the approaches are typically effective in a particular student community or for different gender groups. At the end of the semester, written evaluations of students and professors, students' project scores in the previous semester, and the current semester in which the MPL was conducted were recorded to evaluate whether the results comply with the expectation or not. The students' MPL scores were used for assessment. Further, many of the exams were changed to online assessment to analyze the effect of online assessment.

Table 1. Survey questionnaires.

	Questions Statements
MPL approach for a senior-level course and the capstone course	• Was the Mobile Application development project of the course an effective self-learning process? • Was the Mobile Application development project helpful in your Senior Design Project (ELEC499)? • Do you think the Mobile Application development project helped in developing real-life problem-solving skills? • Did the Mobile Application development project work in a group help in improving teamwork skills?
Online Assessment technique	• Was the time for the online quizzes enough? • Are online quizzes as convenient as paper-based quizzes? • Was the format of online quizzes and feedbacks helped in a clear understanding of the concepts? • Were the online video lectures convenient due to the options of stop, play, and pause?

The authors have used statistical analysis tools such as the two-tailed *t*-test, Chi-square analysis and hypothesis testing using z-test on R software. Details of the statistical analysis are in the results section.

4. Results

The two research questions are unfolded by Section 4.1, proposing a framework for the design and implementation of MPL, and Sections 4.2–4.4 evaluate its implementation based on students' perception towards MPL activities, comparing students' results on former non-MPL and current MPL courses, while Section 4.5 observes creativity in project deliverables.

The evaluation of the MPL implementation is conducted in four ways: Section 4.2 compares the overall course grade with a previous semester when the same course was taught by the same instructor, Section 4.3 investigates the effect of online teaching during MPL Implementation by comparing the similarity between the responses of male and female students using a *t*-test, and Section 4.4 chi-squares statistics to investigate if the survey results are as per the assumptions perceived by the author while implementing it. Section 4.5 analyzes the observations of the project deliverables for evidence of the creative thinking of the students.

4.1. Framework for Designing Multi-Course Project-Based Learning

In a previous study [11], the authors presented a framework for the design and implementation of MPL, which received feedback from instructors and students. A revised framework flowchart is presented in Figure 2, which was implemented in this study and can be replicated in other programs.

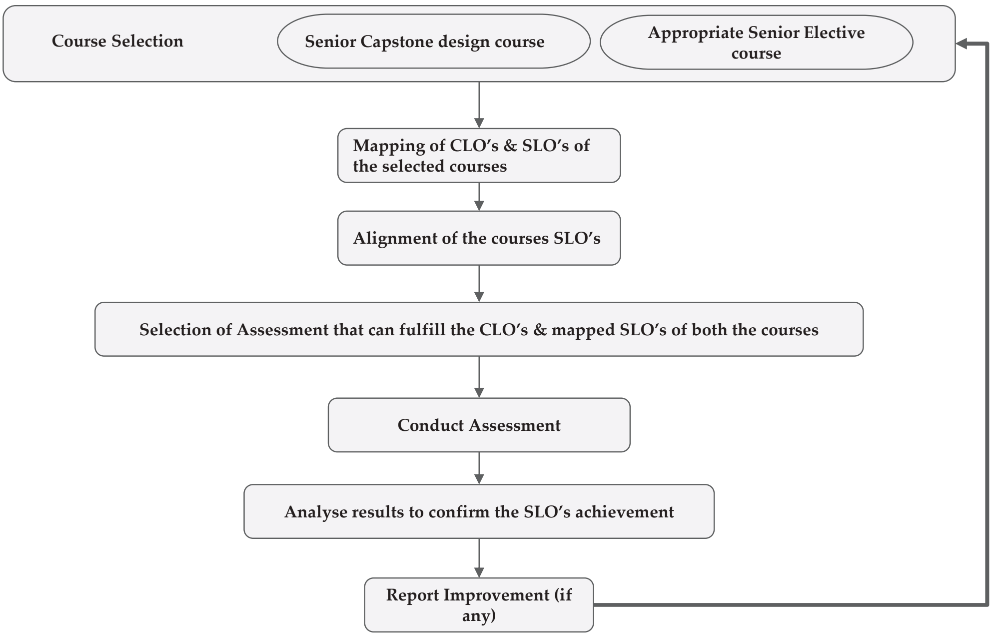

Figure 2. Proposed Framework flowchart.

First, the courses are selected for the MPL. It is important to have one senior capstone or mandatory design course, and the other course can be any senior level elective course. Second, the Course Learning Outcomes (CLOs) with the Student Learning outcomes (SOs) are mapped, as shown in Figures 3 and 4. Third, the SOs have to be decided, which is fulfilled by both the courses, i.e., stated as an alignment of the courses' SOs in the flowchart (Figure 2). Fourth, there should be a discussion of the assessment that can be used to fulfill the CLOs and the corresponding SOs (which was already decided in the previous state) of the courses involved. Fifth, the assessment is conducted. Sixth, the results are analyzed to confirm the performance of the students and validate the effect of the framework. Finally, the scope for improvement is reported on.

The central crucial activity is the mapping of the CLOs with the SOs of the selected courses, which is shown in Figure 3 (for course ELEC 472) and Figure 4 (for course ELEC 499).

The project was used to evaluate the CLO "h" of ELEC 472 and the CLO "e" of ELEC 499. Each of the CLOs is associated with achieving the common SO 3.

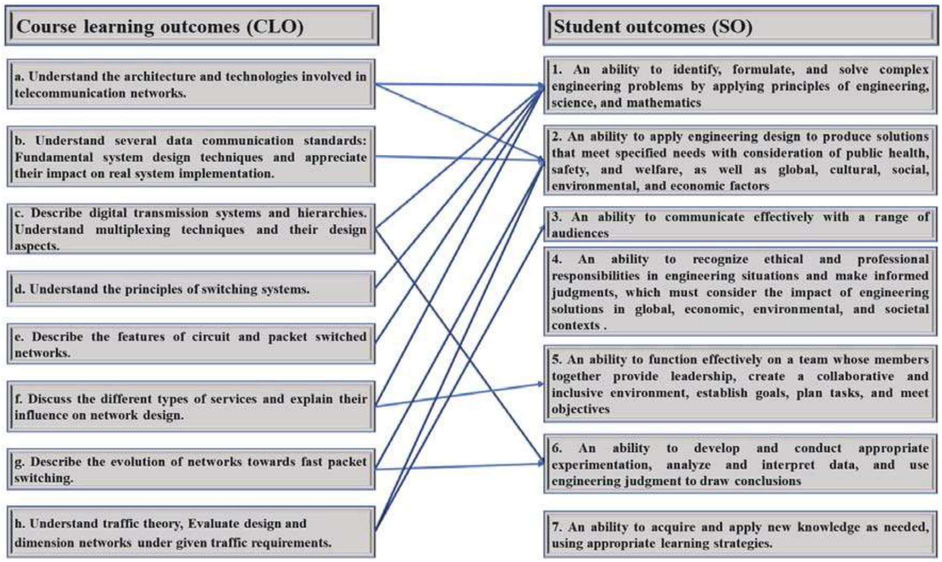

Figure 3. CLO and SO mapping of ELEC 472.

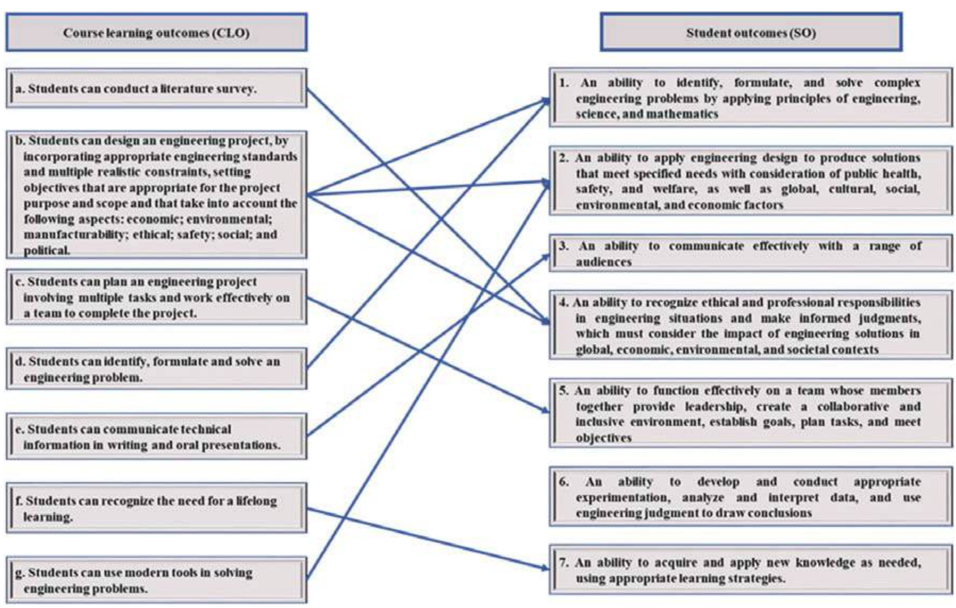

Figure 4. CLO and SO mapping of ELEC 499.

4.2. Investigation of the Impact of MPL Implementation on Students' Performance

This section covers the second contribution of the paper by investigating the impact of the MPL implementation on students' overall course grade by comparing the MLP-implemented semester (that is, Spring 2020) with the previous semester. Course-wise, course grades from the two semesters were compared gender-wise and overall.

Figure 5 shows the letter grade distribution during the two semesters. A higher number of students obtained better grades (A, B+, and B) when the MPL and online assessment were implemented. Therefore, there has been a positive effect of the MPL and online assessment approach on the students' grades in the 'In-COVID-19 semester'. Moreover, it is also interesting to see that none of the students were in the lower grades, such as grades D and F.

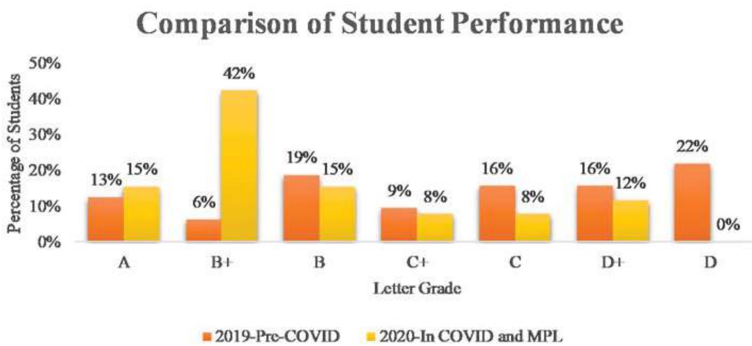

Figure 5. Comparison of the overall course grade in the two semesters.

The improvement in student performance in the MPL implementation during the COVID-19 teaching period was also confirmed using the z-test using R-software, where the below hypothesis was accepted using the statistics in Figure 5.

Hypothesis (H_0): The probability of obtaining an A and B+ is larger in MPL-designed course participants than among the non-MPL students.

4.3. The Effect of MPL Implementation

An analysis of students' responses regarding their experience during the course shows the effect of online teaching during MPL implementation.

The survey questions was structured in such a way that the responses help to examine the conclusions of whether the students found the MPL, online assessment, and online lecturing helpful. A detailed two-sample *t*-test was conducted on the survey results from the Male and Female students. The responses of the students in Figure 6 were used in the two-sample *t*-test analysis to conclude from the student responses.

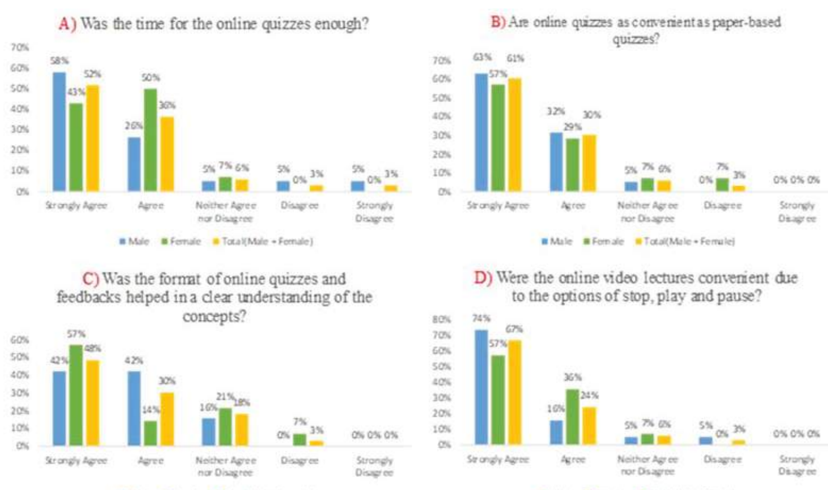

Figure 6. *Cont*.

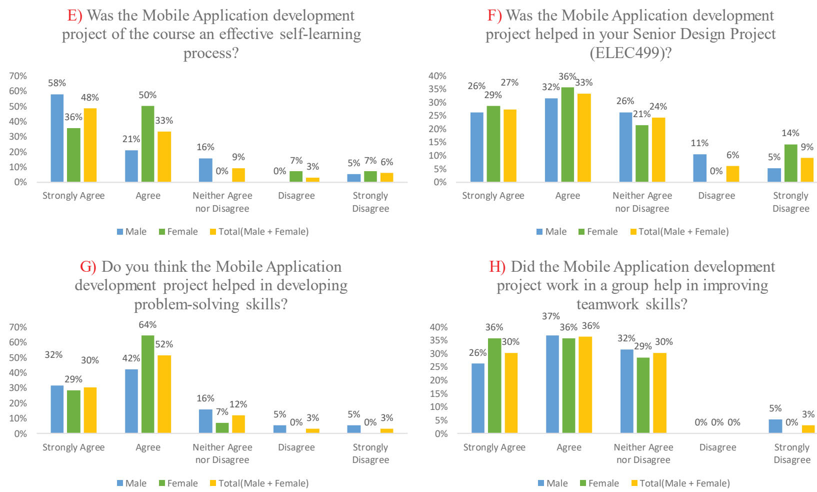

Figure 6. Summary of the student response from the survey questions.

Table 2 summarizes the results and interpretations of the *t*-test analyses. This will be used to make suggestions and concluding remarks from this case study and also to assess the findings of the study. Moreover, the questions were designed specifically to obtain feedback on the online assessment technique and the MPL approach, as shown in Table 2.

Table 2. Outcomes and conclusions from the Two-sample paired *t*-test on the survey answers.

Category	Questions	Two-Sample *t*-Test Analysis	Conclusions Drawn
Online Assessment technique	Was the time for the online quizzes enough?	μ_m = 1.74 μ_f = 1.64 Not Significantly different	The quizzes that were covering important topics to be assessed in the course were designed well, with the majority of students agreeing that the time was enough.
	Are online quizzes as convenient as paper-based quizzes?	μ_m = 1.42 μ_f = 1.64 Significantly Different	The response is mixed, with a majority of the males having responded that the online quizzes were as convenient as written quizzes, whereas some females disagreed.
	Was the format of online quizzes and feedbacks helped in a clear understanding of the concepts?	μ_m = 1.74 μ_f = 1.71 Not Significantly Different.	The response is really important to understand the effect of the quizzes helping to comprehend the concepts of the course. The similar positive response of both the students is really motivating.
	Were the online video lectures convenient due to the options of stop, play, and pause?	μ_m = 1.42 μ_f = 1.5 Significantly Different.	The response is positive, with the majority of the students in favor of the videos due to the convenience, but some male students disagreeing with it as it provides less interaction

Table 2. *Cont.*

Category	Questions	Two-Sample *t*-Test Analysis	Conclusions Drawn
MPL approach for a senior-level course and the capstone course	Was the Mobile Application development project of the course an effective self-learning process?	μ_m = 1.74 μ_f = 2 Significantly Different.	There were mixed responses from the students, though the majority of the male and female students agreed to the effective self-learning process involved in the assigned project. This feedback is important to be considered in a future implementation where more guiding materials can be provided to the students to enhance their self-learning skills.
	Was the Mobile Application development project helped in your Senior Design Project (ELEC499)?	μ_m = 2.37 μ_f = 2.36 Not Significantly Different.	This was an important responsibility, as it helped in understanding the effect of MPL in achieving CLOs from both courses and the students understanding them. Both the males and females had the majority of the students in favor of the MPL approach, but there were some groups of students who were not impressed with the extra work involved in the project.
	Do you think the Mobile Application development project helped in developing real-life problem-solving skills?	μ_m = 2.11 μ_f = 1.79 Not Significantly Different.	This was an important response as it helped in understanding the effect of MPL in improving problem-solving skills. Both the males and females had the majority of the students in favour of this aspect of an implemented MPL approach.
	Did the Mobile Application development project work in a group help in improving teamwork skills?	μ_m = 2.21 μ_f = 1.93 Not Significantly Different.	This was an important response as it helped in understanding the effect of MPL in improving teamwork skills. Both the males and females had the majority of the students in favour of the this aspect of an implemented MPL approach.

4.4. The Effect of MPL Implementation Including Online Implementation Is Not by Chance

The authors assumed that the students would evaluate the MPL implementation, including the online activities, as having a positive impact compared with the reviews from the professors on the same course in the earlier semesters. This assumption was tested with the use of chi-square distribution [41] for comparing proportions from two groups [42]. All the survey questions were asked, and positive answers for the questions were predicted by the authors, i.e., the forecast of the authors. Based on the results obtained from the survey, and conducting chi-square analysis assuming alpha level (α) = 5 percent, the degree of freedom (c) = 4 (i.e., number of categories—1, there were five categories as shown in Figure 2). For all the questions, the authors have assumed the null hypothesis (H_0) as: students would respond positively (Strongly Agree or Agree). This inference was analyzed with the answer observed, and chi-square analysis was conducted to validate whether the assumption should be accepted or refused.

The implementation was carried out with positive assumptions, i.e., all the students either agreed or strongly agreed with the questions as stated in the previous analysis phase section, which as confirmed with the chi-square analysis carried out on the students' responses, as shown in Table 3. Besides this, chi-square analysis was carried out separately based on male and female responses to confirm the results. It was found that the results were similar (Table 3).

Table 3. Chi-square statistics on survey responses.

Question Statement	Accept or Reject the Positive Prediction Based on the Chi-Square Analysis (*chi−square critical value*, χ_c^2 = 9.49 with Degree of Freedom = 4, α = 5%)
The time for the Online Quizzes were enough	$\chi^2(all\ students) = 1.87 < \chi_c^2$ $\chi^2(male\ students) = 2.25 < \chi_c^2$ $\chi^2(female\ students) = 2.80 < \chi_c^2$ Thus, Do Not Reject
The Online Quizzes are as convenient as the Paper written quizzes	$\chi^2(all\ students) = 4.33 < \chi_c^2$ $\chi^2(male\ students) = 3.5 < \chi_c^2$ $\chi^2(female\ students) = 1.87 < \chi_c^2$ Thus, Do Not Reject
The format of Online Quizzes and feedbacks helped in clear understanding the concepts	$\chi^2(all\ students) = 38.73 > \chi_c^2$ Thus, Reject $\chi^2(male\ students) = 5 < \chi_c^2$ Thus, Do Not Reject $\chi^2(female\ students) = 13.47 > \chi_c^2$ **Thus, Reject**
The Online Video Lectures were convenient due to the options of Stop, Play and Pause. It helped in going back to them for clarifying concepts	$\chi^2(all\ students) = 7.53 < \chi_c^2$ $\chi^2(male\ students) = 7.63 < \chi_c^2$ $\chi^2(female\ students) = 2.67 < \chi_c^2$ Thus, Do Not Reject
The Mobile Application Development Project of the course was an effective self-learning process	$\chi^2(all\ students) = 5.13 < \chi_c^2$ $\chi^2(male\ students) = 8.13 < \chi_c^2$ $\chi^2(female\ students) = 1.97 < \chi_c^2$ Thus, Do Not Reject
The Mobile Application Development Project helped in preparing for the Senior Design project (SDP 499) as it was linked with it.	$\chi^2(all\ students) = 53.47 < \chi_c^2$ Thus, Reject $\chi^2(male\ students) = 18.63 < \chi_c^2$ Thus, Reject $\chi^2(female\ students) = 6.67 < \chi_c^2$ Thus, Do Not Reject
The Mobile Application Development Project in group helped in improving real-life problem-solving skills	$\chi^2(all\ students) = 10.93 > \chi_c^2$ Thus, Reject $\chi^2(male\ students) = 4.5 < \chi_c^2$ Thus, Do Not Reject $\chi^2(female\ students) = 5.87 < \chi_c^2$ Thus, Do Not Reject
The Mobile Application Development Project in groups helped in improving teamwork skills	$\chi^2(all\ students) = 84.27 > \chi_c^2$ Thus, Reject $\chi^2(male\ students) = 27.75 > \chi_c^2$ Thus, Reject $\chi^2(female\ students) = 11.17 > \chi_c^2$ **Thus, Reject**

4.5. Students' Creative Way of Thinking

The MPL implementation was expected to engage students in group activities and demonstrate creative thinking while solving challenges together. The creativity of the students was observed while grading the final submissions. Figure 7 shows four screenshots of mobile application interfaces, which show the creative functionalities ideated for solving the problems of the respective projects. Since only one project had to be delivered instead of two different projects for the two courses, the additional time and the concepts learned from both courses enabled the students to be more creative. It is noted that creativity levels can be improved if the mobile application development project can be made a more effective self-learning process with the help of more guiding materials.

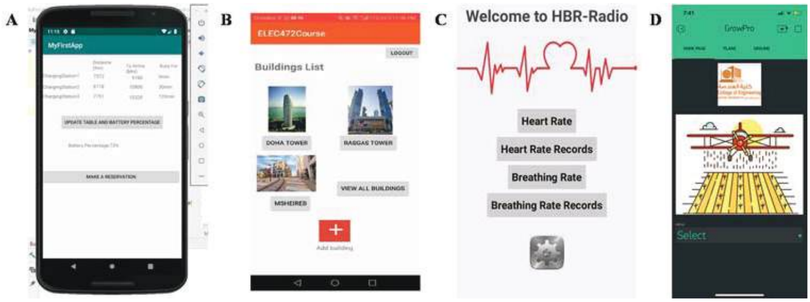

Figure 7. Screenshots of Mobile Application developed by students linking to their ELEC 499 course. (**A**) Mobile Application to book EV charging station, (**B**) Mobile Application to book drone cleaning services for the exterior glasses of a building, (**C**) Mobile application to monitor the ECG of the patients, (**D**) Mobile application to monitor the crop health and take necessary actions using drones.

5. Conclusions

This paper has tried to analyze the use of innovative approaches and online teaching on the effect of SO's attainment with the help of the respective assessment grades, comparing them with a previous semester where such approaches were not deployed. The paper has also answered the research questions that motivated the study by analyzing the effect of MPL on the student grades and also finding the student perceptions with the help of survey. The results are important for the research community to further improve our innovation with the proposed framework in preparation for the already existing hybrid teaching trend, which was a necessity during the COVID-19 pandemic. The adopted strategy has proven successful in promoting PBL's core values, with certain difficulties. Some students were unable to develop their comprehension because they felt the learning was too difficult and needed additional tasks. Some students had trouble operating in groups or teams, with some students not contributing at all to the projects and others contributing heavily and upsetting other team members. The teacher must be imaginative in order to resolve the problem of increasing the motivation of such students. To enhance teacher-student relationships, teachers must be able to solve problems, especially when working with students who have low abilities, motivation, or lack concentration [11]. Furthermore, students offered suggestions that indicated steps that could be taken to enhance the experience. The students also had concerns with interaction due to online assessment and teaching. The limitations of the study can be categorized into (i) theoretical framework and the activities for the development and implementation of the multi-course project-based learning, (ii) online assessment. The limitation of the theoretical framework was discussed in detail in the discussion.

There was a limitation of the online quizzes that could be improved to make it as convenient as paper-based exams with the help of equation editors and training the students on how to use them, as the students should be able to quickly write equations in their answers and then deduce the answers. The feedback for the quiz should be more detailed and should refer to the chapter, so that the students can use it to review it for future exams and so that it can be provided immediately after the test is taken. In order to do so, a large pool of questions should be provided to avoid students who finish the exam earlier sharing the questions and answers with other students. The feedback mechanism can also help the student to understand the concepts better. The online video lectures can be posted in advance for the students to refer them before the lecture so that during the actual lecture session more interactions are made possible by letting the students ask questions.

In summary, the outcomes of this MPL study contribute more than similar works conducted in PBL-based studies [43,44,50]. This paper discusses the step-by-step implementation of MPL for a senior and capstone course, which can help attain the competencies required for ESD. This is an extension of the work done by authors for two undergraduate courses in [11]. The limitations of the study (stated in the previous paragraph) could be further improved in a future implementation. The paper also talked about how online assessment can help in improving students' performance and learning, which is the need of the hour in pandemic situations. Some of the changes that can be made to make the methods more successful have also been outlined in this report. The authors have also found a positive response for the innovations implemented in this study, verified in Table 3. This paper discusses the effect of online assessment and MPL implementation for two senior-level courses and was designed to report the innovative teaching methods that can be useful for the pandemic situation. Innovative online teaching methods using online assessment and MPL can help in developing competencies in students to look for sustainable solutions. Positive feedback on this method was provided by the survey conducted at the end of the semester. Based on the students' feedback, suggestions can be made that would be beneficial to improving the approach. Being an ABET accredited program and having proper linking of SOs with CLOs, as well as having clear assessments to confirm the achievement of the CLOs [28,29,52], the student grades can help in understanding the impact of the implemented approaches. This can be further confirmed with a future implementation of the framework with the suggested improvement of the limitations stated by the students. This case study will be useful for inspiring engineering programs with more of these methods. The case study of an online course along with MPL for senior-level courses can also help in adding to the existing innovative teaching practices body of knowledge.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

SO	Student Learning Outcome
CLO	Course Learning Outcome
ABET	Accreditation Board for Engineering and Technology
MPL	Multi-Course Project-Based Learning
ESD	Sustainable Development Education
ELEC 472	Senior Course of Electrical Engineering Department of Qatar University T itled-Wireless Network and Application
ELEC 499	Capstone Course of Electrical Engineering Department of Qatar University Titled -Senior Design Project II

Appendix A

Figure A1. Project Guidelines screenshot and Text from the Learning Management System.

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Article

Impact of the COVID-19 Confinement on the Physics and Chemistry Didactic in High Schools

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Abstract: Online education due to COVID-19 confinement impacted the use of the Information and Communication Technology (ICT) in Spain, where it was poorly implemented. The aim of this paper was to inspect the methodological changes in Physics and Chemistry teaching during the confinement as well as in the ICT use and the lockdown impact afterwards. For this purpose, an online survey was administered by email to the Physics and Chemistry teachers of three provinces of Spain. Based on the analysis, the most widely used methodology was the traditional one. Still, during the lockdown, its use decreased, and others, such as the flipped classroom, increased significantly. Other adaptations included increasing the use of virtual simulations and self-learning by the student. It can be outlined the incorporation of new tools such as WebQuests, the smartphone, or online education platforms, whose use has continued. The ICT was used for new functionalities such as evaluation or answering student questions. According to the respondents, the lockdown had entailed that they strengthen implementation of ICT. In conclusion, there have been changes that have remained in the Physics and Chemistry didactic and in the ICT use due to the lockdown situation.

Keywords: educational technologies; digital technologies; teaching experiences; learning experiences; pedagogy

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1. Introduction

COVID-19 confinement caused an absolute rupture of the way life had been until then. Everyone was forced to remain at home and significant changes had to be implemented in order to minimize disruption on the economy and life. In this regard, education was one of the affected areas since there was a huge shift, especially in primary schools and high schools, from face-to-face teaching to online teaching.

Even if Information and Communication Technology (ICT) has a large presence in the classrooms, it has been proven that they are not really used during the lessons [1]. Nevertheless, due to the confinement, its implementation was imposed.

The aim of this article is to acquaint the changes in the Physics and Chemistry didactic due to the COVID-19 global confinement and its impact afterwards in the employed methodologies and in the use of ICT. For this purpose, an online survey was administered to the secondary teachers of Physics and Chemistry working in three provinces of Castille and Leon, Spain.

For this purpose, first, the situation of the ICT in high schools in Spain was analysed, as well as its main applications in the Physics and Chemistry didactic and the difficulties encountered to implement them in the classroom. In addition, the use of the ICT during the confinement is presented in the introduction. Next, the methodology employed is described. Then, the results are analysed, and last, we present the the discussion and the conclusions of the paper.

1.1. Situation of the ICT in Spain and in High Schools

The proportion of high schools with Internet access and computers was 100% in Spain in 2020. Moreover, 95.4% of households report to have an Internet connection and 91.3% of people used it frequently, at least once a week [2].

During the 2018–2019 academic year, the number of students per computer was 2.9 in high schools; 96.7% of the classrooms had an Internet connection, and 60.1% had interactive digital systems. Besides this, 89.1% of the educational centres counted with a website. Many centres, 45.4%, employed learning visual environments, which allow the interaction of the students so that they can continue with the learning process, and 59.2% supplied cloud services. Lastly, the mobile phone was used in 42.2% of high schools for younger students, and 50.2% for the older students [3].

Hence, high schools in Spain account to have a good supply of technology as well as Internet connection. Nevertheless, they were not that widely used, and the resources employed were very limited, as explained in the following section.

1.2. Causes of the Low Implementation of ICT in the Classrooms

The application of ICT in education is very limited [4–6]. ICT is barely used in comparison to the presence they have in high schools [7]. Moreover, the supply of ICT in the classroom has not meant almost any changes or adaptations in the teaching methodologies [5,8,9].

Some of the causes of this low use are the need of methodological changes in order to integrate ICT into the classes, which take time; the adaptability of educators to change, since they are comfortable with the methodologies they already know [10,11]; and the lack of knowledge on how to implement ICT in their classes [6]. Other causes are the poor formation of ICT tools and applications [9,11], together with the insecurities it generates or the frustration when the exercises implemented do not have the expected outcome.

Because of that, the ICT are mainly used by means of the traditional methodology for exposition or search purposes, and there is no real application of all the available resources [1].

1.3. Main Applications of ICT in Education and for the Physics and Chemistry Didactic

Even if not frequently implemented, some of the most common applications of ICT are short research on the Internet, and assignments and presentations with PowerPoint or the virtual classroom [9,11]. Interactive digital boards are also employed [12].

As for the Physics and Chemistry didactic, other applications are the use of simulators to illustrate phenomena, explanatory videos or measuring applications [11,13]. Nevertheless, there are a wide variety of methodologies or projects that could be implemented by means of the ICT but there is no real place for them in most of the classrooms. Some of them are the use of projects to research about everyday phenomena by implementing the scientific method and the ICT [8] or the use of WebQuest to guide the student in long projects [14].

Nonetheless, COVID-19 confinement necessitated the change from in-person to online education, forcing the use of ICT and a total rupture with classic high school education.

1.4. Ict Use and Didactic during Covid-19 Confinement

The COVID-19 confinement led to a complete shift from face-to-face teaching to fully online education in Spanish high schools from 12 March 2020 until the end of the academic year (30 June 2020). Because of this situation, teachers had to adapt and transform their didactic in order to perform online teaching [15]. Some of the taken measures were the use of online environments, the creation of online content and the implementation of online evaluation. It supposed a situation of huge learning of ICT tools by the educators. Online platforms, such as Zoom or Classroom, were used in order to interact with students; new materials, such as infographics, podcasts or applications, were also implemented, as well as new activities [15].

Besides these, there was a need to adapt the methodologies that had been employed until then, since technology as the main educational resource had never been used before [16–18]. In terms of online education, active methodologies are considered as the ideal ones. In them, the students are mainly responsible of their learning and they are more autonomous. These methodologies include project-based learning or the flipped classroom [19,20].

Thus, COVID-19 confinement entailed a completely new teaching situation, shifting from in-person to online education. Because of that, new resources, applications as well as methodologies should have been used during this period. Still, it demands the question whether physics and chemistry teaching was really adapted or if the methodology changed during that period.

1.5. Research Objectives

COVID-19 confinement should have led to a complete adaptation of the teaching methodology as well as to the adoption of new ICT resources. Before the lockdown, most educators implemented the traditional methodology with a very limited use of ICT in their classes [1]. Nevertheless, in terms of online education, active methodologies are recommended, and the education process must be implemented by means of the ICT resources.

Hence, the aim of this article was to learn about the changes that the confinement situation led to in the teaching methodologies and in the ICT tools being employed for teaching. Moreover, it was of interest to study if these tools have remained in education with the return of face-to-face education.

In more detail, the specific objectives were:

(i) Researching the methodologies that had been used for the didactic before, during and after lockdown.
(ii) Learning how ICT was used for the Physics and Chemistry didactic and how the lessons were taught during confinement.
(iii) Learning about the changes that there had been in the ICT implementation in the Physics and Chemistry didactic before, during and after confinement, as well as the ICT tools and resources that had been implemented.

Once the objectives were defined, the research technique was chosen as described in the methodology. For this purpose, an online survey was implemented and was answered by Physics and Chemistry teachers in some of the regions of Castile and Leon in Spain.

2. Materials and Methods

In this article, a social investigation was implemented. In order to achieve the research objectives, a self-administered online survey was designed and completed by secondary school Physics and Chemistry teachers in the regions of Salamanca, Avila and Zamora in Spain. This research technique was chosen so that the largest sample could be reached and to collect the maximum number of responses. Hence, for this purpose, first, the survey was created (Section 2.1), then, the data was collected by sending the survey access link to the teachers via email (Section 2.2), and last, the responses were analysed (Section 2.3). The phases of the whole research process are summarised in Figure 1.

2.1. Questionnaire Development

The questionnaire was designed based on the literature review and on the defined objectives. Some of the questions from the survey were directly extracted or adapted from similar questionnaires [4,11,21–25]. Besides this, the ICT tools, websites, platforms and so on, asked on the questionnaire were the ones that are used in the high schools based on the bibliography research.

The development of the questionnaire and the final drafting of the questions involved different stages of refinement and correction. First, the topics to be covered in the survey were determined. Then, the questions within each topic were drafted. Finally, the order of each topic, and of the questions within it, in the questionnaire was decided. In the workflow of the questionnaire, which is depicted in Figure 2, the question grouping can be seen.

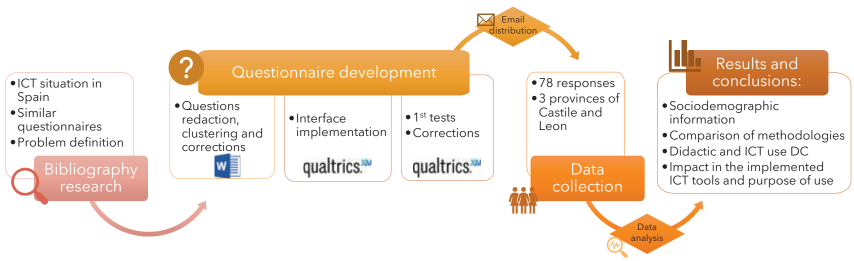

Figure 1. Phases of the research process. Abbreviations: DC, During Confinement; ICT, Information and Communication Technology.

The final structure of the questionnaire was as follows: firstly, socio-demographic variables (e.g., gender, age, years of teaching experience, professional category; size of the high school or province where the teacher worked, etc.) were included. Secondly, the questions related to the methodologies that the educators implemented were presented. Prior to this cluster, the methodologies were defined in order to ensure that all the respondents knew what each methodology implies. Thirdly, they were asked about the didactic experience during the confinement. This includes how the lessons had been implemented, what tools they had used, what modifications had been made and so on. Subsequently, questions related to changes in the use of ICTs—which ones they used and for what purpose—before, during and after confinement were included. Finally, respondents were given the opportunity to add additional comments on their experience during confinement. In contrast to the other, close-ended questions, this last question was drafted in an open-ended format.

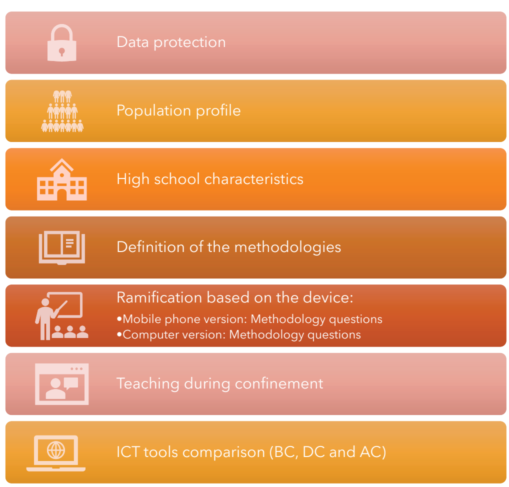

Figure 2. Questionnaire workflow and grouping of the questions that was done. Abbreviations: AC, After Confinement; BC, Before Confinement.

Once that they were completely clear, the survey was created in Qualtrics application [26], where different question formats, filters and logical conditions were implemented. Besides this, two versions with different formats were generated to provide enhanced visualisation depending on the device being used to response, either mobile phone, tablet or laptop. The differences in the two versions of the questions (one for computers and the other for mobile phones) that were created in the Qualtrics software are displayed in Figure 3;

both the version prior to the adaptation and after are shown. Once the questionnaire had been designed and implemented in the application, a pilot study was conducted. In this pilot study, respondents were fellow students from the masters program that qualifies for Secondary Education teaching in Spain [27].

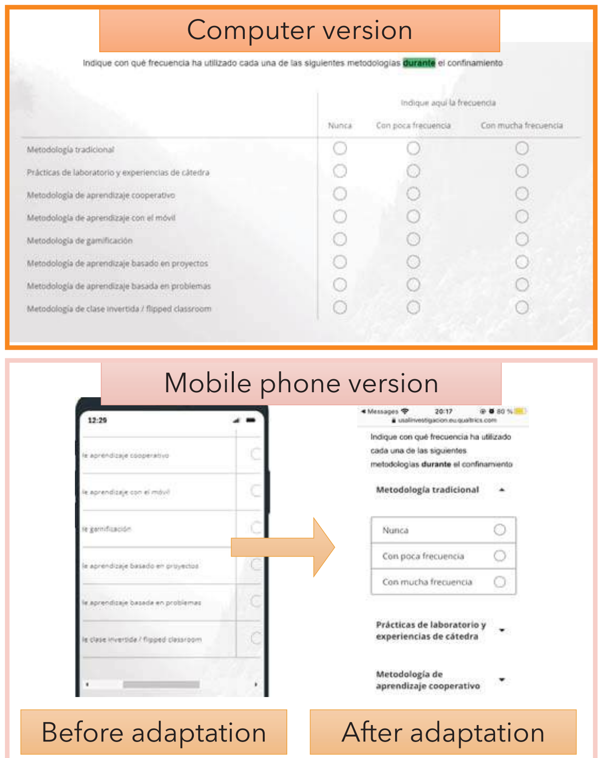

Figure 3. At the **top**, computer version of one question. At the **bottom**, mobile phone version of the same question: on the **left**, before adapting the questionnaire to the device; on the **right**, after adapting it to the device.

This pilot study allowed some questions to be revised and some response options to be completed. Hence, the average response time for the complete questionnaire was estimated to be 15 min, which was considered adequate. Once that the survey was completed and corrected, it was sent to the target population sample.

2.2. Data Collection and Sample

The final developed questionnaire was sent to high school Physics and Chemistry educators of the provinces of Ávila, Salamanca and Zamora (Spain) by electronic mail. It was also distributed to the high schools, asking for their collaboration in informing and requesting the responses of the teaching staff of that department. In addition, fellow students in the masters program were asked to send the questionnaire to their internship advisors and to other teachers, since they were doing their internships in high schools by that time. By doing so, it was aimed to reach the target population by several strategies in order to achieve a large sample.

Based on the Castile and Leon Resolution of 8 April 2021 [28], the estimated population of Physics and Chemistry teachers is 164 for the three provinces, counting private and public high schools. In order to answer the survey, some conditions were required: first, having been informed about their data being used only for the study; second, having accepted the research conditions; and, third, being a Physics and Chemistry teacher in the provinces of Ávila, Salamanca and Zamora. Since the survey was completed by 78 teachers who accomplished the imposed conditions, and considering the population indicated in the aforementioned resolution [28], almost 50% of the total population was reached. However, not all teachers taught at all three points in time. Some people retired during this time and were replaced by others. It is not possible to calculate the achieved sample reliably as we have not been able to access a sample census that includes teachers who did teach at all three points in time.

2.3. Data Analysis

Data was registered in the Qualtrics platform. Afterwards, both the platform, with its reports tool, and Microsoft Excel were used to analyse the responses.

The conducted study of the results was mainly descriptive so as to inspect the changes in the methodology due to the confinement and its impact on the use of ICT.

3. Results

The results were clustered into four different categories: the first one referred to the population profile (Section 3.1); the second to the methodological changes implemented because of the confinement (Section 3.2); the third one about how the didactic was during confinement (Section 3.3); and the fourth one showing the evolution in the employed ICT tools and how they were used (Section 3.4).

3.1. Sociodemographic Information

There were in total 78 investigation respondents that continued until the end of the survey. Among them, most were women, accounting for 60.26%. In terms of age, only 6.41% were younger than 30 years old; 71.4% of the sample was older than 41 years, with the largest group of age being between 51 and 60 with 35.9% of the responses. Even if the sample was of advanced age, 25.32% accounted with less than 5 years in teaching. Hence, most of them started teaching after the age of 25.

A total of 58.23% of respondents taught in municipalities larger than 25,000 residents, so most of them worked in big areas rather than small villages. Then, 80.52% of the sample was employed by the public sector, with 69.35% having a permanent position. The centres accounted with 201 students or more in 74% of the cases; and in 62.47%, there were at least 401 students. Hence, the teachers taught in larger high schools. The most reduced class had less than 15 students for 61.54% of the respondents, and their largest class had between 16 and 25 students for 69.23%.

In terms of ICT media, most teachers (63.64%) taught in centres where there were 1 or 2 IT rooms, and 35.06% where there were 3 or more. Only in 1.30% of the centres were there no IT rooms. Besides this, in 71.9% of the cases all the classrooms had a projector and a computer; in 25.64% these were only available in some classrooms; and for 2.56% they did not have them available in the classrooms.

3.2. Comparison of the Methodologies Employed before, during and after the Confinement

The methodologies were compared in two different ways. Firstly, by asking the frequency in which they were used (never, little/low frequency or much frequency). Secondly, by the methodology that was employed the most during their lessons. In both cases, the question was posed for the three periods of time: before (BC), during (DC) and after confinement (AC). In Table the percentage of teachers and the frequency ("never" in the central column and "very frequently" in the right) at which they used each of the teaching methodologies is depicted for the three periods of time. This evolution can be observed graphically in Figure 4, which displays the percentage of teachers that "very frequently" employed each methodology before (BC), during (DC) and after (AC) the confinement, as well as in Figure 5, which shows the percentage of teachers who "never" used each methodology before (BC), during (DC) or after the confinement (AC).

For the first comparison, there was a significant change in the methodologies that were employed very frequently from before to during the confinement. More specifically, the traditional methodology passed from 90.4% of the teachers employing it very frequently (BC) to 47.2% (DC), as shown in Figure 4. The mobile learning methodology increased from 7.0% (BC) to 35.3% (DC) of the survey respondents that used it with much frequency before and during the lockdown. Moreover, the flipped classroom rose significantly from 1.4% (BC) to 33.8% (DC). The same observation can be made in terms of the methodologies that were never used before and during the confinement, since the percentage of respondents that never used the mobile learning and flipped classroom methodologies decreased from BC to DC.

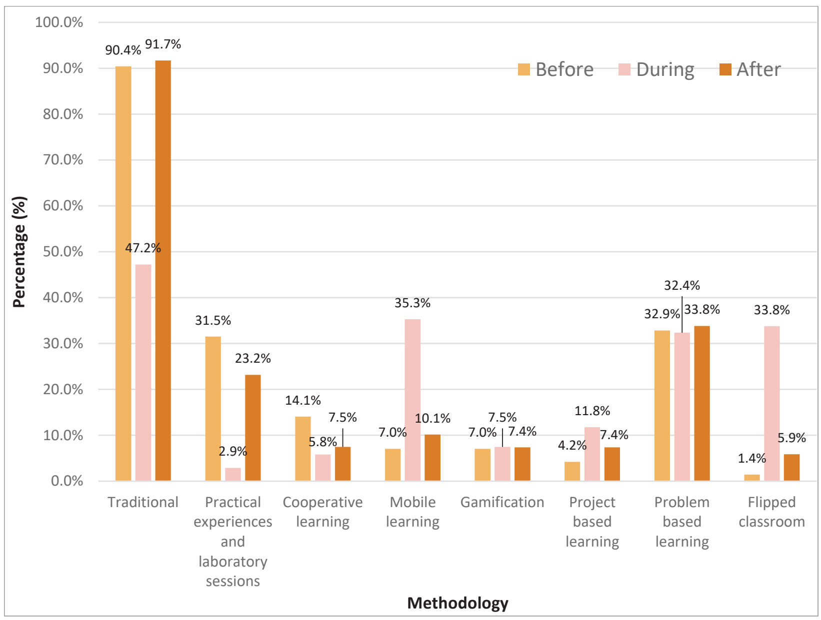

Figure 4. Percentage of teachers that employed very frequently each methodology before, during and after the confinement.

The fact that these methodologies (mobile learning and flipped classroom) started to be used during confinement had an impact for the period afterwards, since it decreased the percentage of teachers that never employed them from 57.7% (BC) to 44.9% (AC), and from 71.4% (BC) to 63.2% (AC), respectively, as depicted in Figure 5.

In terms of the most used methodology, from before, during and after the confinement, there were also some changes, as detailed in Figure 6, similar to the aforementioned. Hence, before confinement, the most used methodology was the traditional (83.8% of respondents). Then, during confinement, this methodology decreased to 37.3% of the teachers using it predominantly, and others, such as mobile learning and flipped classroom, increased to 22.4% (DC) and 20.9% (DC) of educators using it the most. After the confinement, the implementation of the new methodologies decreased again to their original values, and the traditional one was again the most employed methodology with 86.8% of the responses.

3.3. The Didactic of Physics and Chemistry during the Confinement and ICT Use

A total of 98.55% of the respondents considered that they had adapted the methodology during the lockdown. Besides this, 71.69% stated that they had kept these changes afterwards.

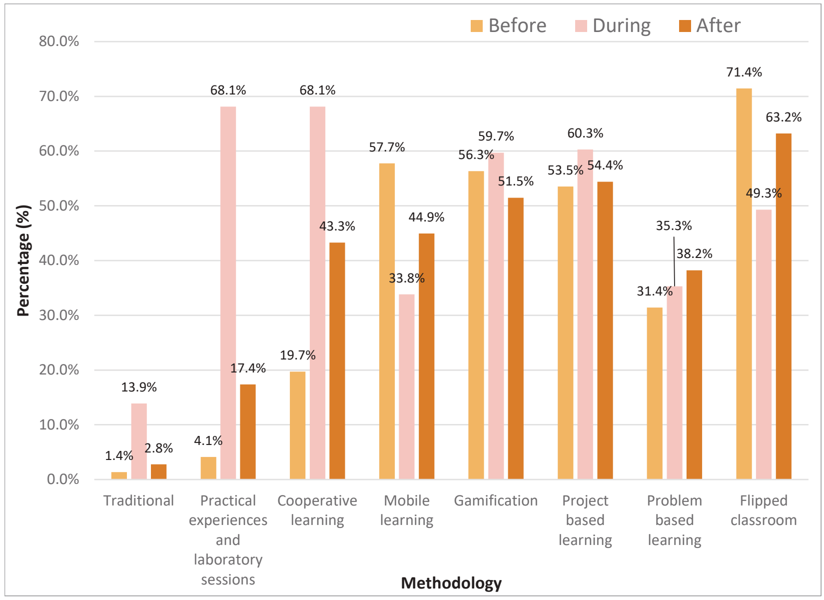

Figure 5. Percentage of teachers that never employed each methodology before, during and after the confinement.

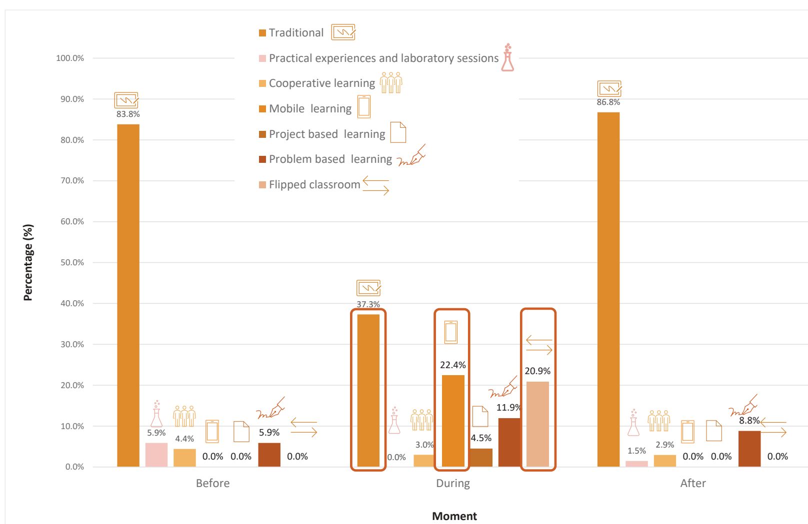

Figure 6. The most used methodologies before, during and after the confinement.

In Figure 7, some of the methodological changes that took place during confinement are shown, and presents if their implementation was decreased, increased or remained the same. Among the implemented changes, 56.72% increased the amount of student assignments, and 61.76% the student autonomous learning. Moreover, the use of virtual simulators and PowerPoint presentations increased for 65.67% and 64.71% of the respondents respectively. The participation of the students during classes was decreased for the case of 53.73% as well as the number of exposition lessons by the teachers, for 42.65% of the educators. Still, there was 48.53% of them that kept the exposition as before confinement. The percentage of respondents that used the cooperative learning in the same proportion was 56.92%. All the detailed data can be found in Figure 7. Thus, the use of virtual simulators, PowerPoint presentations, autonomous learning and student assignments increased the most, and the participation of the students, the exposition lessons and the interaction with the students decreased the most.

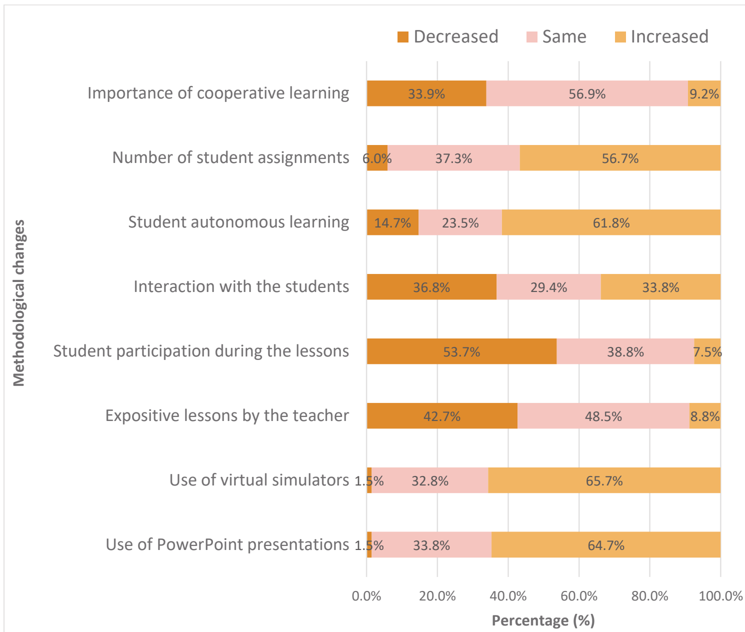

Figure 7. Methodological changes that took place during confinement, either their use was decreased, increased, or remained the same.

In terms of the exposition lessons, they were performed with spoken explanations in a virtual platform by a majority, 43.48%. A total of 20.29% used PowerPoint or similar tools, 18.94% uploaded notes to the platform, 7.25% employed their own videos and the 4.35% used mostly the book.

In order to solve exercises and problems, most of them did them virtually live, accounting for 47.83%; next, 36.23% of the teachers uploaded the solutions to the platform so that the students could ask questions; lastly, 13.04% gave the exercises with no solutions, so the students asked about the ones they did not manage to solve.

3.4. Evolution in ICT Tools Implementation before, during and after the Confinement and How They Were Used

In terms of the implementation of ICT, there was an increase in their use for each of the methodologies after the confinement, as shown in Figure 8.

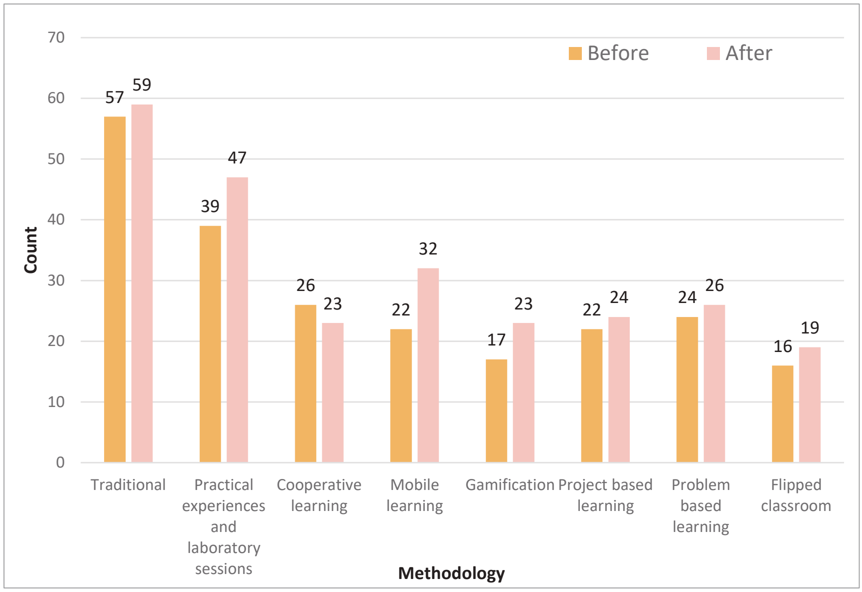

Figure 8. Number of teachers that used ICT for each methodology (from a total of 78 responses).

For this section, the respondents were asked to answer at which time period they had used any of the tools. These periods of time could be that they had implemented them before, during and/or after the confinement. Moreover, they could indicate if they had been using them for the three time periods: BC, DC and AC, as shown in Figure 9.

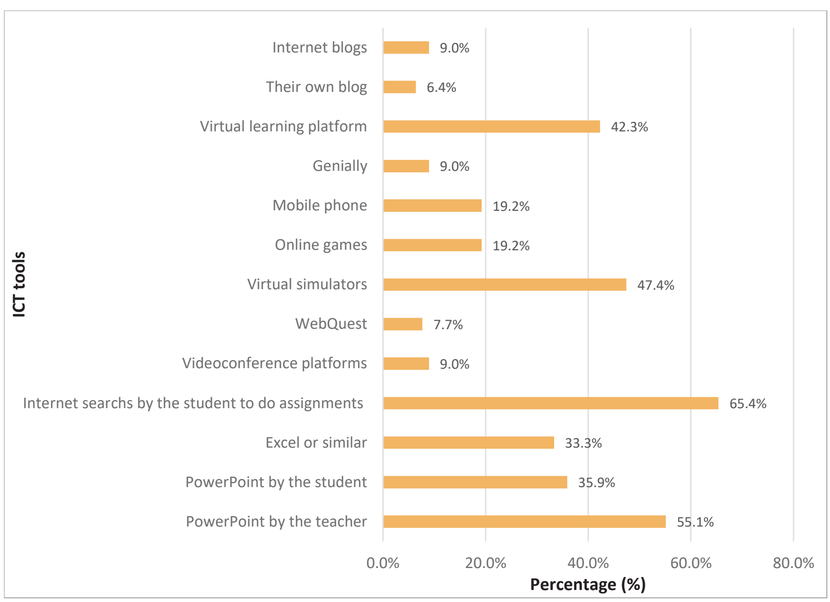

Figure 9. Percentage of teachers that employed these ICT tools before, after and during confinement (from a total of 78 responses).

The respondents had been using mostly Internet for students' research assignments, PowerPoint and virtual simulators, with more than 45% each. The least used were Genially, having their own blog, WebQuest and videoplatforms, as shown in Figure 9.

During quarantine, the largest differences in implementation were for the video platforms (almost 70% of the teachers), then the virtual education platform, the mobile phone and then WebQuests, with at least the 25% of the respondents starting to use them, as depicted in Figure 10. After confinement, the ones that continued to be implemented in the highest number were the video platforms, the virtual education platform and WebQuest. Their use continued after the lockdown but in lower proportion.

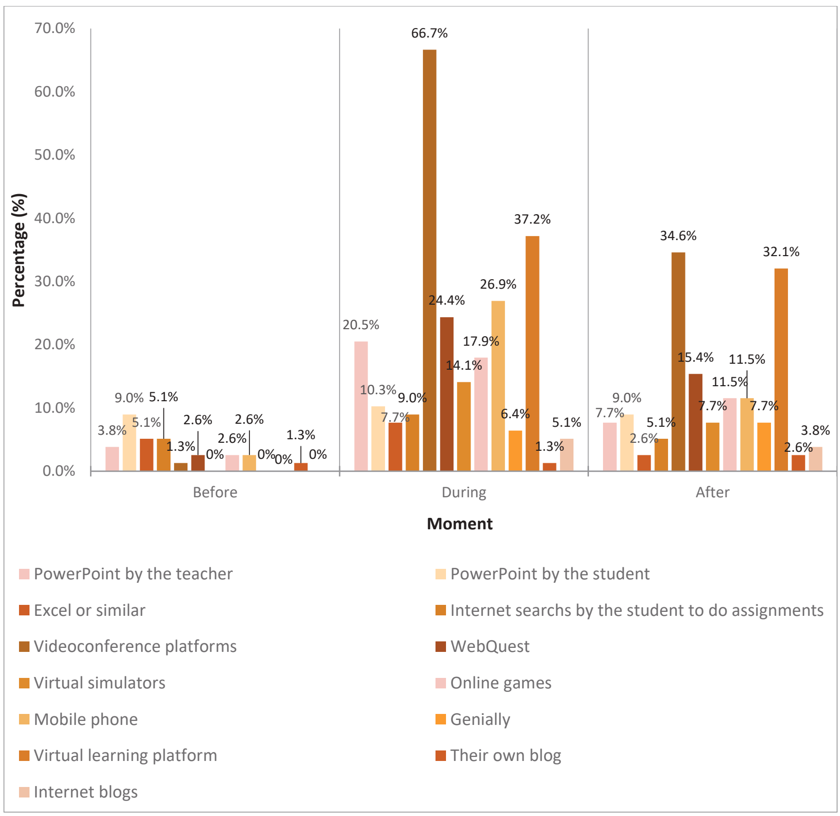

Figure 10. Percentage of teachers that employed the ICT tools at each time period: before, during or after confinement (from a total of 78 responses).

The simulators and websites that had been employed the most for the three time periods were Educacyl (Castile and Leon educational platform) [29], Educaplus [30] and Phet simulator [31] (both websites with educational simulators), with more than 30% of educators stating that they used these. During confinement, the most implemented website for new users was Educacyl (20% of the teachers), and most of them kept with it afterwards.

The most employed ICT resources during the whole period were the interactive resources and the YouTube videos, both with 55% of users. The least used was the Podcast. During confinement, 20% and 17% of respondents started using YouTube and the interactive resources, respectively, and most kept them afterwards.

In terms of the finality, the most common uses are depicted in Figure 11. It depicts the percentage of teachers and the purpose for which the ICT were used before, during and after confinement. Hence, the ICT had been used at all times to present the lessons by means of PowerPoint and use of online resources, with 46% of responses. The least voted purposes were creating materials and online activities.

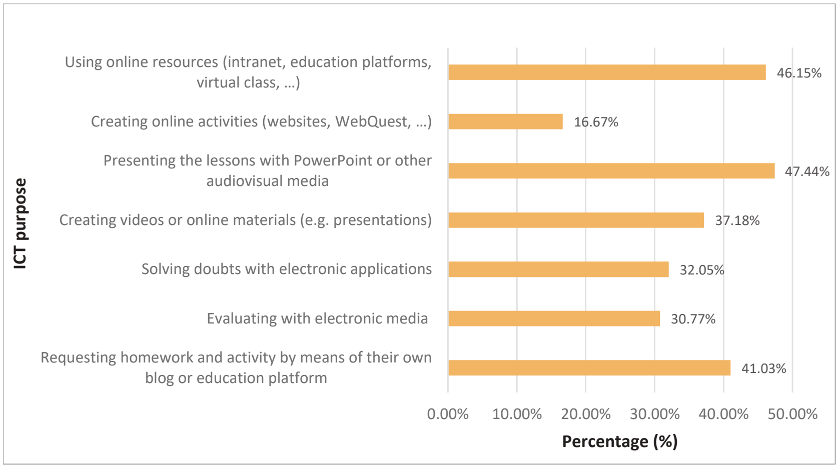

Figure 11. Percentage of teachers and the purpose for which the ICT were used before, during and after confinement (from a total of 78 responses).

During confinement, ICT started to be used for new functionalities and many of them continued. In Figure 10, it can be seen the number of teachers and the purpose for which the ICT were used BC, DC or AC. Some of them were resolving questions, evaluating, using online resources and asking for assignments with at least 32% of responses there.

During lockdown, the main implemented tools for video conference were Microsoft Teams (74.63% of the respondents); followed by Meet, with 14.93%; Zoom and Skype. Currently, 75% of respondents continued using them after confinement. In order to communicate with students, Microsoft Teams was again the favourite platform, with 50.75% of educators using it during confinement; then Moodle and email, with 20.90% for each during confinement. Their use was kept by 91.18% of respondents afterwards. To upload or send materials to the students during confinement, 44.12% employed mainly Microsoft Teams; 20.59% Moodle; and 19.12% via email. The two latter applications had been used at all time periods to upload materials and to communicate with the students, accounting with more than 40% users among the respondents. However, during lockdown, these tools started to be implemented as well for evaluation, delivery of assignments and exercises, communication with the students and uploading materials, ranging from 51% to 30% of the respondents respectively for the DC period. Many of them continued to use these tools for these purposes upon the return to classrooms.

A total of 89.39% of the respondents consider that the lockdown had entailed that they implement more the ICT afterwards. In terms of the main learning during this period, 46.27% responded that they learned new resources and ICT tools; 22.39% new methodologies and didactic options; and 22.39% that they improved their abilities with the ICT.

Last, some respondents stated that because of confinement, the differences in ICT resources in the centres were visible, since, while in many centres they were totally instituted, in others had not almost been used. Moreover, remarkable differences were appreciated between the rural and the city centres. In terms of the main difficulties encountered, they mentioned the students' low implication and the great effort they had to make, which led to new learnings. Others responded insisting on the importance of in-classroom education.

4. Discussion

The present article has allowed to analyse the methodological changes in the Physics and Chemistry didactic that were implemented because of the COVID-19 confinement and the situation afterwards. Besides this, the implemented ICT tools and the use made of them has also been inspected for the time periods before, during and after the confinement. Hence, this paper has permitted to compare the didactic for the three periods of time, including the impact on the use of the ICT after the confinement. This contrasts with many of the previously conducted research, since, to the authors' knowledge, investigation has focused on the experiences before and during lockdown, but the didactic situation afterwards has not been specifically inspected [32–34]. In addition, the specific employed methodologies have been assessed. Thus, by means of this research the truthful impact of the quarantine in the Physics and Chemistry didactic can be evaluated with the return to face-to-face education.

Based on the questionnaire, most of the high schools reported to have good ICT equipment, with 71.74% of them having a computer and a projector in each classroom. The most employed methodology is the traditional one; even if its use decreased during the confinement situation, it was again implemented with the return to classes. As seen, the presence of ICT has not led to significant changes on the didactic and the traditional methodology is still the most employed, as already exposed by [5,8,9]. Moreover, as shown in Figure 8, the ICT were mainly implemented by this methodology. This also stays in line with the European Commission Survey of schools [1], as it was stated that the ICT were mainly used by this methodology for exposition, search purposes or the use of the virtual platform [9,11]. This is also confirmed by the findings made on this survey (Figure 10). In addition, for the didactic of the Physics and Chemistry subject, other common uses of the ICT were virtual simulators or explanatory videos [11,13], which were also very common uses according to this survey.

Nonetheless, during the lockdown, there were some significant changes for the implemented methodologies as well as the ICT tools and functionalities being used.

During the lockdown, methodologies such as the mobile learning and the flipped classroom were favoured, and they started to be used at this period. Although the frequency of use decreased after the lockdown, it has risen in comparison to the situation before lockdown, as depicted in Figure 5. Hence, during confinement, more active methodologies were employed (Figures 4 and 6). The increase of the active methodologies and autonomous learning shown in this study matches other studies performed in terms of the didactic during confinement [35,36]. The fact that the autonomous learning of the student was favoured during this period can also be observed in Figure 7. As shown in Figure 5, the Practical experiences and laboratory sessions were very much affected DC, since they were never employed at much higher rates than BC or AC. This stays in line with other studies, where it was seen that the amount of experiences decreased DC, but the impact afterwards was not evaluated [32]. Still, there are papers where the teachers' effort to continue with the practical experiences are visible and their implementation DC is described [33,37–39].

Only 56% of the respondents were familiar with all the mentioned methodologies, remarking that there is a large lack of awareness on new methodologies. On the other hand, 99% considered that they adapted their methodology during confinement and 71.72% has kept these changes. Besides this, the number of teachers that use the ICT for each methodology has increased from before to after, as depicted in Figure 8.

During confinement, the theoretical lessons were taught mostly by verbal explanations in a virtual platform, by PowerPoint or by uploading notes. In order to solve exercises, most of them either solved them live online or gave the solutions. Furthermore, the use of virtual simulators, PowerPoint presentation, the autonomous learning of the students and the number of assignments increased. The participation of the students and the interaction with the students decreased as well as the amount of exposition lessons (by 42.65% of respondents); however, there was a high percentage that kept them the same (48.53%) as depicted in Figure 7. These results agree with previous studies, where the video conference or the individual activities with live corrections played a role during confinement [35,40–42]. There have been other studies where the role of computer simulators and PowerPoint presentations during lockdown has been shown [34,42,43] as in this study.

Because of quarantine, some of the ICT tools incorporated and whose use has continued afterwards were video-conference platforms, education portal, the mobile phone and WebQuest, as shown in Figure 9. In addition, some of the new purposes for which ICT were used during confinement and that have continued were PowerPoint presentations, website materials, answering questions, evaluation, and homework assignment as depicted in Figure 12. According to the present study, the most used platform was Microsoft Teams, followed by Moodle. In this aspect, in terms of the preferred platforms, there is a wider variety of results over literature. According to some papers, the most used platforms were Moodle or Google Classroom in Spain [43], with Google Classroom being favoured if they were public employees, while others claimed it to be Classroom and Meet in Spain [44,45], or Zoom and Google Classroom as the most mentioned platforms according to a COVID-19 paper review [46]. In terms of communication with the students, there are again more dissimilar results. For instance, in Castile and Leon, the preferred platforms were Teams (by 50.75%), followed by Moodle and email (with 20.90%). Nevertheless, according to other studies, email [35,47] or Meet [44] were the most widely used tools for communication.

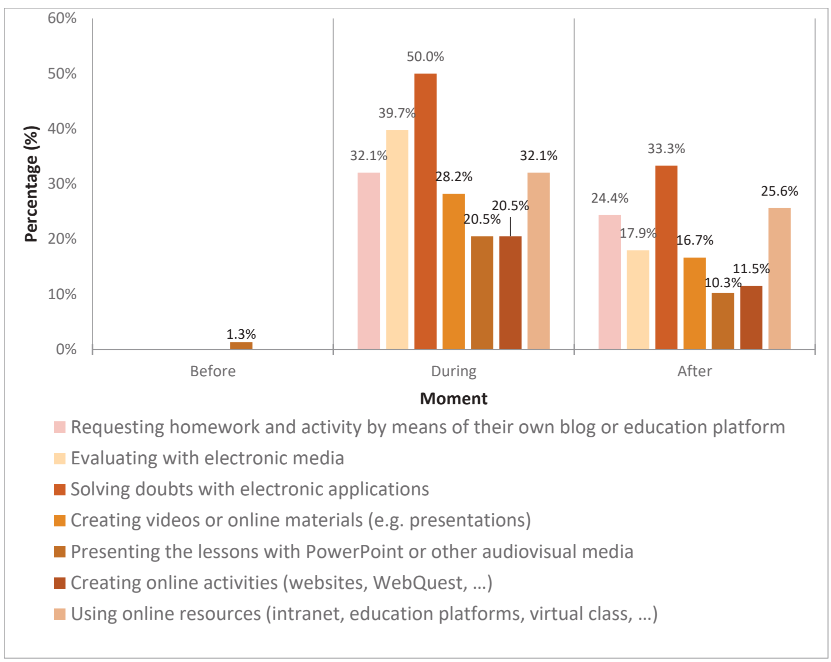

Figure 12. Percentage of teachers and the purpose for which the ICT were used before, during or after confinement (from a total of 78 responses).

It is remarkable that 89% of the respondents considered that, due to confinement, they currently employed more frequently the ICT. This was also the case in other studies where it was stated that the teachers were planning to continue with the ICT use [32,44,48]. Moreover, all of them had some learning because of the lockdown, either related to the methodologies, the ICT tools and possibilities or their ICT abilities. Many of them remarked that they acquired big learnings because of this situation. As stated by [6,9–11], some of the causes of the low use of the ICT in the classes were the teachers' low formation in ICT tools and applications, in how to implement them, and that they were comfortable in the methodologies they used. Hence, thanks to these new learnings, the situation might be reverted in the coming years as the importance of being formed and prepared for the ICT implementation has been proven. According to literature, during confinement it has been seen that the teachers lack knowledge on the ICT use [32], whereas, in another study [49], the teachers claimed to have a medium level of knowledge in ICT according to their own perception. Other papers have also noted the learning of the educators with regard to this situation, and they have pointed out the need of formation plans and training for them in these technologies [40,42,43,47,50].

Moreover, by means of the last open-ended question, the respondents pointed out the noticeable differences between centres, the urban and rural areas, the low implication of the students, and the great effort they made. These differences must also be tackled since the digital divide can have a great impact on the education of the students as shown by several studies [48,51,52]. Other concerns reflected by the respondents (such as the low implication of the students) have already proven to have impacted on the students' results according to conducted research [53–55], where it has been shown the lower performance levels (with a decrease in Maths or Physics and Chemistry) as well as the influence of excessive parental participation during confinement.

Limitations and Future Work

The main limitation of the current study is the fact that the sample that responded the questionnaire was not very large since they had to accomplish the conditions that they had been teaching Physics and Chemistry before, during and after the confinement in specific provinces of Castile and Leon. Hence, they had to have been active for a period of time and to continue working by the time they responded. Consequently, only a descriptive analysis of the data collected has been carried out.

Future lines of work should include the extension of the study population and, therefore, of the sample. It could also be convenient to incorporate all the provinces of the selected Autonomous Community or even implement a nationwide study. Furthermore, it would be appropriate to carry out a bi-variate analyses that would allow to determine, for example, whether the location of the workplace in rural areas influences the implementation of ICT tools or not.

On the other hand, based on this and other analyses, recommendations could be made to improve the training of educators in ICT and methodologies. This could also be of special interest to the universities teaching the masters program that qualifies for Secondary Education teaching in Spain and that aims to adequately prepare students and future educators. In this aspect, there have already been papers making recommendations about how to evaluate, virtualise the lessons, train the teachers in ICT, or other pedagogical suggestions [50].

5. Conclusions

In conclusion, this study has allowed to inspect the changes that the confinement has supposed in the Physics and Chemistry methodology as well as in the ICT use and in the purpose for which they were employed. Moreover, how the lessons were implemented during the quarantine has been evaluated. Based on the results, recommendations and measures could be proposed for future situations. Thus, it has been concluded that, during the lockdown, the traditional methodology was less employed while others, such as the mobile learning and flipped classroom methodologies, were implemented more frequently. With the return to the classrooms, the traditional methodology increased again and, even if the implementation of the introduced methodologies decreased, it has increased in comparison to the initial situation. In terms of the ICT tools, it must be outlined the importance of the virtual platforms and education websites during and after lockdown, being Microsoft Teams the most widely used. Moreover, the ICT were applied for new purposes (such as evaluation). All the survey respondents considered that they had acquired some knowledge and 89% stated that they had increased their use of the ICT due to the lockdown situation.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data will be available in: https://gredos.usal.es/handle/10366/139417 (accessed on 11 May 2022).

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AC	After confinement
BC	Before confinement
DC	During confinement
ICT	Information and Communication Technology

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Students' E-Learning Domestic Space in Higher Education in the New Normal

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Abstract: The objective of this study is two-fold. Firstly, to analyse and discover the ability of HE students to use the physical home context for e-learning via ICT during the new normal; and secondly, to ascertain the underlying patterns of the adequacy of such domestic spaces. The authors offer a multidisciplinary approach combining pedagogic, architectural backgrounds with considerable experience in didactics, organization management of education, and ICT applied to education. A qualitative, arts-based research methodology that analyses photographs was used. A total of 220 domestic work environment photographs sent by higher education students were analysed. Results and conclusions show that students are able to attend virtual classrooms in a domestic atmosphere. Bedrooms and studies are usually the most-used spaces. Laptops and smartphones are the most frequent central hubs of student learning sessions. Students use other training resources (desktop computers, tablets, etc.) to supplement the most common digital devices. An intense relationship is observed between Space (bedroom and other rooms) and the Sofa and Beds variables, while a moderate one is observed between Age and Care items. The relationship between other variables is weak or non-existent.

Keywords: higher education; digital technologies; online learning; distributed learning environments; media in education; domestic space

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1. Introduction

The evolution of the Information and Communication Technologies (ICT) impacted on methods and techniques used in the higher education (HE) teaching [1]. Some of these strategies are supported on the Internet, as synchronous or asynchronous communication. Synchronous means use real-time connections for direct interactions with other members such as students, teachers, or other professionals. Examples of synchronous means are the phone, chat, or web-conference. Asynchronous means allow a delay between participant interactions. Examples of asynchronous means are mail, a forum, or social media. In these cases, the utterers could be connected at different times, and they do not need real-time connections. At this moment, there is a clear growth of synchronous means related to immediacy and mass media, and some chat tools are very popular, especially WhatsApp [2]. Transferring this tendency to HE didactics, web-conference tools are also becoming more and more popular, for different reasons. One of them was the confinement during the COVID-19 pandemic. Nevertheless, there is no doubt that university responses to this problem would not have been the same two decades earlier. Most persons were caught off guard in terms of reinventing their living space and converting home into a new classroom. Many activities, jobs, and businesses were converted to telecommuting. Thus, HE students and teachers faced an important challenge of using home space and their own technological resources. Students were forced to carve an area within the home for e-learning. This situation resembles what was already pointed out at the creation of learning environments, understood as symbolic inhabited spaces where people protect themselves, train, evolve, and manufacture their identity [3]. Living in society is akin to living in relationship spaces, and their analysis can throw more light on human life than the one obtained either through individual consideration, or through the diverse positions assigned to it by science and metaphysics [4].

Generally speaking, actions taken by students also converge when they take on different challenges to facilitate ubiquitous learning [5,6]. Domestic life accompanies each person throughout his or her journey, and forms his or her inner construct and understanding of private relationships. People's aspirations about their home space may be conditioned by images they receive through the media, social media, or their digital device screens. The visibility of intimate environments generated a very direct perception of reality because domestic spaces were highly exposed. It is during this time, more than ever before, that students learned about the private environments of their peers and teachers, and possibly expanded their understanding of the lives of such people.

Web-conferences, web meetings, and web tutorials open your own home to partners, colleagues, and students. Living in this reality demands a previously non-existent domestic and pedagogical framework. Many meetings, classrooms, tutorials, conferences, etc., changed to virtual environments, both in face-to-face education and in distance education. People's daily lives, and that of students in particular, changed dramatically. Movement restrictions, social distancing, and forced migration of work and learning spaces into the domestic sphere meant a radical transformation. This led to changes not only in habitat management, but also in public areas for interaction and coexistence. Private spaces were made public. The possible difficulties generated by these new physical variables were appeased by using ICT. Therefore, formal and informal meetings today do not take place exclusively within a conventional physical framework, but are often reduced to virtual meetings, where multiple screens are the protagonists.

1.1. New Learning Spaces and ICT

The diverse digital communication platforms and multiple learning environments were already typical in the various forms of distance education, and accelerated the construction of the usual teaching–learning structures during confinement. This unexpected situation forced many HE institutions into a largely unplanned distance education process [7,8]; organizational factors contribute to the successful implementation of emergency remote teaching, and individual factors are also relevant. Moreover, the resultant crisis requires utilisation, not only of new methodologies and resources, but also of the characteristics of a new workplace, which is probably less suitable for training HE students than physical classrooms [9].

Digital tools were already generating greater citizenry participation, and of HE students both inside and outside the classroom. Nevertheless, training with digital resources and innovative methodologies still needs continued and systematic support, in order to expand the arising educational changes in the home environment. The Sustainable Development Goals (SDG) themselves include digital competence as a key aspect in the 2030 Agenda. In addition, the implementation of digital transformation plans at the meso-level will ensure the sustainability of organizations and jobs in the new normal [10]. Digital devices, the Internet, and e-learning platforms are essential to the learning, communication, and expression of university students. All of this not only meant a change in the way we perceive and use our homes, but also new mental and relational constructions between the home environment and that of the classroom group.

The regulatory principles of distance education include student responsibility for self-study through the use of digital tools, self-assessment, and hetero-evaluation (primarily a teacher competence), opportunities for interaction, collaborative work, and diversification of learning tools [11,12]. This transformation led to a rapid and unavoidable transition from face-to-face to e-learning, or to hybrid modalities in HE students and, in general, profoundly transformed everyday life [13,14].

The outstanding role played by the home and digitalization during teleworking and live virtual activities confers greater significance on intimate space and items owned for personal learning. However, the individual and group domains are mixed in virtual classes, due to constant sharing of the physical environment. This situation leads to peculiar interactions where home and academic life develop from multiple foci. All HE students were subjected to intensive use and overexposure to ICT during these activities. Nonetheless, the use of digital tools can improve academic learning, through increased student involvement in their education [15,16]. Moreover, students that use mobile devices and digital tools for learning gain higher levels of digital literacy and training than those who use traditional resources [17].

The way students face classes in this new reality generates multiple micro-situations and narratives that embody a new image of the classroom and the learning process. The threshold of the physical classroom was definitively crossed, and the private and public lives of students and teachers are now intertwined. The virtual class contains personal elements at home that are displayed on computer screens. Hence, students lose home privacy during training when they share their surrounding space through webcams with other users.

Digital learning environments in the domestic context can be termed as local cosmologies, and interpreted as systems that represent and redefine personal and collective identities [18]. Now, more than ever, students reinvented their academic space within their homes, which can be analysed through the specific weight of the items therein. Exposure through digital devices reveals the most intimate home environment, which can be equated to that of television, defined as a medium that is not only optical or acoustic, but also tactile, i.e., equipped with a texture that confers new meaning to reading screen content [19].

The unavoidable use of ICT as a means of meeting educational needs and shortfalls in face-to-face teaching is an atypical reality, from which we could draw ideas to implement new educational methodologies. In fact, changes in teaching methodologies are transforming dominant models through new knowledge access mechanisms that develop globalised learning and social relations [20,21]. Academic activities carried out beyond specific spaces preconceived for that purpose can generate new links with knowledge. In this regard, ICT resources are an essential component for accessing information and learning [22]. Governments now support the improvement of digital literacy and high digital skills in student training, so that citizens can achieve greater economic, environmental, and social development [23].

Digital tools managed to dilute boundaries between the domestic and academic spheres. The construction of communities that process and share information through the Internet is a reality, which, in turn, boosts the development of a network-based university education [24]. Moreover, digital screens can provide equal access to education, and generate a more inclusive, democratic, and fair reality. Hence, teachers should use methodological strategies that offer new opportunities to generate and share learning, and reinforce students' interest in improving performance and make a positive impact [25]. The inclusion of ICT resources in the classroom generally improves student engagement, motivation, and attention, and, furthermore, enhances the development of ubiquitous learning.

HE is now characterized by the juxtaposition of learning spaces, which combine face-to-face and remote modalities. The interaction of local household cosmologies generates a common topology, pedagogical dynamics in which personal items build a joint virtual–educational environment. This collective scenario neutralises the relationship between space and the educational intention because screens homogenise all such projections against the one backdrop. In the physical classroom, teaching is usually conducted through a single-focal point, wherein eyes are directed towards the teacher, a screen, or the blackboard. However, the virtual classroom represents a multi-focal and flexible pedagogical space where attendees participate sequentially, and perform autonomous inquiry using digital tools and more innovative practices.

1.2. Current Study

Several studies have already been carried out on ICT e-learning in HE students from different countries during this exceptional COVID-19 period [26,27]. However, this is a singular article starting from a different point of view; a multidisciplinary approach combining pedagogic, architectural backgrounds. To date, there is only one exploratory study about this topic with preliminary results [28]. Living in this new COVID-19 pandemic reality demanded a previously non-existent domestic and pedagogical framework.

The objective of this study is two-fold: firstly, to analyse and discover the ability of HE students to appropriate to their physical home context for training–learning via ICT, and, secondly, to ascertain the underlying patterns of the adequacy of such domestic spaces. The study was guided by the following research questions (RQs):

RQ1: What are the elements found in the physical learning space of HE students in their homes?
RQ2: Which rooms are used by students for e-learning?
RQ3: What are the features of the rooms based on the academic components they contain?
RQ4: What are the spatial relationships between the home and the digital screens used?
RQ5: What are the screen backgrounds used by students during online training connections?
RQ6: What is the relationship between the analysed variables?

2. Materials and Methods

This study involved analysis of photographs, and essentially followed a qualitative methodology framed within Arts-Based Research (ABR). ABR is quite useful as a data collection and analysis technique in education since it facilitates research into the context surrounding student practices [29]. This type of research avails of tools to analyse the situation under study, and offers a scientific and intuitive view of reality. The value of studying photographs in the present research through ABR lies in the possibility of collecting and capturing evidence of home use by HE students during e-learning.

2.1. Sample and Data Collection

This research was carried out at the Higher Technical School of Architecture, Universidad Politécnica de Madrid (Spain). The University offers undergraduate, master's, and PhD studies in architecture through specialised departments, which, similar to its staff members, enjoy a certain level of autonomy. The Foundations of Architecture, where this research was carried out, is a five year degree program. The fieldwork study was performed with the participation of 31 third year students (20 females and 11 males), 6 fourth year students (2 females and 4 males), and 23 fifth year students (16 females and 7 males).

To facilitate information collection for the study, one teaching staff member and author of this article sent emails to students from the Foundations of Architecture degree program at the Universidad Politécnica de Madrid (UPM), and published this call for participation on Instagram. Emails requested photographs from the aforementioned HE students, asking them to send photographs of themselves taken in the domestic learning environment, which they had shared on their digital screens; students sent their photographs. A stratified sample was used, inviting students from the five undergraduate courses. Participation was voluntary, and, perhaps due to their lack of maturity and commitment, the first and second year students did not send any photographs; this was the reason for not including them. However, voluntary participation is preferable to compulsory participation. The absence of associations between the student's levels and other variables does not allow the idea that the participation of first and second level students would change the results obtained.

In qualitative research, the sample is traditionally justified on the saturation point [30]. We analysed the occurrence of new subcodes in groups of six environments during the analysis while controlling internal consistency with Cronbach's alpha (Figure 1) [31]. It is observed how, starting from the 42 photographs analysed, having reached 68 subcodes out of a total of 73, a consistency higher than 0.80 is achieved and maintained from that point on. This point could be considered the saturation point; starting from this point, further analysis are confirmatory.

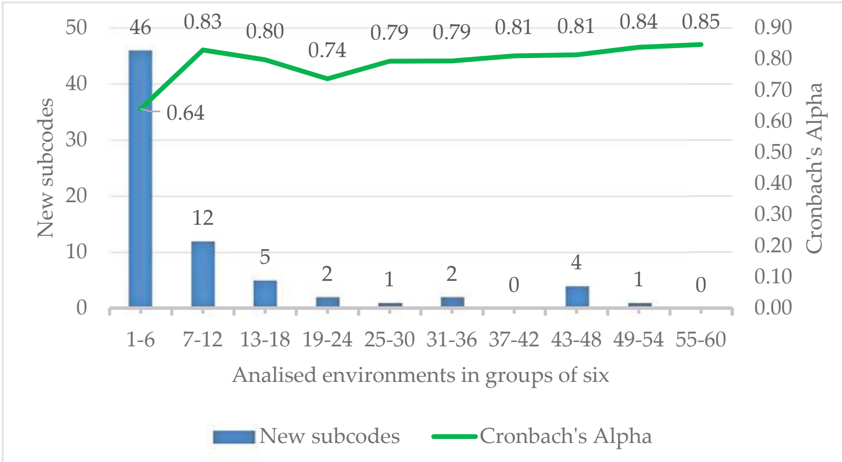

Figure 1. Analysis of new subcodes and Cronbach's alpha during coding new environments. Note. This is a dual scale graph. The blue bars indicate the new subcodes registered during the analysis of environments grouped six by six (left scale), while the green line reflects the evolution of internal consistency through Cronbach's alpha (right scale).

HE students that collaborated in this research provided a set of photographs that reflected their domestic learning environment. To visualize the entire room on a 360° basis, each student sent 4 photographs, one of each wall, or 2 × 180° panoramic photographs. A total of 50 students sent 4 photographs, and 10 students sent 2 photographs × 180°. The study sample consisted of 220 photographs provided by 60 students.

2.2. Data Analysis

The information collected was subject to content analysis using the AQUAD (version 7), and Excel (for performance of content and contingency analysis). The analysis categories were linked to the respective research questions [32]. The different categories were extracted by an inductive process from the photographic content analysed, and the absolute frequency of coding was computed to detect preponderance or absence. Code frequency is commonly used in content analysis [33], and can be completed with other calculations or analysis strategies.

The following content analysis order was used to construct the analysis categories: detailed identification of the items that make up the new academic spaces of HE students at home; determination of the physical variables that influence digital device screen location inside the home; and characterization of the rooms at home. Information was analysed from an individual and group perspective, for which researchers met from time to time to discuss coding. In the final stage, the researchers shared and discussed all results, and reached agreement whenever slight discrepancies occurred. Credibility of results was strengthened by maintaining balanced independence among researchers [34].

Excel was also used to study any possible associations between variables to ascertain their relationships. Cross-checks were performed not only between the profile variables (gender and age), the identified content analysis element categories, and use of HE students in the domestic sphere for e-learning with ICT, but also between the content variables themselves. To this end, a contingency analysis was applied, to obtain own statistics.

Values from the contingency tables were used to calculate the expected ones, chi-square (χ^2), *p*-value, and Cramér's V, which determines the intensity of association between the different variables (for a 95% confidence level, $\alpha = 0.05$). The independent variables were grouped into balanced dichotomous categories whenever there were three or more categories, to perform analyses, gain robustness, and, thus, strengthen contrast and concentrate values. The following Cramér's V values were used to interpret the degree of association between variables [35]: 0–0.19 (very low); 0.20–0.39 (low); 0.40–0.69 (moderate); 0.70–0.89 (high); 0.90–1 (very high).

3. Results

The results of this study are grouped in sub-sections, to match the study objectives and research questions.

3.1. Everyday Household Items Used by Students (RQ1)

The analysis provides codes and subcodes categorising the elements used by students for e-learning, and to establish order relations that define the patterns that shape these local cosmologies (Table 1). The five standard elements found in all home study environments are doors, windows, radiators, ceiling lamps, and cell phones. Less common elements ($\leq$5%) include floor-to-ceiling carpentry, sofa beds, low tables, side tables, dining tables, bookcase cum TV cabinet, clocks, and baby cots.

Table 1. Elements used by students for learning in the domestic scenario.

Category		n	%
Code	**Sub-Code**		
Architectural elements	Interior door	60	100.00
	Exterior door	3	5.00
	Window	60	100.00
Thermal comfort	Radiator	60	100.00
	Air conditioning	7	11.67
Illumination	Window curtain	25	41.67
	Window roller blind	24	40.00
	Ceiling lamp	60	100.00
	Floor lamp	8	13.33
	Bedside table lamp	12	20.00
	Adjustable lamp	49	81.67
Sofas/Beds	Sofa	6	10.00
	Sofa-bed	3	5.00
	Bed	29	48.33
Tables	Desk table	43	71.67
	Integrated table and bed	12	20.00
	Table and shelf (study cabinet)	13	21.67
	Adjustable low table	3	5.00
	Dining Table	2	3.33
	Coffee table	3	5.00
Seating	Chair	15	25.00
	Wheelchair	34	56.67
	Ergonomic office chair	13	21.67

Table 1. *Cont.*

Category		n	%
Code	**Sub-Code**		
Storage	Bookshelf-library	33	55.00
	Shelf	31	51.67
	Living room furniture	3	5.00
	Sideboard-comfortable	4	6.67
	Cabinet	14	23.33
	Wardrobe	33	55.00
Technological devices	Mobile	60	100.00
	Desktop computer	5	8.33
	Laptop	59	98.33
	Display screen (dual screen)	29	48.33
	Tablet	18	30.00
	Printer	16	26.67
	Scanner	15	25.00
	Telephone	4	6.67
Work accessories	Desktop organizer/Pen holder	43	71.67
	Filing cabinet	20	33.33
	Case	44	73.33
	Bookstore (more than 10 books approx.)	48	80.00
	Calendar	24	40.00
Decorative elements	Wall decoration (photo, painting...)	51	85.00
	Plant	15	25.00
	Mirror	15	25.00
	Wall clock (time control)	3	5.00
Leisure	TV	7	11.67
	Stereo	15	25.00
	Musical instrument	7	11.67
	Sports equipment	11	18.33
	Gymnastics equipment (exercise bike, elliptical...)	4	6.67
Care	Children's equipment (playground, cot...)	1	1.67
	Pet	6	10.00

Note. Every code identifies a type of element that is described by several elements identified by a subcode. The percentages are calculated with respect to all 60 environments analysed.

Among the variety of items found in the rooms at home, those worth highlighting are laptops (98%); decorative wall paintings (85%); books (80%); desk tables (72%); office chairs (57%); and wall shelves (55%). The presence of the laptop against the desktop computer (8%) is striking.

The usual work accessories are books (80%), pencil cases (73%), pencil containers (72%), and calendars (40%). The home environment of these students also contains leisure and personal care items, such as floor exercise machines (18%), televisions (12%), pets (10%), and baby cots (2%). Some have built-in tables and beds (20%), indicating that the bedroom is dual purpose: rest and work; and ergonomic chairs (22%), designed to spend hours in front of computer screens, revealing that the activities require many hours.

3.2. Rooms Used to Study in the Domestic Scenario and Their Transformation (RQ2, RQ3)

The analysis shows a variety of rooms that HE students use to interact with digital screens in their home learning sessions. Room characteristics were extracted from the data, and help us identify their type from the items they contain. The results further indicate whether the initial purpose is domestic or academic use. HE students use the following rooms to connect digitally for training:

Bedroom (59%), of which 61% have an average area of between 10 and 15 m^2;
Study (25%), of which 53% have an average area of between 10 and 15 m^2;
Living room (6%), of which 50% have an average area of between 15 and 20 m^2;
Kitchen (2%), very rarely.

Analytical sub-atlases specific to each environment were developed, based on the graphic representation of the four domestic spaces, to depict the different academic items found there. Various items are found to be used purely for academic purposes within homes. This is the case of desk lamps, desk tables, shelf–table units, ergonomic chairs, bookshelves, cell phones, laptops, additional screens, printers, scanner, desktops, books, pencil cases, pencil containers, calendars, and filing cabinets. The room with the most items related to academic tasks is the study (64%), which is followed by the bedroom (52%), and the rooms with the least transformation possibility are the living room (33%) and the kitchen (31%), since they have few items destined for work. As well, the academic items used by students, for example in bedrooms and studios at home, could be compared (Figure 2).

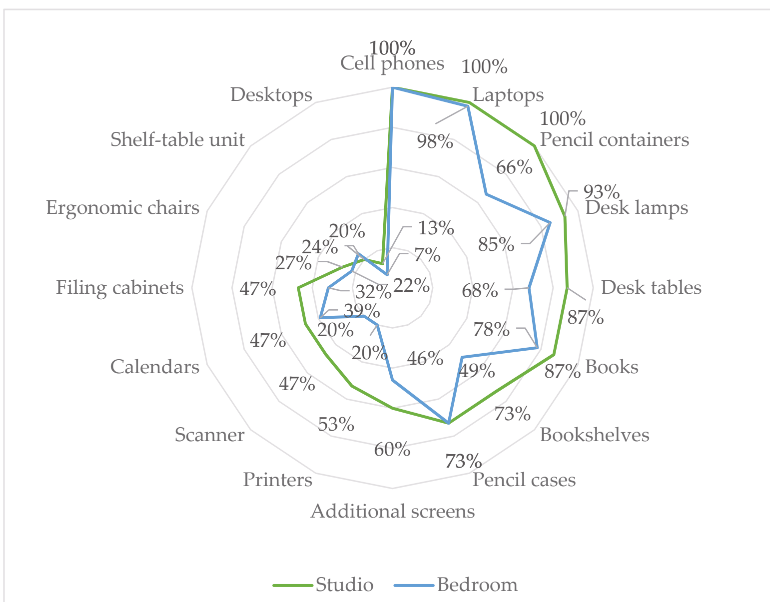

Figure 2. Academic items used by students in bedrooms and studios at home. Note. The percentages are calculated with respect to all 60 environments analysed.

3.3. Spatial Relationship of Digital Screens in the Home and Backgrounds Seen during Connections (RQ4, RQ5)

Results are depicted as drawings of the room types used by students. They show the spatial relationships between the essential architectural elements (such as windows and doors), the digital device screens used, and the screen backgrounds used during online learning connections.

The position of the digital device with integrated camera (broadcast source) is either located on one side, in front of, or behind the door; while the position of the device, with respect to the natural light source, windows, is either at the side (laterally), behind, in front, or in the zenith position (Figure 3).

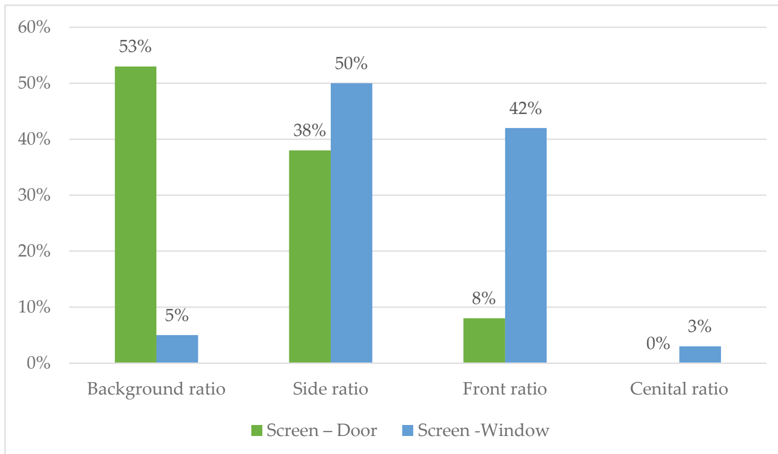

Figure 3. Relationship between the architectural elements and the broadcasting source (screen). Note. The percentages are calculated with respect to all 60 environments analysed.

The broadcasting device of most students is placed behind the door (53%), although a sizeable number also place it laterally (38%). With respect to the window, the device is mostly placed laterally (50%), although a sizeable number also place the device in front of the window (42%). Placement in a location at the back (5%) and in the zenith position (3%) occurs rarely.

The backgrounds exhibited by students in their online connections with camera have two variables. The first is related to the colour of the background wall (white or other colours). The second relates to items that are viewed as a backdrop, which can be: neutral or empty; have minimum décor; or display a number of items, thereby providing a wealth of information about users. The physical background shared in digital connections is mainly white (52%), but in other cases, it contains other colours or prints (48%). The elements found in most rooms comprise a complex backdrop of items (43%), but other environments show an empty or neutral background (40%). Some backgrounds (17%) have decorative elements.

3.4. Associations between Variables (RQ6)

The relationships between the different variables were analysed, and, depending on the Cramér's V results obtained, the interactions are presented as high (0.70–0.89), moderate (0.40–0.69), or low (0.20–0.39).

The highest association is seen between the variables Content, Space (bedroom and others), and Sofas and beds (sofa, sofa bed, bed) which give a $\chi^2 = 29.1275$ and $p = 0$, with a Cramér's V = 0.87551. On the other hand, one moderate and two low associations are also detected. A moderate association is seen between the profile variable Age (<23 years and >22 years) and presence of Personal care items (Cramér's V = 0.41667), while two low associations with values 0.34331 and 0.32604 respectively, are observed in the profile variables. These low relationships are seen between variables Age and Access to room (lateral, in front, or behind), and between Gender (female and male) and Storage unit (wall shelves, shelves, bookcase cum TV cabinet, sideboard or chest of drawers, closet, built-in closet).

Moderate association in the content variables is seen between Space (bedroom and others) and Tables (desk table, built-in table and bed, shelf–table unit, low table, side table, dining table), and between Sofas and beds (sofa, sofa bed, bed) and presence of Storage units (wall shelf, shelf, bookcase cum TV cabinet, sideboard or chest of drawers, closet, built-in closet). Another moderate association is seen between Access to room (lateral and others) and the presence of Tables (desk table, built-in table and bed, shelf–table unit, low table, side table, dining table), Sofas and beds (sofa, sofa bed, bed), and the Light source (in relation to screen position: lateral, frontal, back, and zenith). Colour (white and others) is associated with the type of workspace (bedroom, study, living room, kitchen), with Tables (desk table, built-in table and bed, shelf–table unit, low table, side table, dining table), and with the presence of care items (baby cots, pets). There is some association between Area (up to 10 m^2 and > 10 m^2) and the presence of Personal care items (baby cots, pets) (Table 2).

Table 2. Moderate associations between content variables.

Variable 1	Variable 2	χ^2	*p*-Value	Cramér's V
Space	Tables	22.34925	0.00045	0.54228
Sofas and beds	Natural light source	12.73325	0.00525	0.46067
Colour	Space	11.32152	0.01011	0.43439
Access	Sofas and beds	7.10983	0.02858	0.43255
Colour	Tables	13.57603	0.01854	0.42265
Colour	Personal care items	1.21528	0.27029	0.41667
Area	Personal care items	1.21528	0.27029	0.41667
Access	Tables	13.08293	0.02261	0.41490
Space	Storage	20.21256	0.00114	0.41388

Legend. Chi-square (χ^2), *p*-value, and Cramér's V, which determines the intensity of association between the different variables (for a 95% confidence level, α = 0.05).

A low association is seen between the Natural light source (lateral and others) and the presence of Tables (desk table, built-in table and bed, shelf–table unit, low table, side table, dining table). The Background (neutral–empty and other) is associated with the Natural light source (lateral, frontal, back, zenith), and with presence of Sofas and beds (sofa, sofa bed, bed). Colour (white and others) is associated with three variables: Leisure facilities (music equipment, floor exercise machines, television, musical instrument, fitness equipment); relationship with Access to room (lateral, frontal, back); and with the presence of Sofas and beds (sofa, sofa bed, bed). Lastly, also notable is the presence of three other associations between Access to room (lateral and others) and Space (bedroom, studio, living room, kitchen), the estimated Area (5–10 m^2, 10–15 m^2, 15–20 m^2, >20 m^2), and Storage unit (wall shelf, shelf, bookcase cum TV cabinet, sideboard or chest of drawers, closet, built-in closet) (Table 3).

Table 3. Low associations between content variables.

Variable 1	Variable 2	χ^2	*p*-Value	Cramér's V
Light	Tables	11.35117	0.04485	0.38647
Background	Natural light source	8.75000	0.03281	0.38188
Colour	Sofas and beds	4.20323	0.12226	0.33258
Access to room	Storage	11.89883	0.03620	0.31755
Background	Sofas and beds	3.78320	0.15083	0.31553
Access to room	Tables	5.91830	0.11565	0.31407
Colour	Access to room	5.87029	0.05312	0.31279
Colour	Leisure facilities	4.13049	0.38863	0.30639
Access to room	Space	6.36878	0.09498	0.30381

Legend. Chi-square (χ^2), *p*-value, and Cramér's V, which determines the intensity of association between the different variables (for a 95% confidence level, α = 0.05).

As the first whole example of analysis, we present the gender analysis (Table 4). This variable does not show relationships with any other except the Storage Units (Library shelf,

Shelf, Living room furniture, Chest of drawers, Wardrobe cabinet). In this case, we find a low association, with a *p*-value of 0.02805 and Cramer's V of 0.32604. In other cases, *p*-values are greater than 0.05000, and Cramer's V is less than 0.30000.

Table 4. Associations between student's gender and other variables.

Variable	χ^2	*p*-Value	Cramér's V
Workspace type	2.48570	0.47788	0.20354
Area	0.63020	0.88949	0.10249
Screen and physical background colour	0.36915	0.54347	0.07844
Screen and physical background object	1.38296	0.50083	0.15182
Screen and room access	2.26272	0.32259	0.19420
Screen and light access	3.70335	0.29533	0.24844
Doors and windows	1.12513	0.56975	0.09564
Heating and air conditioning	1.86942	0.17154	0.16704
Curtains and blinds	1.70273	0.19193	0.18641
Types of lamps	2.43628	0.48692	0.13743
Types of sofas and beds	0.62030	0.73334	0.12776
Types of tables	5.24766	0.38641	0.26277
Types of chairs	0.59538	0.74253	0.09799
Storage units	12.54352	0.02805	0.32604
ICT devices	6.50161	0.48254	0.17765
Desktop items	1.35840	0.85139	0.08711
Decorative elements	4.27119	0.23363	0.22549
Leisure equipment	2.22711	0.69407	0.22498
Children's equipment and pet	0.02431	0.87611	0.05893

Legend. Chi-square (χ^2), *p*-value, and Cramér's V, which determines the intensity of association between the different variables (for a 95% confidence level, α = 0.05).

The second example is about the students' level (Table 5). Only a low significant relationship is found between the Screen and room access, and the level of students with a *p*-value of 0.02914 and Cramer's V of 0.34331. According to only the Cramer's V, we also found a moderate relationship with Care items (0.41667). In other cases, there are no associations. There were no answers from students of level 1 and 2. However, no data suggests that the results would change, at least in the descriptive and qualitative dimension.

Table 5. Associations between student's level and other variables.

Variable	χ^2	*p*-Value	Cramér's V
Workspace type	3.15635	0.36814	0.22936
Area	4.78357	0.18835	0.28236
Screen and physical background colour	0.61477	0.43300	0.10122
Screen and physical background object	3.03671	0.21907	0.22497
Screen and room access	7.07163	0.02914	0.34331
Screen and light access	0.30701	0.95871	0.07153
Doors and windows	3.12541	0.20957	0.15940
Heating and air conditioning	0.00174	0.96671	0.00510
Curtains and blinds	0.18133	0.67023	0.06083
Types of lamps	2.24272	0.52358	0.13185
Types of sofas and beds	1.70155	0.42708	0.21161
Types of tables	8.47126	0.13211	0.33386
Types of chairs	1.29231	0.52406	0.14437
Storage units	6.14879	0.29201	0.22827
ICT devices	4.99258	0.66087	0.15568
Desktop items	3.05387	0.54885	0.13062
Decorative elements	1.44968	0.69393	0.13137
Leisure equipment	5.85107	0.21055	0.36466
Children's equipment and pet	1.21528	0.27029	0.41667

Legend. Chi-square (χ^2), *p*-value, and Cramér's V, which determines the intensity of association between the different variables (for a 95% confidence level, α = 0.05).

4. Discussion

This study shows that the elements surrounding HE students in the physical space at home during ICT-mediated e-learning can be grouped into different types. In this sense, many household items are detected in spaces used for academic purposes. Among digital devices, worth mentioning are laptops and cell phones, whose proportion is higher than any other item, allowing for greater flexibility, and showing complementarity between the different devices, clearly reflected by the presence of multiple screens. The desktop seems to be a technological device that supplements the two most commonly used devices (cell phone and laptop). This preponderance of mobile devices in education reinforces the characterisation already seen among citizens. Moreover, the main advantages of digital mobile devices lie in the possibilities they offer for communication, interactions, ubiquitous learning, and information management in general [36,37].

The new HE context forced a reversal of the classic classroom structures, and conferred relevance to homes and digital devices. A possible adaptation of items present in the respective rooms to a pedagogical environment is also seen, based on the symbolic and functional distribution of items within the environments analysed. More than ever, students use household items for their educational purposes. This implies a topological, rather than a distributive, spatial organization.

The most frequently observed scenarios are bedroom, study, living room, and kitchen; nevertheless the most common is the bedroom and, due to its functionality, the study is the room with the highest possibility for affinity to e-learning space and use of ICT. This reaffirms the suitability of this domestic space for training HE students. The daily life of university students is marked to a great extent by the relationship between the home items and possibility to alter the use of space, i.e., space-reconfiguring possibilities. Some studies report that spatial changes and the emotional state of HE students do not affect their academic performance, but they do affect the incorporation of innovative tools, such as ICT, used for learning [38].

At home, students often place the digital device cameras to face the access door; but its position with respect to the window is mainly lateral or at the back of the device, to avoid light reflection during sessions. Insofar as the items identified in the spaces analysed are concerned, the environment is intentionally customized by students, to reflect a generally neutral environment during learning sessions. In general, students avoid transmitting excessive private information.

This new pedagogical reality within the domestic scenario, and its relationship with the home elements, characterise the configuration of new classrooms, highlighted by the atypical use of home space and interaction through digital screens. The effort put in by HE students to resolve online learning requirements embodies the educational response to connect to innovative tendencies, and to ensure continuity of training, despite the prevailing deficiencies in knowledge, pedagogical techniques, and resources [39]. Moreover, an essential function of education is to promote student use of digital technology, to benefit from the changing environment [40].

This study shows that the space in which we live can be used to a new hybrid domestic–academic reality. However, this appropriation for virtual education is a besieged reality, in which screens and hyper-connectivity have also become the main protagonists. The virtual means confirms the great versatility offered by homes for space use, as well as the need to create versatile spaces for the different activities carried out in the home. Therefore, digital infrastructure, fast Internet connection, and institutional and educational support are the essential requisites at all educational levels [28,41].

Of the associations detected between the variables analysed, worth highlighting is the interaction between the variables Space and Tables, which can be considered as a confirmatory relationship, because the type of room somehow determines the furniture in it. The study shows that students have a good knowledge of space, which helps them to transform the physical environment easily and in a particular way [42]. In other cases, and in line with our expectations, a moderate association is seen between the variable Age and the presence of Personal care items. Some moderate associations are seen in Access to the room (lateral and other), presence of several types of Tables, sofas (among other items), and the Natural light source (in relation to location of the digital device). The latter association shows that there is complementarity between the Natural light source and Access to the room. On the other hand, the position of the Natural light source is related to the presence of Tables, which is consistent with the technical recommendations regarding light source and work area. In fact, daylight is an essential element in studying [43].

Room colour is associated with the presence of Personal care items, tables, and room type. This association attributes white colour to rooms other than bedrooms, such as the living room or the study, which is somewhat confirmatory, because users often prefer warmer colours in intimate spaces. On the other hand, it should be noted that Space is associated with the presence of Storage furniture and Tables, which is likewise coherent. Moreover, it should be noted that daily home activities such as sitting, watching TV, or working on the computer are common routines and users appropriate space and furniture to avoid body stress [44].

Lastly, this research detects weak associations between the profile variables Gender and Age, as well as between Storage furniture and room access variables. One study finds differences in time spent on household activities by gender [45], which may explain differences in the spatial organization of environments, since cultural issues and habits rooted in society can influence.

5. Conclusions

The most common items seen in virtual classes are parts and elements of their homes, and laptops and cell phones are the most used devices, indicating that students are prepared to easily move their workspace. Four scenarios in student homes were identified for training (bedroom, study, living room, and kitchen), highlighting the occurrence of the bedrooms and the functionality of the study for attendance to e-learning sessions and use of ICT.

Students intentionally customize the environment to reflect a generally neutral environment during learning sessions, avoiding transmitting too many private data. The digital device cameras often face the access door, at a mainly lateral or back position with respect to the window, to avoid light reflection during sessions. The screen backgrounds used by students during online training connections confirm the great versatility offered by homes for space use, and attendance for the different activities carried out in the home. The absence of clear patterns reflects the great versatility of homes and uses. Most frequent associations are only confirming logical relationships.

6. Limitations and Prospects

It should be noted that this study was carried out on a small sample within the context of the Foundations of Architecture HE degree program, and hence, one would expect the participating students to not only have a sound awareness of the importance of spatial order, but also better strategies, as compared to other students, when transforming home space into an academic environment. Moreover, the user profile in this study is more concerned about design, and, hence, conclusions drawn may not be directly transferable to other profiles.

On the other hand, a bigger sample would help ascertain whether the moderately stable associations observed between the analysed variables are reaffirmed or increase. New studies are needed to confirm the low intensity associations between the different profile variables.

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Article

Visualizing Source-Code Evolution for Understanding Class-Wide Programming Processes

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Abstract: The COVID-19 pandemic has led to an increase in online classes, and programming classes are no exception. In such a learning environment, understanding every student's programming process is mostly impractical for teachers, despite its significance in supporting students. Giving teachers feedback on programming processes is a typical approach to the problem. However, few studies have focused on visual representations of the evolution process of source-code contents; it remains unclear what visual representation would be effective to this end and how teachers value such feedback. We propose two feedback tools for teachers. These tools visualize the temporal evolution of source-code contents at different granularities. An experiment was conducted in which several university teachers performed a user evaluation of the tools, particularly with regard to their usefulness for reviewing past programming classes taught by another teacher. Questionnaire results showed that these tools are helpful for understanding programming processes. The tools were also found to be complementary, with different aspects being highly evaluated. We successfully presented concrete visual representations of programming processes as well as their relative strengths and weaknesses for reviewing classes; this contribution may serve as a basis for future real-time use of these tools in class.

Keywords: programming education; feedback to teachers; programming process; visualization

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1. Introduction

Computer programming has been one of the fundamental skills for computer engineers and scientists over the years. Today, the demand for programmers is expanding widely, beyond engineering and science fields; many universities now offer introductory programming courses to non-STEM students. Robins et al. [1] reviewed novice programming education and discussed the difficulties that students experience. Many novice students struggle to write a program because they have to learn many things at the same time, such as complex new concepts, strategies for constructing programs, and debugging skills. These programming difficulties often lower learner motivation, which is an important factor for success in learning computer programming [2,3]. Such difficulties can lead to students dropping out of classes. Thus, it is crucial to offer appropriate support to learners.

However, it is not easy for teachers to identify such students during class. Help seeking, defined as an ability to ask for help from various resources including teachers, is known to be a difficult metacognitive skill [4]. It cannot be always expected that the students who need help will ask the teachers for help. In the past couple of years, more and more programming classes have been taught online due to the COVID-19 pandemic. Traditionally, teachers would go around the classroom to find students who needed assistance and to answer questions. However, such activities are seriously limited in online classes. Therefore, it has become increasingly important to realize sustainable programming education under such drastically changing circumstances, and teachers must be supported by information technologies.

One of the typical approaches for informing teachers of student learning situations is learning-analytics dashboards [5,6]. Dashboards provide teachers with an overview of their students' situations through statistics, performance indicators, visualization, and so on. They are also utilized in the domain of programming education. For example, Fu et al. [7] proposed a real-time dashboard for C programming courses, which visualizes student situations by focusing mainly on compile errors. Matsuzawa et al. [8] developed a dashboard with four coding metrics: working time, lines of code, compile-error correction time, and block-editor usage ratio. Aside from the dashboard, López-Pernas et al. [9] combined data from two different systems to understand students' programming learning processes by using process and sequence mining techniques. However, the actual contents of students' source code were not considered; teachers have little or no way of knowing how a students' source code has changed as exercises progress.

Yin et al. [10] presented a visual representation of a set of source code for easily exploring and obtaining a comprehensive understanding of the source code variation. However, their representation was not designed for understanding programming processes, and its effectiveness as feedback to teachers was not investigated. Therefore, much is unknown about effective visual representations of programming processes for teachers. For example, it is not clear how much detailed information should be presented and how the information presented is perceived by the teacher.

This study focuses on understanding class-wide programming processes collectively and seeks to answer the following research question:

RQ: What are the effective visual representations for feedback to teachers about programming processes?

We propose two kinds of visual representations of programming processes with different granularity levels employing a student's sequence of source-code snapshots to represent an individual programming process. One is coding trajectory maps (CTMs), which provide source-code-snapshot-level views of class-wide programming activities. The other is cluster flow diagrams (CFDs), which offer a rougher view of source-code status transitions as graphs. We made handy web-based tools for reviewing programming processes in a past class, each embedded with one of these representations, and conducted an experiment in which university teachers performed user evaluations of the tools.

2. Materials and Methods

The proposed visual representation was created from a set of source-code snapshots. This study used a dataset previously collected in an introductory programming course, and no new data were collected for the purpose of this study. Therefore, the evaluation of the proposals in this study was performed through a post-evaluation of the classes; i.e., the programming activities in classes that had already been completed were reviewed later through the proposed tools. Figure 1 illustrates the methodology of the present study.

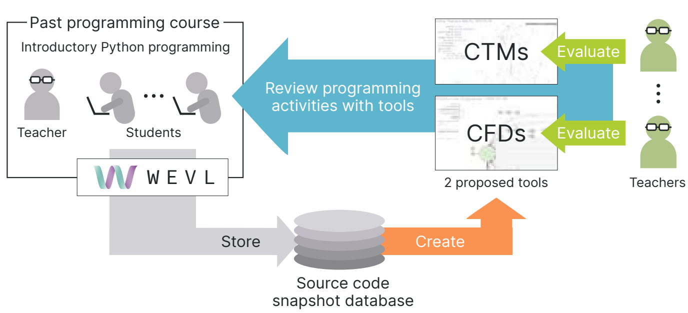


Figure 1. Overview of the methodology of the present study.

2.1. Data Collection via an Online Programming Environment

In this study, we rely on the dataset collected through our own online programming environment called WEVL. We developed this system to keep a detailed record of students' programming activities. Figure 2 shows the user interface of WEVL. The system takes a snapshot of source code at three different times. The first is an auto-save, which happens three seconds after a user stops typing; if any input is made to the editor within three seconds, it will be postponed to three seconds later, counting again from there. The second is the timing of the execution; if the snapshot of the source code has not been taken yet at the time of execution, it will be taken before the execution. The third is at the time of view switch on the system; users mainly use the editor view, but there are different views for other functions. When the user switches from the editor view, the snapshot of source code is taken if it has not been taken yet at that time.

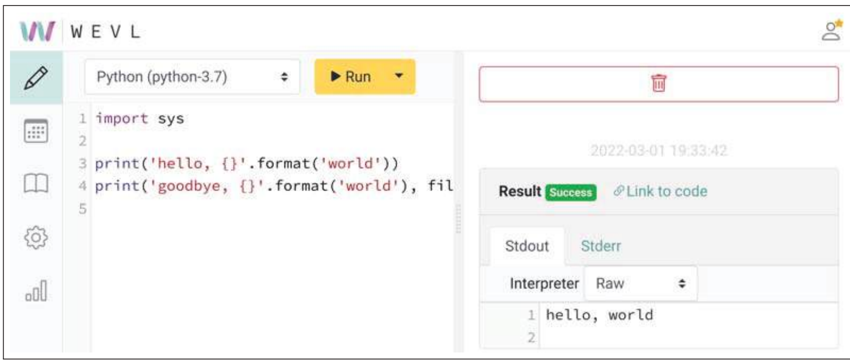
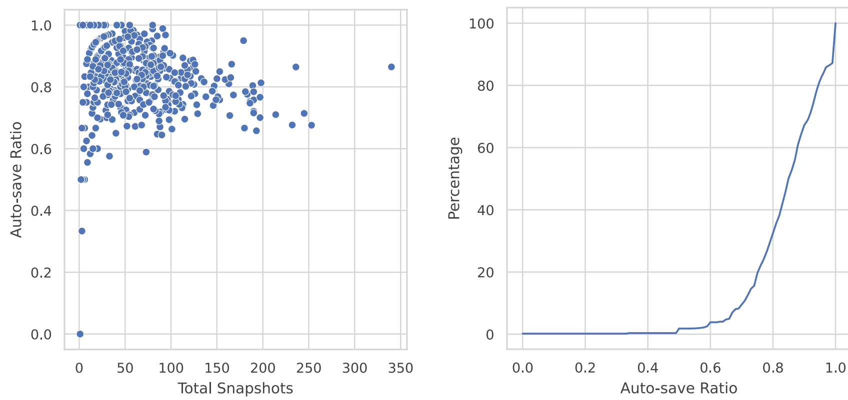


Figure 2. The WEVL online programming environment we developed to record students' programming activities including source-code snapshots.

The granularity of the data collected can vary greatly depending on the delay before auto-save. If the delay is too short, the process of source-code changes will be recorded in detail, but the system will be overloaded. On the other hand, if the delay is too long, the process of source-code changes will be only roughly understood. Therefore, the authors tried several candidates during the system development and subjectively decided on the number of seconds that would be appropriate as a break in typing without overloading the system.

In total, there were 36,355 source-code snapshots in the 14 weeks; 30,464 (83.8%) were auto-saves, and 5891 (16.2%) were from execution. Only 39 snapshots (0.107%) were recorded by switching view. Auto-saved snapshots were dominant in the dataset, and this is also the case for each student per class. We calculated the auto-save ratio per class for each student and made charts: in Figure 3a we contrast the auto-save ratio with the total number of snapshots, and in Figure 3b we show the cumulative distribution of auto-save ratios. Figure 3a shows that the auto-save ratios exceed 60% in most cases, regardless of student or class content. In addition, Figure 3b shows that the auto-save ratios are higher than 80% in more than half of the cases.



(**a**) Total snapshots per week vs. auto-save ratio. (**b**) Cumulative distribution of auto-save ratio.

Figure 3. High auto-save ratios were observed in the dataset.

Although the auto-saves only occur when the learner stops typing for three seconds, we can see it is very common for learners to take a break while writing code. Therefore, the auto-saved snapshots would allow for a higher resolution representation of the evolution of source code in a variety of cases.

The collection of our dataset was performed in the introductory Python programming course of our university, which one of the authors taught during the first semester of the 2020 academic year. The course was primarily for first-year undergraduate students and aimed at learning the basics of programming in 14 weeks. It covered fundamental programming concepts, basic Python syntax, and data structures. Table 1 details the weekly contents of the course.

Table 1. List of the contents of the course where the dataset was collected.

Week	Contents
1	Introduction to Python
2	Variables and Types
3	Numeric Types and Functions
4	Conditionals
5	Loops
6	List
7	Sequence Types and For Statement
8	Debugging
9	Visual Presentations and Abstraction
10	Dictionary
11	Random Numbers
12	Simulations
13	Comprehensive Exercises 1
14	Comprehensive Exercises 2

In each week, some programming assignments were given to students, which were due on the next class day. In a class, the teacher first lectured on the week's topic, and then students had time to do the exercise. In this study, we ignore source-code snapshots written outside of class, only considering the coding activities carried out within the class period. Additionally, the time length available for exercises differs from week to week depending on the amount of lecture content.

At the beginning of the course, we told the students about the collection of their learning activities through learning systems. They were able to opt out of the research use of their data. The dataset used in this study only includes snapshots from 76 students who agreed to the research use of their data.

2.2. Coding Trajectory Maps

The goal of CTMs is to give a big picture of the overall class-wide programming activities while preserving access to the details of written source code. To this end, we show every source-code snapshot written by students in the representation, which allows teachers to select the source code they are interested in to see its details. At the same time, we want the representation as a whole to depict the class-wide programming progress. We can imagine there might be some common source-code states. For example, there usually exist some expected final states of source code in an assignment; students will ultimately converge on such states if they progress successfully. In fact, source-code clustering has often been used in assessments of submitted source code [11,12], and researchers have used experts' source code as references to measure student progression [13]. In addition, intermediate states of programming can also be similar or identical [14].

In this sense, the programming process is considered to have a certain structure. Since this structure is based on the commonality of the source code, it is believed that the structure can be shown through visualizations that reflect similarities among source codes.

2.2.1. Generating Visual Representation

Our visualization method is based on the t-SNE algorithm [15] and the Levenshtein distance [16]. We first compute a distance matrix of source-code snapshots using the Levenshtein distance. The Levenshtein distance is often used to measure the distance between strings, which is defined as the minimum number of modification steps required to transform one string into the other through editing operations such as inserting, deleting, and substituting characters. We set all the operation costs to one. We then apply the t-SNE algorithm giving the computed distance matrix. The t-SNE algorithm takes a distance matrix of entities to visualize (source-code snapshots in our case) and outputs low-dimensional coordinates of the entities that optimally preserve the given distances in the low-dimensional space. In our visualization, the t-SNE algorithm arranges source-code snapshots in two-dimensional space. Finally, we visualize a set of source-code snapshots as the distribution of points in the plane with the obtained coordinates. Snapshots are drawn with their attributes in mind; their appearance may differ depending on their characteristics.

In the resultant visualization, the distances between points do not perfectly represent the original distances (Levenshtein distances); however, those that were originally close to and far away from each other will also be positioned close to and far away from each other, respectively, in the low-dimensional space. As we utilize many transient source-code snapshots, there are many data points that bridge the gap between largely different source codes, showing us visual trajectories of programming processes as a result. Therefore, this method of visualization fits our goal very well.

Please note that this usage of t-SNE algorithm is different from the usual and common usage, in which low-dimensional vector representations are calculated for high-dimensional vector datasets. It is certainly possible to represent source code as high-dimensional vectors—for example, with recent neural-network-based methods [17–20]. We choose not to adopt such an approach and instead employ Levenshtein distance to directly compute the distance matrix of source code for the following reasons. First, Levenshtein distance does not require source code to be free of errors. Many neural-network-based methods rely on an abstract syntax tree of source code to generate vector representation, which needs source code to be syntactically correct. As we utilize many transient snapshots of source code, such a requirement does not fit well. The second reason is versatility. With the neural-network-based approach, we must train our own model or employ an existing pre-trained model to encode source code into vector representations. This means that the model can be applied only to source code written in those programming languages included in the training data. In contrast, our approach can be applied to any kind of strings including even natural-language texts. The last reason is intuitiveness. The advantage of neural-network-based methods is that they can capture the semantics of source code. However, this would allow source code written in different styles but with equivalent meaning to be visualized as similar. While this can certainly be beneficial in some cases, at the same time, it may limit the teacher's opportunity to grasp the multiple different writing styles of the source code adopted by a student. Therefore, in this study, we emphasize that more intuitive differences are expressed in the visualization, and we employ Levenshtein distances that represent more superficial differences.

2.2.2. User Interface

Figure 4 shows an example of CTM. In the figure, source-code snapshots have different shapes; for each student, the first source code written in class is shown as a star, the last code as a flag node, and any others as circles. The meanings of node colors are as follows: gray indicates the code was not executed, green that it was executed without any errors, and red that it was executed with some errors. Please note that even source-code snapshots with exactly the same content will be drawn in slightly different locations. This makes it easy for us to see how much of the same source code is densely populated. The snapshots coming from the same student session are connected by a line in chronological order with different line colors indicating different students. The intersection of the vertical and horizontal lines indicates where the empty source-code snapshots are distributed; we can think of the point as the origin of the source-code space. We should not, however, think of these straight lines as axes with any meaning. These lines exist only to indicate the intersection point.

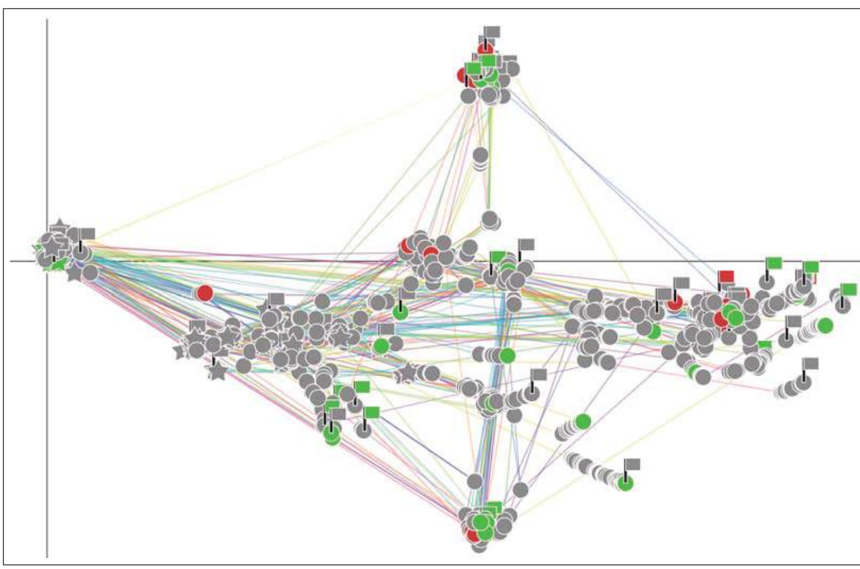


Figure 4. An example of coding trajectory map.

As shown in Figure 4, where students start and end writing source code varies from student to student, and even more so when it comes to intermediate source code they pass. We can also see structural patterns in the figure; there are clusters of similar source code and a bunch of lines connecting such clusters. With this visual representation of programming process, teachers can see how students solved exercise problems, what similar source-code groups existed, what popular writing strategies were used, and what individual coding activities students performed. In addition, the use of colors allows teachers to easily identify source code that is prone to errors.

CTM as an interactive reviewing tool consists of two parts: the visualization of source-code distribution and the property panel. Figure 5 shows the appearance of the tools; the property panel is shown on the left, and the visual representation of programming processes is shown on the right. (The property panel is actually shown over the visualization.) A user can access the detail of source code on the property panel by selecting one in the visualization. The information shown in the panel includes the user ID, date and time, code and parent code IDs, cluster ID, the reason it was saved, whether there was an error or not, number of compiles, number of runs, and content of the source code. Furthermore, selecting a snapshot also affects the visualization; to make the trajectory containing the selected snapshot stand out, the other trajectories will be semi-transparent.

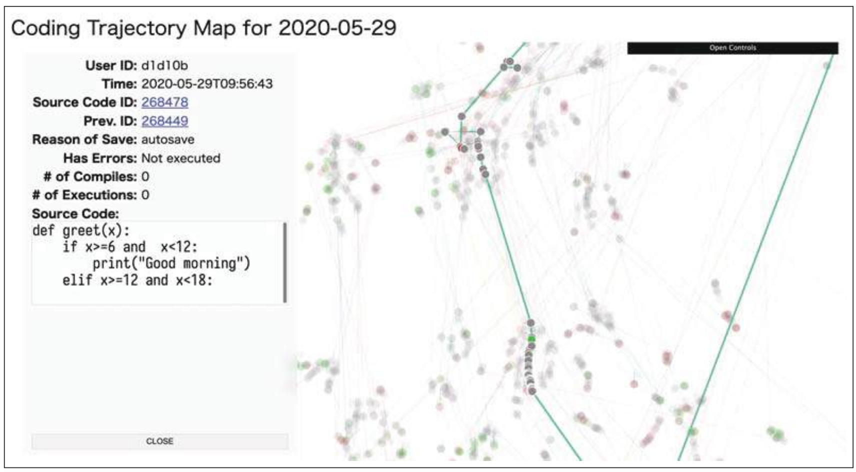


Figure 5. The user interface of the coding trajectory map as a reviewing tool.

2.3. Cluster Flow Diagrams

CTMs make many details of programming activities available to teachers while maintaining reasonable complexity. Although the structure of progress could be seen in the maps, it is not explicitly represented and requires teachers to spend additional time to understand it. Hence, we also propose that CFDs provide apparent, rougher perspective on the structure of class-wide programming progress. The important point here is to capture the major patterns in the evolution process so that the structure is emphasized. It can be realized by performing some kind of clustering to group similar activities together. To this end, both of the following points must be addressed by the clustering algorithm at the same time:

- Similarity in source-code content must be considered, and
- Alignment of programming processes is required because writing activities are not synchronized from student to student.

2.3.1. Generating Visual Representation

We propose a clustering algorithm that addresses these points based on the dynamic time warping (DTW) algorithm [21]. Figure 6 illustrates an example process of clustering by our algorithm. Our algorithm takes as an input a set of sequences of source-code snapshots, each of which represents a programming session of a student. The output of our algorithm is a set of clusters consisting of source-code snapshots. The DTW algorithm is used to address the alignment problem of programming sessions in the first step of the algorithm. The algorithm computes the optimal alignment (matching between source-code snapshots) between different programming sessions (see Step 1 in the figure). The computation of alignment requires a distance measure for sequence elements (source-code snapshots, in our case). We employ the Levenshtein distance for this purpose.

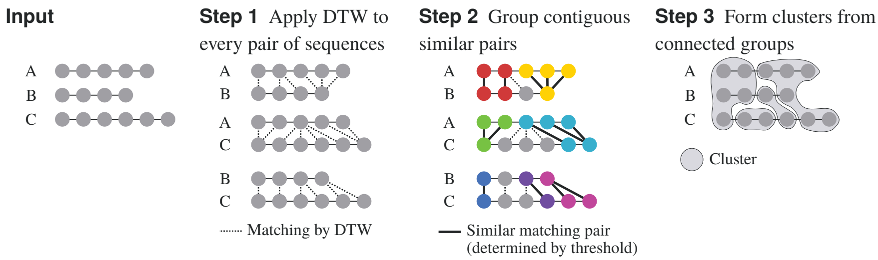


Figure 6. Illustration of the proposed clustering algorithm.

The second step of the algorithm is to group source-code snapshots. This step is performed on each pair of sequences independently. We consider two matching snapshots from different sessions to belong to the same group using the following rules:

- When both are non-empty source codes, they are grouped together if the normalized Levenshtein distance (described below) between them is less than a threshold.
- Otherwise, they are grouped if both are zero-length regardless of the Levenshtein distance between them.

We repeatedly apply these rules to all the matching pairs from the beginning to the end of the sequences. We retain the same group as much as possible in the repetition until we find a pair that cannot be grouped; a new group would start if we found such a pair. In the figure, color indicates such groups, and thick lines between sequences represent matching pairs with a Levenshtein distance less than a given threshold.

Given strings x, y, the normalized Levenshtein distance *nlev* between them is defined as follows:

$$nlev(x,y) = \begin{cases} 0 & (|x| = 0 \vee |y| = 0) \\ \frac{lev(x,y)}{\max(|x|,|y|)} & (\text{otherwise}), \end{cases} \quad (1)$$

where $lev(\cdot,\cdot)$ is the Levenshtein distance function, and $|x|$ is the length of the string x. We use the same operation cost values of one in computing the Levenshtein distance as in the case of CTMs.

The last step of the algorithm is merging groups into a cluster. We merge two groups if they share at least one snapshot. This operation is applied to the entire set of groups to compute the final set of clusters. In the figure, snapshots belonging to the same cluster are surrounded together.

2.3.2. Choosing Appropriate Threshold Value

Our algorithm has the threshold of normalized Levenshtein distance as its only parameter, which is responsible for controlling the granularity of the clusters. In this study, we take a data-driven approach to determine the threshold value. The algorithm uses this threshold to determine whether a matching pair should be grouped together or not. Suppose that the threshold value is also used as a criterion to determine if two adjacent snapshots in a single programming session are sufficiently similar. We can think most of such adjacent snapshots are relatively close compared to snapshots from different sessions because of the possible timings of taking snapshots. If the value is too small, many such pairs are incorrectly determined to be dissimilar.

We investigate the distribution of the normalized Levenshtein distances between every pair of adjacent snapshots in our dataset. Figure 7 shows the cumulative distribution of the normalized Levenshtein distances. The horizontal axis represents the normalized Levenshtein distance, and the vertical axis represents the fraction of adjacent snapshot pairs.

As we would like to focus only on how much difference the programming process could make in source code, we exclude the adjacent snapshot pairs of the exact same content.

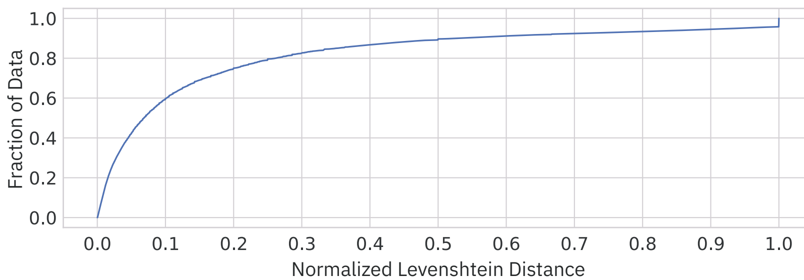


Figure 7. Cumulative distribution of the normalized Levenshtein distance between adjacent codes within a single session.

From this plot, for example, we can see that, if we take 10% of normalized Levenshtein distance as the threshold value, only about 60% of the adjacent snapshot pairs in the same session will be determined as similar pairs, which is too tight. In order for 90% of the pairs to be considered similar, however, we must allow for a normalized Levenshtein distance of about 40%, which seems too loose. Hence, we choose 20% (0.2) as the threshold, in which case about 80% of adjacent pairs are considered as similar.

2.3.3. User Interface

Based on the clustering results, we can see a programming process as a sequence of clusters. Simply presenting such cluster sequences would not be helpful because the underlying structure of programming process would not be unveiled. To make such structures apparent, we employ a directed graph representation in which obtained clusters are drawn as nodes, and transitions between clusters are drawn as edges (arrows). Unifying every occurrence of the same cluster into a single node, we obtain a kind of transition graph. Such a representation is commonly used by the literature in the context of sequence mining; however, in such graphs, the transition flows are folded too much to understand how students' source code diverged and joined.

To address the problem, we propose a slightly different representation that only moderately folds the same clusters into the same node. Figure 8 shows an example of such a representation, which we call CFD. Please note that, in the figure, the same cluster appears several times. We distinguish occurrences of the same cluster in a single session by the number of occurrences of each. That is, for example, a session sequence $1 \to 2 \to 1 \to 1 \to 2 \to 3$ is considered to be a sequence of indexed clusters $1_1 \to 2_1 \to 1_2 \to 1_3 \to 2_2 \to 3_1$. This ensures that all indexed clusters appear at most once in a single session. We then normally generate a transition matrix from the indexed cluster sequences.

In addition, node size varies in proportion to the number of students who visited the cluster while node color reflects the execution results of the source-code snapshot contained in the cluster. Given the percentage of executed source code in the cluster that terminated with an error, the color is red for 100%, green for 0%, white for 50%, and intermediate between these colors otherwise. If none of the source code was executed, the cluster color is gray. If transitions occur more than once between the same pair of indexed clusters by different students, they are depicted as separate arrows. To render the diagram, we use the software Graphviz [22] with the "dot" layout engine. We expect this visual representation to make it easier for teachers to understand the structure of class-wide programming processes thanks to the visual patterns found in the graph.

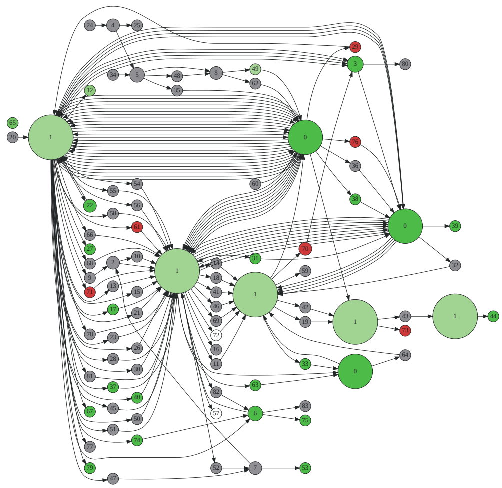


Figure 8. An example of cluster flow diagram.

CFD as an interactive reviewing tool consists of the property panel and the visualization part, as in the case of CTMs. Figure 9 shows the user interface of the tool. When a user clicks on a node, the detailed information of the corresponding cluster is shown on the left of the view, as shown in the figure. The information shown includes the cluster ID, number of source code, number of unique users who contributed to the cluster, ratio of the executed source code that did not have errors, ratio of the executed source code that had errors, indegree and outdegree of the node, and the shortest and longest source code included in the cluster.

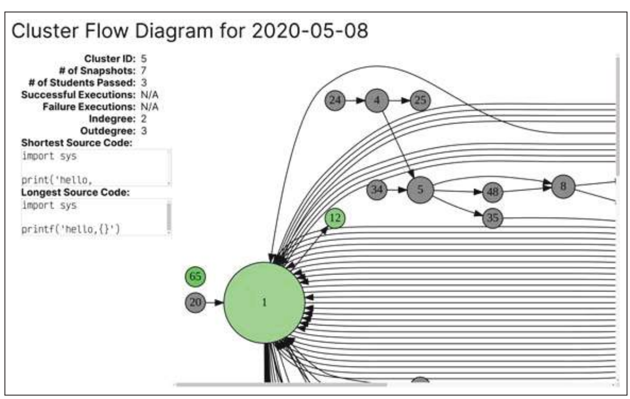


Figure 9. The user interface of the cluster flow diagram as a reviewing tool.

2.4. User Evaluation

We conducted an experiment for user evaluation of the reviewing tools based on the proposed visual representations of programming processes. We asked seven university teachers who had previous experience teaching programming to evaluate the tools in the context of reviewing past classes. Those teachers were asked first to learn how to use the tools and then to review three weeks of programming exercises with them. We provided instructions on how to use these tools in both text and video formats. After reviews, they were asked to answer a questionnaire for each tool on a 5-point Likert scale to measure the degree of agreement on each question with 1 standing for strongly disagree and 5 standing for strongly agree. For the first question of each questionnaire, respondents were asked to describe the reasons for their answers. In addition, we also asked respondents for free-description comments on the tools. Those questionnaires are not based on existing ones. The question texts are shown in tables in the next section. These tables also show the questionnaire results: the mean score and the standard deviation for each item.

We provide some additional information about the question texts as follows. Regarding CTM-1 and CFD-1, these questions actually ask whether each tool is as described or not. The descriptions of the tools that the participants read explained what they could do with each tool, and these questions contain those explanation texts almost verbatim. In this sense, these questions are equivalent questions. In questions CTM-4 and CFD-4, we mean source-code editing activities that are common or uncommon among many students by major or minor programming activities, respectively.

The participants reviewed 3 weeks of classes out of 14 weeks in the dataset. While our goal is partly to understand the learning activities of the class as a whole, another important objective is to identify students and cases in need of assistance. For this reason, we chose the early weeks: the first, third, and fourth weeks. It is expected that students are particularly vulnerable to problems in the early weeks.

3. Results and Discussion

In Table 2, the coding trajectory maps were given a high score of 4.43 on question CTM-1. This suggests the tool successfully provided the details of the individual coding activities. The following lists the reasons for the responses:

- I think that it is useful for reflection and improvement after the class, because I can visually grasp the number of similar errors and their number, while grasping the transitions that the target students have made in their source code.
- The coding process is detailed, so it is possible to understand it precisely.
- Since it is possible to see how the students implemented the program, it is easy to point out efficient implementation methods and follow up on any stumbling blocks.
- By using this tool, I can grasp each student's exercise process in detail, which is very useful as information during instruction. By clicking on a node, the actual source code is displayed, and the coding process of each student can be traced, making it possible to visualize the areas in which they are stumbling. Therefore, it is possible to grasp the contents that require explanation for the class as a whole and the contents that should be taught individually, and I judge that this tool is useful because it enables more detailed instruction.
- Because it is possible to check overall trends and specific behaviors at the same time.
- Because the location of errors can be grasped immediately, and in addition, it is possible to move to the past/future along the time axis.
- It would be easier to analyze if each node could be abstracted and combined into a single node for a macroscopic view.

Table 2. Questionnaire results for the coding trajectory map ($N = 7$).

ID	Question	Response Mean	SD
CTM-1	The Coding Trajectory Map is useful for understanding the process of each student's exercise in detail by checking the content and status of the source code at any given time, including the presence or absence of runtime errors.	4.43	0.53
CTM-2	The Coding Trajectory Map is useful for understanding what kind of code presented a struggle for students.	4.29	0.76
CTM-3	The Coding Trajectory Map is useful for identifying typical examples of code written by students.	3.57	0.79
CTM-4	The Coding Trajectory Map is useful for understanding each major and minor programming activity in the class.	4.14	0.69
CTM-5	The Coding Trajectory Map helps the teacher reflect on the lesson.	4.00	0.82

In summary, it is clear that teachers commonly appreciated the ability to see detailed information and to follow the process of changes in the source code over time. In addition, the comments also indicate that some teachers valued the abilities to identify programming errors, the ways programs were written, common tendencies, and peculiar behaviors. Although it seems that the last comment is not the reason for the response, the comment addressed the need for a coarser visualization, such as CFDs.

In terms of source code, we can say that the teachers considered the tool helpful for finding source code that is problematic to students (CTM-2). In contrast, it is not as helpful for identifying typical code examples (CTM-3). Concerning coding activity patterns, it is suggested that common patterns and abnormal activities could be easily identified by teachers (CTM-4). As for students, we can expect the tool may help notice students we should pay attention to (CTM-5), although the score is not very high. Overall, it is shown that the coding trajectory maps have functions useful to find important code, students, and activities in programming exercise, and teachers agreed that the tool is useful for reflecting on classes (CTM-6).

From Table 3, we can see the CFD was rated as being useful for checking the progress of the entire class through the cluster-level transition patterns (CFD-1). However, the score is a bit lower than that of CTM's equivalent question (CTM-1) The reasons for the responses are as follows:

- I think it is useful because it allows us to statistically grasp the trend and wrong points of the programs in the whole exercise. On the other hand, there are some difficulties in the visualization method, which will require further improvement.
- It is easy to grasp the branches on the path from the start of programming to its completion at the individual or group level.
- The size of the circles is intuitive and easy to understand.
- While the CTMs show the students' programming transitions, I think the CFDs allow us to grasp the students' tendencies thanks to the grouping of students. I would like it to show how I should understand and grasp the trend.
- Common source code such as *import* statements automatically become clusters. When grasping the details of the source code, the number of nodes is expected to increase as the amount of source code increases, and it would be cumbersome to use this information to grasp the progress of the entire class exercise. For example, regarding the writing of *if* statements, a similar process can be implemented in a grammar using the ternary operator, but in that case, the tool will represent them as different nodes, and therefore, as the source code grows, it will be complicated to grasp the entire process. However, if students write almost the same source code, I believe that using this tool would be beneficial as a countermeasure against the copy-and-paste problem.
- Because it allows a rough grasp of the transitions of students' source code.
- Because I can see the size of clusters and the overall picture of transitions between clusters, as well as detailed source code.

As we can see in the comments, the participants appreciated CFD's ability to see the trend and the big picture of the exercises. Meanwhile, two participants pointed out difficulties related to the complexity of the visualization, and one participant wanted a more specific presentation of trends. These comments suggest that teachers may have difficulties in reading programming trends from CFD's visualization. Therefore, future studies may need to improve the visualization method and/or to present concrete trend patterns together to assist in reading the visualization.

Table 3. Questionnaire results for the cluster flow diagram ($N = 7$).

ID	Question	Response Mean	SD
CFD-1	The Cluster Flow Diagram helps the teacher see the progress of the whole class as a pattern of state transitions based on clusters of source code.	4.14	0.90
CFD-2	The Cluster Flow Diagram is useful for understanding what kind of code presented a struggle for students.	3.71	1.25
CFD-3	The Cluster Flow Diagram is useful for understanding the typical example of the code written by the students.	4.29	0.76
CFD-4	The Cluster Flow Diagram is useful for understanding each major and minor programming activity in the class.	3.57	0.53
CFD-5	The Cluster Flow Diagram helps the teacher reflect on the class.	3.86	0.69

Regarding source code, even though the mean score of CFD-2 is not low, it is hard to say the tool is suitable for identifying the source code with which students struggled. In contrast, the tool received the high score of 4.29 for CFD-3, which suggests teachers thought the tool was helpful for identifying representative source-code instances. In terms of coding activities, its score for CFD-4 is relatively low compared to other questions but not lower than 3. This might be because the tool aggregates continuous source code into clusters, and actual coding activities are not apparent. Teachers weakly agreed that the tool was useful for reflecting on the classes (CFD-5).

Overall, the CFD received a certain amount of positive feedback although these scores are not as high as CTM's except for the use case of identifying typical examples of source code (see CFD-3 and CTM-3). This result reflects the advantage and disadvantage of the tools. From the result, we can say CFD is better than CTM at showing representative source code instead of individual source code that, for example, causes errors.

In the free-description comments, one of the most anticipated features was the interoperability function. Teachers wanted to jump from one tool to the other. This suggests that the teachers also considered these tools to be complementary. Another feature requested most was a temporal presentation of the flows. The current versions of the tools are designed to reflect on classes and be statically implemented. It would be a future project to realize real-time feedback with the interoperable versions of the tools.

Our research question was "What are the effective visual representations for feedback to teachers about programming processes?" According to Tables 2 and 3, the teachers valued the effectiveness of both proposed visual representations, especially in reviewing classes. In comparison, the score of CTM (CTM-1) was better than CFD's (CFD-1); however, the latter score was by no means low. Furthermore, we found the tools are complementary; while CTM fits better in reviewing source-code-level programming activities (CTM-2, CTM-4), CFD works better in identifying representative source code from entire programming sessions (CFD-3).

In addition, the comments from the participants provided helpful insights for future research. Although CTM and CFD were proposed as separate tools in this study, it may be more convenient for teachers to develop them as a single tool and to allow teachers to adjust the granularity of its visualization as needed. Moreover, while this research focused mainly on visualization, we believe that extracting and presenting useful patterns related to programming activities can also support teachers and may be even more effective when used in conjunction with the proposed visualization.

In summary, this study successfully presented two different concrete visual representations for understanding class-wide programming sessions. From the questionnaire result, we can say that CTM is definitely one of the effective visual representations for the purpose. On the other hand, the usefulness of CFD was recognized to some extent, but there is still room for improvement in its visualization method.

Several studies proposed visualization methods to better understand students' programming processes. For example, Yan et al. [23] tried to understand programming processes through milestones of graphical output generated from student programs. Simon et al. [24] proposed a visualization technique to represent the programming process in Scratch. Diana et al. [14] proposed a dashboard that shows an interaction network representing students' transitions over code states. However, their methods cannot be directly applied to the goal of visualizing the evolution of textual source code, and research targeting this goal is limited.

Yin et al. [10] presented a visual representation of a set of source code, which is similar to our CTMs. The most important difference is that it relies on the abstract syntax trees of source code. This makes it impossible to generate their representation from a source-code dataset that includes grammatically incorrect source code because abstract syntax trees cannot be constructed from such source code. This property of the representation is not suitable for programming processes because the source code in the process of being written is almost always incomplete. Of course, we can visualize only correct source code with their method; however, this significantly reduces the resolution of the rendered processes.

Regarding CFDs, clustering of source code is one of the widely used techniques in understanding a large set of source code: for example, plagiarism detection [25,26] and analysis of programming assignment solutions [27]. Clustering usually requires measuring the similarity between source codes. There are two major approaches to measuring similarity based on source-code content: grammar-based [28] and semantic-based [10,17,29]. The semantic-based approach typically relies on abstract syntax trees and is therefore unsuitable for the reasons discussed above. Our approach could be categorized as one of the grammar-based approaches. In particular, our approach differs from others in that we view source code as a sequence of characters rather than a sequence of tokens. In writing programs, tokens are unstable entities. For example, the number of tokens can easily change if the space separating two identifiers is replaced by an underscore. Further, placing a single double quotation mark anywhere will cause many subsequent tokens to be treated as part of a single string literal. We cannot tolerate such instability because we track changes in the source code over time, and therefore we employ a character-by-character sequence as a robust method. This approach has the additional advantage of being programming language independent, since it does not require a programming language grammar or a language-dependent training dataset or model.

Several clustering methods have been employed to perform source-code clustering: spectral clustering [27], a graph-based approach [30], k-means algorithm [31,32], and so on [10,33]. However, few clustering algorithms consider the persistent evolution of source code over time. For example, Piech et al. [33] proposed a hidden-Markov-model-based analysis to model student progress. In their study, progress states (corresponding to clusters in our study) were extracted with a k-medioids algorithm without considering source-code evolution. In contrast, our clustering algorithm uses the Levenshtein distance to consider similarity of source-code content and, in addition, uses the DTW algorithm to simultaneously consider temporal ordering.

4. Conclusions

This study addressed the problem that visual feedback to teachers on learners' programming often fails to consider the temporal evolution of the source-code content. We proposed coding trajectory maps (CTMs) and cluster flow diagrams (CFDs) as visual representations of class-wide programming processes. They can present information to teachers at different granularities, taking into account the content of the source code. The CTMs are built on top of the visualization based on the t-SNE algorithm in conjunction with the Levenshtein distance of source-code contents and designed to show precise programming activities in the processes as well. CFDs, on the other hand, provide a rougher perspective for understanding the programming processes based on the clustering results from the proposed clustering algorithm. The proposed algorithm considers the temporal evolution in source-code contents in sessions employing the dynamic time warping algorithm and Levenshtein distance. We conducted an experiment for user evaluation of the proposed visual representations specifically in the context of reviewing past programming classes. From the results of the questionnaire, it can be said that CTMs were recognized by the teachers as an effective visual representation for understanding programming processes. On the other hand, although the teachers found CFDs useful to a certain extent, there is still room for improvement in its visualization method. The results of this study have the potential to enable teachers to gain a detailed understanding of students' programming processes even during online classes under special circumstances, such as COVID-19, and will contribute to sustainable programming education in the future.

This study has three main limitations. First, the use of the tools was different from the original intended use. The proposed tools was intended for teachers to check the status of their students' exercises during or after class and then to intervene in student learning. However, in our experiment, the participants could not intervene because they only reviewed past classes. The reason for this is that it is difficult to match the actual content of classes given by different teachers. In this study, the emphasis was on confirming the usefulness of the tools objectively under identical conditions. It would be an issue for future research to conduct more realistic evaluation in different teachers' classes.

Second, the efficiency of the tools was not examined. While efficiency is undoubtedly an important factor in actual use, this study placed the highest priority on establishing an effective visualization method. In future studies, we plan to evaluate the efficiency of the proposed tools in classes and develop more efficient methods. For example, comments obtained from participants mentioned the implementation of interoperability between the two tools, which could be one way to increase efficiency.

Third, the participants did not review every week's programming sessions with the proposed tools. In this study, the evaluation was conducted on programming activities in the early weeks of the course, when students are particularly likely to have problems. As students progress in their learning, their understanding of programming will deepen, and the way they make mistakes may change. Furthermore, since the lesson content differs from week to week, there remains the possibility that individual differences in programming may not be well-represented in some cases. Therefore, the results of this study are only applicable to classes in which students do not have advanced skills and the content is relatively basic.

Future studies should examine how the proposed tools can be used during actual classes and what improvements teachers can make by using them. At the same time, it is also important to improve the tools so that teachers can use them effectively in the limited time they have in class, including integration of the proposed tools.

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Impacts on Student Learning and Skills and Implementation Challenges of Two Student-Centered Learning Methods Applied in Online Education

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Abstract: Online education became more prevalent during the COVID-19 pandemic in many countries around the world, including the Gulf Cooperation Council (GCC) countries. This study aims at assessing the impacts on learning and skills of two student-centered instructional strategies (problem-based learning (PBL) and just-in-time teaching (JiTT)) used online and their implementation challenges. The PBL and JiTT were implemented in modules taught in various courses delivered at different bachelor's study levels and disciplines. The research used a mixed design research method. Quantitative data were collected from exam scores and two self-administered surveys. Qualitative data were collected using individual structured interviews. The lecture-based learning method was used for comparisons. A total of 134 students participated in the quizzes and exams, 85 students completed the self-perceived impacts on learning and skills survey, and 82 students completed the implementation challenges survey. Ten students participated in the structured interviews. Tests and survey scores showed that both online PBL and JiTT had significant impacts on students learning and skills and that these effects are consistent across various disciplines. A non-conducive online learning climate, internet connectivity problems, heavy workloads, and time management issues were reported as the implementation challenges. The PBL and JiTT can be considered as effective teaching/learning strategies in online education.

Keywords: online problem-based learning (PBL); online just-in-time teaching (JiTT); impacts on learning and skills; implementation challenges

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1. Introduction

As information becomes more readily accessible, technology more widespread, and competition more prominent, modern professions call for graduates with complex skills such as critical thinking, problem-solving, communication, organizational, collaboration, and self-directed learning, in addition to the core professional skills. To cope with the changing market needs and promote the achievement of required skills, higher education institutions had to reform their curricula and call for adopting innovative instructional practices methods relying on student-centered learning (SCL) pedagogy and digital technology [1,2]. Qatar University, as a leading institution of higher education, has embraced the need for instructional change and has endorsed student-centered education and digital learning by considering them as education excellence themes [3].

Student-centered learning (SCL), also known as learner-centered education, broadly encompasses teaching and learning methods that focus on creating and implementing active roles of the learners by placing them at the heart of learning [4]. It encourages students to deeply engage with the material, develop a dialogue and collaboration, critically think, and reflect on their progress [5]. It promotes many cognitive and soft skills such as critical thinking, problem-solving, organization, collaboration, and life-long learning. SCL is founded on the constructivism learning theory that enables learners to actively construct their knowledge from new and prior experiences [6].

There is a myriad of SLC instructional strategies such as problem-based learning (PBL), case studies, just-in-time teaching (JiTT), flipped classrooms, and many others. These strategies focus on providing tools and learning environments that facilitate interactions and collaborations between students while promoting deep learning [7].

The benefits of integrating SCL instructional strategies in the physical classroom setting were reported to seem substantial in terms of improved learning outcomes compared to the traditional instructional methods [8–10]. In addition, SCL strategies increase in-class teaching efficiency and effectiveness. They also improve students' preparation for the class sessions, endorse collaborative problem-solving during the class session, enhance student motivation for learning, and promote the ongoing formative assessment of student learning (by both instructors and students) [11]. In addition, they adopt the active learning approach that was found to promote student learning [12]. Furthermore, they provide structured opportunities for students to actively construct new knowledge from prior knowledge [11].

Online education, also called e-learning, distance learning, and distance education, is a form of education in which the main elements include a physical separation of teachers and students during instruction and the use of various technologies, digital tools, and learning platforms to facilitate teacher–student and student–student interactions. Correspondence courses were among the first types of distance education, but distance education did not pick up steam until communications technology evolved in the 1990s [13]. Moreover, the advent of the COVID-19 pandemic has given a push for the acceleration of digitalization of universities all around the world and led to the need for a rapid transition to online education [14]. The transition from traditional face-to-face learning to online education was smooth for universities that had established experiences in online education, and students appreciated the online education during the pandemic, the teacher's teaching skills, and the quality of online courses [13]. Nevertheless, this transition presented many challenges for the universities that did not engage in online education prior to the pandemic. These challenges were reported to be related to the flexibility of the available learning platforms and digital tools, acquaintance with information and communication technologies (ICT) of both educators and the learners, learning environments, and readiness for online teaching/learning [15–24]. It also raised uncertainties on the learning pedagogy that applies best to the online setting [17] and opened opportunities for good practices that are necessary for professional development [25].

Although some groups have already shared their teaching practices in online education, very few of them addressed SCL in the online setting [16–24,26]. Thus, it remains uncertain whether SCL instructional strategies delivered in the physical classroom setting will yield similar results when delivered online due to contextual differences such as lack of face-to-face interactions, lack of instructor availability during the whole time of the session, non-conducive at-home learning environment, internet connection interruptions, and social isolation. Moreover, most of the previously published studies were reported from countries outside Qatar. Since the cultural background and social context might be fairly different, the findings of these studies cannot be fully extrapolated to the Qatari context to learn lessons and pave the road for future changes in the higher education system. In addition, most of these studies reported online education experiences instead of measuring their impacts on student outcomes. In addition, very few previous studies were performed using a structured methodology, and according to our knowledge, they rarely assessed the effectiveness of a teaching method. Thus, we designed this research to address these research gaps and respond to the research needs in the field of online education in general and the Qatari context in specific.

Therefore, this research aims to test the impacts of two student-centered learning (SCL) strategies, namely problem-based learning (PBL) and just-in-time teaching (JiTT), on student learning of the subject matter and skills, mainly critical thinking, problem-solving, communication, organization, and collaborative and independent learning skills, that are needed for contemporary professions. It also aims to assess whether these effects on learning and skills are consistent across the various course subjects and the students' study levels and are sustained over time.

Figure 1 shows the research questions that are addressed by the current study:

A. What are the impacts on the short-term learning of the traditional instructional strategy?
B. What are the impacts on the long-term learning of the traditional instructional strategy?
C. SCL instructional strategies effectively improve learning when used in the in-class physical setting compared to traditional instructional strategies. Would this be also observed in online education?
D. SCL instructional strategies effectively develop students' critical thinking and problem-solving skills when used in the in-class physical setting. Would this be also observed in online education?
E. SCL instructional strategies are effective in motivating students to learn the course material when used in the in-class physical setting. Would this be also observed in online education?
F. SCL instructional strategies effectively develop students' communication, collaboration, and independent learning skills when used in the in-class physical setting. Would this be also observed in online education?
G. What are the challenges in implementing just-in-time teaching (JiTT) that includes short web-based exercises when used in online education?
H. What are the challenges in implementing problem-based learning (PBL) when used in online education?

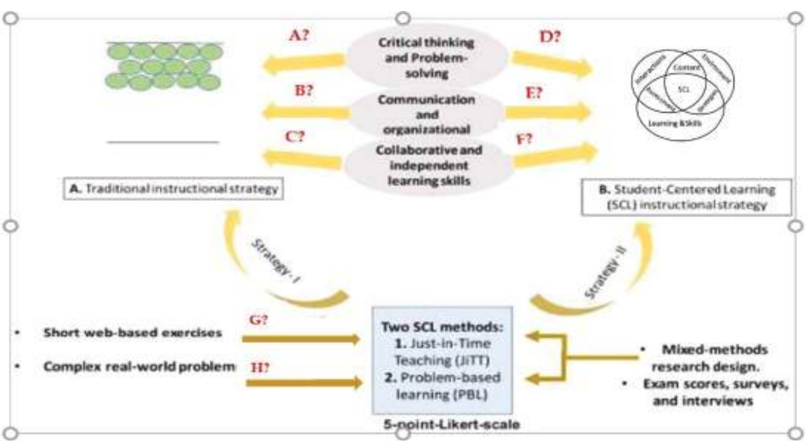

Figure 1. Study methods and research questions.

2. Problem-Based Learning (PBL) and Just-in-Time Teaching (JiTT) Overview

2.1. Problem-Based Learning (PBL)

Problem-based learning is an SCL instructional strategy that originated in medical education and has been widely adopted in diverse disciplines and educational contexts [27–29]. It is a form of active learning where students assume responsibility for their learning [30]. In principle, PBL revolves around four learning principles: constructivism, contextual learning, collaborative learning, and self-directed education [31]. In PBL, students learn about a subject while working in groups to solve an open-ended real-world problem [27]. The problem drives both the motivation to learn and the learning itself [27]. Critical to the success of PBL is the selection of the problem. The problem should be ill-structured, authentic, complex, and unexpected [32]. It should be able to motivate and enable the students to learn new materials in the process of solving the problem [32]. In the context of PBL, instructors act as facilitators, guiding the learning process and conducting a thorough debriefing at the end of the learning experience [31]. In brief, the goals of PBL are the acquisition of an integrated body of knowledge that can be retrieved, applied, and transformed when needed and the development of critical thinking, team-building, and self-directed learning skills that allow students to masterfully deal with new and complex problems in their careers [27]. PBL is a process that starts with a problem that students analyze as a group based on the background knowledge they have. Then, the group brainstorms possible solutions and decides what further information is needed to solve the problem. These ideas and suggestions are formulated as learning objectives afterward. Independent study follows as each group member is tasked to find the desired information. The group members gather again to share collected information, discuss the problem further in light of the new information obtained, and suggest possible solutions [33]. The students complete the learning process by reflecting with the intention to improve their learning performance [34]. They proceed to make generalizations about the problem so they can transfer their learning to new future problems [34]. The process ends with feedback and assessment of their individual work and team members' work [34]. This process has been described as the seven classical steps of PBL: (1) understand the situation/clarify terminology, (2) identify the problem, (3) suggest possible causes (hypothesize), (4) connect problems and causes, (5) decide what type of information is needed, (6) obtain information, and (7) apply the information [35]. The process is repeated in many rounds until the problem is solved [34]. There is evidence supporting the effectiveness of PBL across various disciplines [27]. PBL was shown to effectively enhance longer knowledge retention and the application of knowledge [28,29,33,34,36]. In addition, PBL was found to promote the development of critical thinking skills, problem-solving abilities, communication skills, and self-directed learning skills [28,29,33,34,36]. It can also provide opportunities for working in groups and finding and evaluating research materials [37]. Therefore, PBL was reported to enhance interdisciplinary knowledge creation and collaborative skills [28,29,38]. The entire process is very engaging, which has been shown to improve retention and student satisfaction [28,29,33]. However, studies on the process are still inconclusive with regards to which step most significantly impacts students' learning, although causal studies have demonstrated that the whole process is indispensable in influencing students' learning outcomes [28].

2.2. Just-in-Time Teaching (JiTT)

Just-in-time teaching (JiTT) is an SCL teaching and learning strategy that is based on the interaction between web-based study assignments (warm-ups) and an active learner classroom [a]. It relies on a feedback loop between web-based learning materials and the classroom [39–41]. JiTT consists of providing students with learning resources and short web-based assignments that are usually completed and returned to the instructor before the class session [39–41]. The instructor reviews students' responses to the assignments before the class session, adapts the lesson, and tailors class activities according to students' actual learning needs [39–41]. JiTT allows both students and instructors to be better prepared for the class session, yielding a more efficient use of the class time [39–44]. JiTT is built on the constructivism learning theory, where students actively construct their knowledge from prior knowledge [39,41]. Initially developed for introductory physics courses, its use has spread to various disciplines [39,45]. More recently, JiTT using video-based lectures (VBLs) was incorporated and was very well perceived by students [42,46]. JiTT has proven effective in enhancing students learning, promoting the students' responsibility to learn the content, improving classroom climate, motivating students to learn, promoting good learning habits, and fostering deeper learning of the materials [42–44,46–50]. In addition, JiTT was found to increase student satisfaction and cognitive gains [44,47,48].

3. Materials and Methods

3.1. Adopted Instructional Strategies

Two SCL instructional strategies were selected and implemented online in this study, namely just-in-time teaching (JiTT) and problem-based learning (PBL). These strategies were implemented in two independent course modules within the same course. In addition, one course module was delivered using lecture-based learning (LBL) in the physical setting and was considered the reference standard for comparisons.

3.2. Setting

The study was conducted at the Department of Biological and Environmental Sciences, College of Arts and Sciences, Qatar University, between January and May 2022 (spring 2022 semester). The files, consents, and surveys were prepared by the researchers and submitted for Institutional Review Board (IRB) approval using the IRB net website before the start of the study. The study was approved by the IRB with the number 1823096-1.

Four courses (two from biological sciences and two from environmental science curricula) were selected: two courses were delivered at the junior level (BIOL 110 (Human Biology) and BIOL 212 (Genetics)), and the other two at the senior level (BIOL 452 (Molecular Analytical Techniques) and BIOL 433 (Monitoring and Toxicology)) (Table 1). The courses were selected based on the willingness of their instructors to participate in this study. Each course was run in one section and delivered by one instructor, with the exception of the human biology course, which was run in many sections and taught by multiple instructors. However, only one instructor teaching one section of the human biology course agreed to participate in this study. Table 2 presents a summary of the experiment.

Table 1. Description of the selected courses.

Course Number and Title	Course Description	Major and Level	Credits
BIOL 110 Human Biology	This course is an introduction to human biology. It covers principles of structure and function of cells, tissues, and human body systems such as the digestive system, cardiovascular system, respiratory system, nervous system, muscular system, urinary system, and endocrine system.	Biological Science—Junior	3
BIOL 212 Genetics	This course considers the diverse aspects of genetics in both prokaryotes and eukaryotes by pondering the key players involved in inheritance. The following topics are extensively treated: chromosomes and genes, Mendelian inheritance; modification of Mendelian inheritance; gene interaction, inheritance and environment; sex determination; sex linkage; sex-limited and sex-influenced characteristics; linkage and crossing over; chromosome mapping; mutation; cytoplasmic inheritance; quantitative inheritance.	Biological Science—Junior	3
BIOL 452 Molecular Analytical Techniques	The course introduces students to various analytical methods focusing on maintaining a detailed laboratory notebook. Topics include multitasking, hands-on experience with analytical equipment, strategies that can be used in experimental design, troubleshooting experiments, and outcomes.	Environmental Science—Senior	3
BIOL 433 Monitoring and Toxicology	This course introduces students to the principles of environmental monitoring and toxicology. Topics include principles of risk assessment of contaminants with emphasis on the Gulf Region, principles in the design of monitoring systems, monitoring systems for the management of renewable natural resources, and use of monitoring data in assessing natural resource management and pollution risks at both the individual and population levels.	Environmental Science—Senior	3

Table 2. Summary of the experiment.

Course	Number of Course Sections	Implemented Instructional Strategies	Module Where the Instructional Strategy Was Implemented	Number of Students	Instructor
BIOL 110 Human Biology	One section	PBL	Digestive system	46	A
		JiTT	Blood	46	
		LBL	Muscular system	46	
BIOL 212 Genetics	One section	PBL	Gene editing	37	B
		LBL	Mendelian inheritance	37	
BIOL 452 Molecular Analytical Techniques	One section	PBL	Analysis of organic compounds	26	C
		LBL	Analysis of inorganic compounds	26	
BIOL 433 Monitoring and Toxicology	One section	PBL	Risk assessment	25	D
		JiTT	Factors affecting toxic responses	25	
		LBL	Monitoring of environmental pollutants	25	

All instructors who participated in this study had extensive experience in teaching the subject matter and received training on student-centered pedagogy, focusing on PBL and JiTT. All included courses were implementing an online PBL/JiTT component for the first time. These courses were redesigned to include at least one module that is taught online using PBL/JiTT. The course instructors had the freedom to select the module for PBL and to develop the problem.

3.3. Course Material Development and Implementation

All instructors followed the core PBL principles in the scenario design, including contextual, constructive, collaborative, and self-directed learning. Each instructor first articulated the learning objectives of the module that will be delivered online using PBL, and then the PBL scenario was crafted. All crafted scenarios contained minimal information and incomplete picture mimicking real-life situations and an embedded problem emerging from student brainstorming. Moreover, the complexity level of the scenarios depended on the course level; i.e., the courses taught at the junior level had more simple scenarios than those taught at the higher level. All scenarios were reviewed by an expert committee formed of two members who have extensive experience in PBL to guarantee their quality and ability to meet the learning objectives. Examples of PBL scenarios are presented in Table 3.

Table 3. Examples of PBL scenarios.

Course	Module Learning Objectives	Problem Scenario
BIOL 110 (Human Biology)	Explain the process of digestion in the GIT tract in humans. Discuss the absorption of nutrients in the small intestine.	A 45-year-old mother brought her son to a medical clinic for consultation regarding his digestive problems and malnourishment.
BIOL 212 (Genetics)	Explain gene editing and discuss its potential applications in various fields such as medical, agronomy, and zootechny. Create a hypothesis on how to use gene editing to solve medical and agronomic issues.	You have been enrolled as Research Assistant in a Molecular Genetics Unit whose main task is related to gene editing aimed at solving a problem related to hereditary human diseases, crop production enhancing techniques, and animal production. Before you start working in the research team of Molecular Genetics, you have been requested to extensively review the techniques of genetic editing and find applications in real-time situations such as those mentioned in the topics above.

Table 3. *Cont.*

Course	Module Learning Objectives	Problem Scenario
BIOL 433 (Monitoring and Toxicology)	Interpret the evidence from the literature to determine the toxic effects of substances. Determine the safe limit of exposure based on available evidence. Perform risk assessment for a substance and determine its risk level.	After you completed your BSc degree, you were offered an opportunity to work in the Ministry of Public Health. You were called for a meeting by the head of the risk assessment department who would like to share concerns about possible toxic effects observed in the population due to exposure to benzoates.
BIOL 452 (Molecular Analytical Techniques)	Categorize the molecular technologies and equipment used to analyze, purify, and characterize molecules, including organic compounds, nucleic acids, proteins, and other molecules of the environment. Explain how to apply modern molecular analytical techniques. Explain statistical tools used for data analysis.	Your environmental science lab has developed a method for quantifying a particular pharmaceutical product (drug quantitation and quality control) commonly found in hospital wastewater. This method involves an extraction followed by fluorescence measurement at the emission maximum for the drug. One of the samples analyzed in this method gave a result that showed an unusually large amount of this drug in this wastewater sample.

Prior to the launch of the PBL module, the instructors randomly assigned the students who were enrolled in their courses into groups, with each group composed of 4–6 students. Moreover, the instructor explained the PBL process to them and his/her expectations. The PBL module was launched online using the distance-learning window of the Blackboard learning platform. The module was run fully online over four sessions with no face-to-face interactions between the students and the course instructors. The first and last sessions were scheduled by the instructor and conducted in the instructor's presence, while the other two were scheduled by the students according to their own preferences and were conducted in the absence of the course instructors. The first session objectives were to define the problem and formulate learning objectives that would enable solving the problem.

Therefore, in the first session, the scenario was distributed to the students who were asked to clarify concepts. In groups, students started to read the scenario presented to them and unpack its components in an open and inclusive brainstorming process. During this session, the students were guided by the following questions: What information is being given? What information is missing (what do we not know)? What is the problem that we need to address and resolve? What are the information and tools needed to solve the problem? In addition, each group had to define the problem, develop the hypotheses (based on the possible causes), rank them according to priorities, and prepare requests for additional data. The instructor moved among the groups during brainstorming, observing students' interactions, providing guidance when needed, and prompting them for data requests. Then, the whole class reconvened, and each group started to share their hypotheses and their data requests accordingly. Based on their hypotheses and data requests, the instructor released the data incrementally related to the scenario. After exposing the whole scenario, students were again split into their respective groups and started developing the problem statement (in the form of a question), formulating their learning objectives, and dividing tasks among group members. Afterward, during the second session, students had to work independently to investigate a topic area as determined in the first phase and prepare an individual report. This session was followed by the third session where students shared their reports with their groups, essentially teaching their group members what they had learned. The group then discussed how this new knowledge informs the problem. Once all individual reports had been discussed, the group revisited the questions presented in the first session and attempted to address or solve the problem. Moreover, during this session, students also collaborated to prepare a final report that outlined the solution and recommendations. The students were also asked to include supporting and properly cited evidence from their research and evidence for their online meetings and discussions in this report.

In the final session, solutions were shared and discussed in the presence of the whole class, and the instructor provided feedback and a brief recap of the main learned concepts.

The JiTT was introduced in two courses: BIOL 110 (Human Biology) and BIOL 433 (Monitoring and Toxicology). The course instructor also selected the study module where JiTT was to be used. The module was run over two online sessions: one synchronous and one asynchronous. In the asynchronous session, the student had to watch a prerecorded lecture to learn the module content and go through the exercises/case studies and complete them before the scheduled class session time. Once completed, the instructor went over the answers and tailored the content and activities of his/her upcoming lecture based on the learning needs of the students. This session was delivered online in a synchronous mode. Examples of exercises are presented in Table 4.

Table 4. Examples of JiTT exercises.

Course	Module Learning Objectives	Exercises
BIOL 110 (Human Biology)	- Recognize the composition of blood - Explain the functions of blood elements - Identify the role of A and B antigens in blood typing	Persons presenting with anemia usually have a high ventilation rate. Why?
		Would you expect a person with thrombocytopenia (low platelet count) to have an increased or decreased risk of bleeding? Why?
		Can a person with O blood type accept blood from someone with A blood type? Why or why not?
BIOL 433 (Monitoring and Toxicology)	Identify the factors that might affect toxic responses of toxicants	A group of people was exposed to a substance that is known to cause hypertension, arrhythmia, and rash at doses equal to or above 6 mg/kg.bw. Would you expect that all of them develop a similar degree of toxicities from that substance? Why or why not?

3.4. Participants

All students enrolled in the four described above courses participated in this study, yielding 134 students (Table 5). These students were initially divided into four cohorts based on their course enrollment. They were also divided into junior and senior student cohorts based on their study level.

Table 5. Study participants.

Course Number and Name	Cohort/Sub-Cohort	Total Number of Enrolled Students
BIOL 110 Human Biology	Biological science/Junior	46
BIOL 212 Genetics	Biological science/Junior	37
Junior Cohort		83
BIOL 433 Monitoring and Toxicology	Environmental science/Senior	26
BIOL 452 Molecular Analytical Techniques	Environmental science/Senior	25
Senior Cohort		51
Total		134

3.5. Data Generation and Collection

To achieve the objectives of this study, a mixed-methods research design was used. This design combines the strengths of quantitative and qualitative data [51]. Quantitative data were collected from test scores and two surveys. In addition, structured individual interviews were conducted to generate qualitative data that would help explain findings from surveys.

Quizzes and final exams were prepared according to best practices guidelines and were reviewed by a committee composed of the researchers and the course instructors. The quizzes were knowledge-based and were administered to students a week after module completion. A set of knowledge-based questions and problems (or case studies that require higher-order thinking levels) related to the modules taught using these strategies were prepared and included in the final exams. The knowledge-based questions had a similar level of complexity to those of the quizzes. The final exams were administered during the final exam period as scheduled by Qatar University approximately 3 months after the teaching encounter. Mean test scores (±SD) were calculated for the quizzes and the set of questions of the final exams for the module delivered online using PBL and JiTT and for a module delivered in person using a traditional instructional strategy. Moreover, the percentages of students who passed the tests (i.e., graded above 5/10 on quizzes and answered correctly half or more of the questions related to the modules) were determined.

Two surveys that aimed to assess the self-perceived impacts on student learning and skills of the two instructional strategies and the implementation challenges were developed based on a thorough review of the current literature. A committee composed of three experts qualitatively evaluated the face and content validity of the surveys. For the face validity, the experts were asked to give their comments on whether the measured items can—truly assess the concept of the research. As for the content validity, the experts were asked to give their comments about the coherence of the questionnaire and the relevance, difficulty, and clarity of the items. The survey items were modified based on received feedback.

Moreover, the surveys were pilot tested on 34 students to check for their clarity, flow, and time needed to be completed. The pilot test was conducted using a sample of students who were enrolled in another section of the human biology course and were also exposed to PBL and JiTT, just after completing the learning activities. No modifications were made to the surveys based on pilot test results. The internal consistency of the questionnaire was measured by determining the Cronbach's alpha coefficient of the different sections and of the overall surveys (Tables 6 and 7). The Cronbach's alpha coefficient values for the sections of the survey and for the overall surveys were above 0.7, demonstrating that the surveys are reliable instruments [52]. Surveys collected during the pilot testing were not used in the final study sample.

Table 6. Reliability testing for the self-perceived impacts on learning and skills survey.

Factor	Number of Items	Cronbach's Alpha Coefficient
Learning the subject matter	5	0.773
Intrinsic interest in learning	3	0.741
Preparedness level	3	0.864
Critical thinking/problem-solving skills	4	0.756
Personal skills	3	0.865
Overall survey	18	0.785

The students were invited to fill in the surveys at the end of the course. In the invitation, students were informed of the objectives of the study. They were also explicitly told that participation in the surveys is voluntary and will not affect the instructor/student relationships or students' grades and that they can withdraw from the research at any time, without any consequences. The surveys were collected by one of the researchers and coded to ensure anonymity (each student's survey was assigned a code), and collected data were entered into an Excel sheet and treated confidentially to serve the purpose of the study only. In addition, all participants had to provide written consent prior to filling in the surveys.

Table 7. Reliability testing for the implementation challenges survey.

Factor	Number of Items	Cronbach's Alpha Coefficient
Adequacy of learning platform	3	0.837
Teaching and learning methods	5	0.812
Learning environment	2	0.774
Interactions	4	0.796
Overall survey	14	0.815

The self-perceived impacts on learning and skills survey contained three sections with a total of 18 items (Table 6): impacts on learning of the subject matter (5 items); impacts on intrinsic interest to learn (3 items); impacts on preparedness level (3 items); impacts on critical thinking and problem-solving skills (4 items); and impacts on the personal skills (communication, collaboration, and self-directed learning (3 items). All items were assessed using a 5-point Likert scale (1 (strongly disagree) to 5 (strongly agree)), and participants were asked to evaluate the extent to which they agreed with each of the statements included in each section. Mean scores for each section were then calculated to obtain a final score for the section. In addition, the percentages of students strongly agreeing and agreeing with each item statement of the five sections were determined.

The implementation challenges surveys contained four sections with a total of 14 items (Table 7): adequacy of the learning platform (3), teaching and learning methods (4), learning environment (1), and easiness of interactions (5). Each item was also assessed using a 5-point Likert scale (1 (strongly disagree) to 5 (strongly agree)). The percentages of students strongly agreeing and agreeing with each item statement were determined.

Finally, a structured interview was conducted to understand the survey results. The interview questions included questions about the aspects of the teaching method (PBL/JiTT) that they liked/did not like most and the reasons behind that, as well as their feelings towards the use of these strategies in the online setting. The interview questions were administered in the English language to individual students by one of the researchers (who was not the students' instructor), using Microsoft Teams app. The interviews were recorded and transcribed verbatim. An invitation to participate in the structured interview was sent via e-mail to the students enrolled in the selected courses after the end of the course and the survey collection period. Students were offered the option to select the interview date and time that best suited them based on a preset schedule. Here also, it was clearly stated that the participation in the interview is voluntary, it will not affect the instructor/student relationships or students' grades, and collected data will be treated confidentially and used to serve the purpose of the study only. Each participant was assigned a code to ensure anonymity. Moreover, all participants had to provide written consent prior to participating in the interview.

3.6. Data Statistical Analysis

Quantitative data derived from exam scores and surveys were analyzed using descriptive statistics. Means with standard deviations were determined for continuous variables (test and survey scores) and compared using Student's *t*-test (when comparing two groups) and ANOVA (when comparing more than two groups) with post hoc analysis. Percentages were derived for categorical data (passing the exams, agreeing with the survey items) and were compared using Pearson's chi-square test. Pearson correlation and regression analysis between final exam scores and self-perceived impacts on learning of the subject matter were done. Qualitative data generated from the transcription of the individual interviews were subjected to content analysis to explore the narrative themes and the students' main concepts related to impacts on learning and skills and implementation challenges.

4. Results and Discussion

4.1. Test Scores

A total of 134 students participated in this study and completed both quizzes and final exams. Table 8 presents the average test scores of the quizzes and final exams for the modules taught using different instructional methods. The final exam scores showed that the test scores of modules taught using online PBL were the highest, followed by the test scores of modules taught using online JiTT and the test scores of the module taught using in-person LBL. The difference in final exam scores was statistically significant. Moreover, although no statistically significant difference was observed among quiz scores for both courses, the quiz scores of modules taught using online PBL were the highest, followed by scores of quizzes taught using JiTT and the scores of quizzes for modules taught using in-person LBL. This trend was observed among all cohorts and across different disciplines and student levels.

Table 8. Test scores.

	Quizzes PBL Module	Quizzes JiTT Module	Quizzes LBL Module	*p*-Value	Final Exam PBL Module	Final Exam JiTT Module	Final Exam LBL Module	*p*-Value
BIOL 110 (Human Biology)								
Means ± SD of the test scores	9.98 ± 0.05	9.66 ± 0.64	8.32 ± 2.01	0.084 *a 0.078 *b	7.89 ± 1.12	**7.12** ± 0.42	**6.45** ± 0.62	**0.01** *a **0.0098** *b
Number (percentage) of students passing the test	46 (100)	98 (45)	37 (80)	0.23 0.09	**38 (82)**	**36 (78)**	**25 (54)**	**0.03** **c **0.01** **d
BIOL 212 (Genetics)								
Means ± SD of the test score	8.57 ± 0.61	-	8.375 ± 0.12	0.11 *b	**5.2** ± 3.12	-	**3.81** ± 1.72	**0.02** *b
Number (percentage) of students passing the test	37 (100)	-	37 (100)	0.087 **d	**19 (53)**	-	**15 (40)**	**0.98** **d
BIOL 433 (Monitoring and Toxicology)								
Means ± SD of the test score	9 ± 0.5	8.9 ± 0.6	8.5 ± 0.7	0.078 0.08	8.1 ± 0.7	7.7 ± 0.2	5 ± 2.1	**0.001** *a **0.0009** *b
Number (Percentage) of students passing the test	26 (100)	26 (100)	26 (100)	0.16 **c 0.21 **d	26 (100)	23 (90)	13 (50)	**0.03** **c **0.009** **d
BIOL 452 (Molecular Analytical Techniques)								
Means ± SD of the test score	-	-	-		**9.3** ± 0.4	-	**8.3** ± 0.2	**0.05** *b
Number (percentage) of students passing the test	-	-	-		**24 (95)**	-	**22 (87)**	**0.05** **d

- Not done. *a *p*-value obtained by using Student's *t*-test when comparing the means of the test scores after JiTT and LBL. *b *p*-value obtained by using Student's *t*-test when comparing the means of the test scores after PBL and LBL. **c *p*-value obtained by using chi-square test when comparing number of students passing the test after JiTT and LBL. **d *p*-value obtained by using chi-square test when comparing number of students passing the test after PBL and LBL.

4.2. Self-Perceived Impacts on Learning and Skills

A total of 85 students participated in the self-perceived impacts on learning and skills survey, yielding a response rate of 63.4%. Forty-four (52%) students were junior students. Twenty-five participants (30%) were enrolled in the human biology course, 19 participants (22%) were enrolled in the genetic course, and 41 participants (48%) were senior students enrolled in the environmental science courses (BIOL 433 = 25, BIOL 452 = 16). The percentages of students strongly agreeing/agreeing with the statements on the impacts on learning and skills and average scores (±SD) are presented in Table 9. Results showed that the

PBL and JiTT used online were perceived to positively impact the understanding of the subject matter, in terms of improving the learning of the module material, concepts, and applications and enhancing the learning process (engagement with the course material and the instructor). Moreover, the PBL and JiTT used online were also perceived to increase the intrinsic interest in learning in terms of motivation for learning the module concepts (average score ± SD = 4.44 ± 0.83) and improved preparedness level for class discussions, exams, and workplace placement ((average score ± SD = 3.65 ± 0.83). In addition, results showed that PBL and JiTT used online were perceived to enhance the students' skills in terms of critical thinking and problem-solving (average score ± SD = 4.19 ± 1.21) and communication, collaboration, and independent learning skills (average score ± SD = 3.98 ± 0.95). Further, analysis of variance showed that there was a statistically significant difference between senior students' and junior students' survey scores related to self-perceived impacts on intrinsic interest for learning and preparedness level, but not to learning of the subject matter, critical thinking/problem-solving skills, and personal skills. Finally, no statistically significant difference was observed among survey scores of groups enrolled in different courses that are delivered at the same study level (Table 10).

4.3. Correlation between the Self-Perceived Impacts on Learning and Critical Thinking and Problem-Solving Skills and Performance on the Final Exam

Figure 2 shows the correlation between the distribution of the scores on the learning of subject matter section of the survey when online PBL and JiTT are used and the students' performance as reflected by their final exam scores. The linear regression shows a slope of 1.76 and an intercept of 1.1037. Importantly, the regression analysis results indicate that there is a significant relationship (R (83) = 0.852 ($p < 0.001$)) between the scores of the impacts on the learning of the subject matter when online PBL/JiTT is used and the final exam scores on the PBL/JiTT module. The value of R^2 is 0.727.

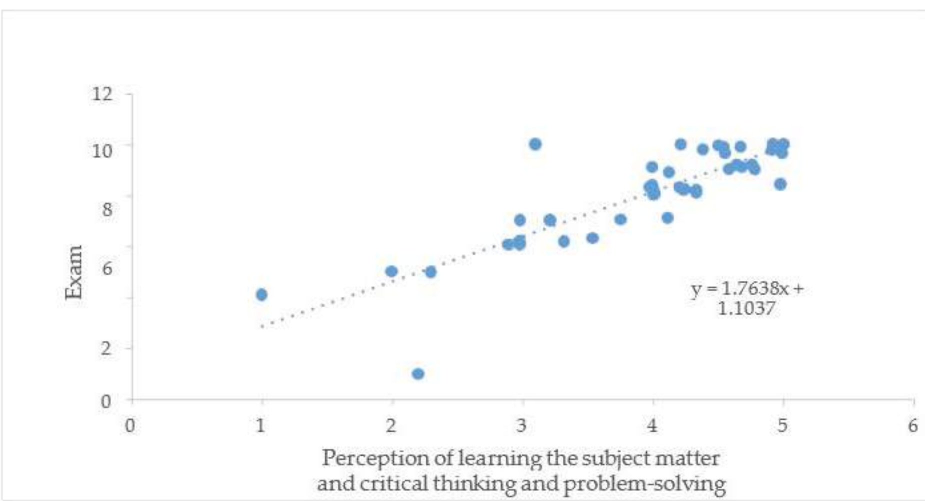

Figure 2. Correlation between scores of the impacts on the learning of the subject matter and critical thinking and problem-solving skills of the survey and exam scores.

Table 9. Self-perceived impacts on learning and skills: number (percentage) of students agreeing and strongly agreeing with the statements and average scores.

Item Statement	Number (Percentage) of Students Strongly Agreeing and Agreeing with the Item Statement
Learning the Subject Matter	
Improved my understanding of the subject matter	72 (85)
Helped me relate subject ideas and concepts	76 (89.4)
Made me engage in the course material in a deeper way	72 (85)
Helped me draw conclusions and come up with recommendations and solutions related to the subject matter	66 (77.6)
Helped me interact effectively with my instructor and colleagues to discuss the subject matter in depth	69 (82.1)
Average score/5 (± SD)	4.48 ± 1.23
Intrinsic interest in learning	
Increased my interest in learning the subject matter	68 (80)
Increased my understanding of the importance of the subject matter in real-life applications	78 (91.7)
Increased my motivation for learning	62 (72.9)
Average score/5 (± SD)	4.44 ± 0.83
Preparedness level	
Online PBL and JiTT made me prepare better for the class session	53 (62.3)
Online PBL and JiTT enhanced my preparedness level for the exams	53 (62.3)
Online PBL and JiTT improved my preparedness level for the work/training	61 (71.7)
Average score/5 (± SD):	3.65 ± 0.83
Critical thinking/problem-solving skills	
Increased my abilities to search for information or data on the problem using appropriate searching strategies	69 (82.1)
Increased my abilities to organize and sort data and findings	70 (82.3)
Increased my abilities to create inferences on why the problem exists and how it can be solved	67 (78.8)
Increased my abilities to analyze data and develop solutions to problems	70 (82.3)
Average score/5 (± SD):	4.19 ± 1.21
Personal skills	
Made me communicate more effectively with my colleagues	63 (74.1)
Made me value teamwork	63 (74.1)
Enhanced my independent learning skills	60 (70.6)
Average score (± SD)/5:	3.98 ± 0.95

Table 10. Self-perceived impacts on learning and skills survey scores distribution among study cohorts.

	Learning the Subject Matter	Intrinsic Interest in Learning the Subject Matter	Preparedness Level	Critical Thinking/Problem -Solving Skills	Personal Skills
All Cohorts Average Score ± SD	4.48 ± 0.23	4.44 ± 0.83	3.65 ± 0.83	4.19 ± 1.21	3.98 ± 0.95
Junior Cohorts (BIOL 110 & BIOL 212) Average Score ± SD	4.37 ± 0.67	3.61 ± 1.1	2.95 ± 0.81	4.01 ± 0.71	4.13 ± 0.21
Senior Cohort BIOL 433 and BIOL 452) Average Score ± SD	4.57 ± 0.47	4.81 ± 0.4	4.45 ± 0.31	4.39 ± 0.31	3.88 ± 0.14
***p*-Value ***	0.14	**0.03**	**0.023**	0.56	0.72
BIOL 110 Average Score ± SD	4.34 ± 0.23	3.72 ± 0.98	3.1 ± 0.78	3.89 ± 0.94	4.21 ± 0.11
BIOL 212 Average Score ± SD	4.13 ± 0.27	3.56 ± 1.23	2.89 ± 0.68	4.11 ± 0.56	4.01 ± 0.45
p-Value **	0.23	0.12	0.220	0.51	0.65
BIOL 433 Average Score ± SD	4.67 ± 0.23	4.87 ± 0.23	4.65 ± 0.33	4.41 ± 0.18	4.05 ± 0.27
BIOL 452 Average Score ± SD	4.51 ± 0.64	4.74 ± 0.33	4.29 ± 0.23	4.29 ± 0.21	3.77 ± 0.03
p*-Value *	0.12	0.84	0.64	0.072	0.09

* ANOVA test. ** Student's *t*-test

4.4. Implementation Challenges

A total of 82 students participated in the implementation challenges survey, yielding a response rate of 61.2%. Forty-four (53%) students were junior students. Twenty-five participants (30%) were enrolled in the human biology course, 19 participants (23%) were enrolled in the genetic course, and 38 participants (47%) were enrolled in the environmental sciences courses (22 in BIOL 433, 16 in BIOL 452). The percentages of students strongly agreeing/agreeing with the statements related to the challenges faced during the online implementation of PBL and JiTT are presented in Table 11. Results showed that the available learning platforms were adequate for the online implementation of both the PBL and JiTT. Moreover, around 90% of the participants strongly agreed/agreed that both learning strategies (PBL and JiTT) were suitable for online education and that it was not difficult for them to sustain focus and interest during online sessions or to collaborate and communicate between them. In addition, 90% and 73% of the participants strongly agreed/agreed that the online interaction with their colleagues and instructors was easy and that it was similar to the in-class physical setting. In addition, more than 50% strongly agreed/agreed that the online learning environment is not conducive to learning because of internet instability and noisy at-home environments. Finally, only 44% of participants strongly agreed/agreed that the interactions and communications with other teams and the whole class were easy as they would have been in the physical class setting.

4.5. Structured Interviews

Ten students participated in the structured interviews, out of which six were seniors. Data analysis indicated the following aspects to be the most liked about using online PBL as an instructional strategy: its ability to fully engage in the learning process; its ability to make students understand how learned material applies to real-life situations; its ability to enhance their learning of the subject matter through teaching others, discussions, and searching for solutions to the problem; its ability to have control over their learning; its ability to enhance their skills such as research, communication, teamwork, leadership, analysis, and problem-solving skills; its ability to engage all team members in learning activities; its ability to make students accept and value the opinions of other team members.

In addition, two concerns emerged related to using SCL instructional strategies. The first addressed workloads imposed by both PBL and JiTT, and the second was related to time management in terms of students having to organize their learning activities and tasks in such a way to be ready for collaborative activities. Regarding online JiTT, data analysis indicated that students found that JiTT made learning more meaningful, provided students with an opportunity for timely feedback, provided them with an opportunity to identify their learning needs, reduced stress during class sessions, and developed students' problem-solving skills.

Table 11. Implementation challenges for the online use of PBL and JiTT: number (percentage) of students agreeing and strongly agreeing with implementation challenges statements.

Item Statement	Number (Percentage) of Students Strongly Agreeing and Agreeing with the Item Statement N (%)
Learning Platform Was Adequate for PBL and JiTT	
Options included in the platform were sufficient to conduct PBL and JiTT conveniently	78 (95)
Options included in the platform were sufficient to post my assignments and receive feedback	78 (95)
The learning platform favors the implementation of teamwork when required	78 (95)
Teaching/Learning Method (PBL and JiTT)	
Online learning is suitable for both PBL and assignment-based learning	74 (90)
Online learning is better for assignment-based learning than PBL	16 (20)
It was not difficult to sustain my interest and focus during online sessions in PBL and assignment-based sessions	71 (87)
It was not hard to collaborate and communicate online between team members in online PBL to organize tasks and discuss topics	76 (93)
It was not difficult to engage all members of the team during discussions in online PBL	78 (50%)
Learning Environment	
Home environment is more noisy and distractive, which would hinder my participation or concentration	50 (60)
Internet instability makes learning and interaction sometimes difficult in PBL	42 (51.2)
Interactions (online is appropriate for interactions with the instructors, team members, and other classmate students)	
It was not hard for me to interact with my instructor and to receive his/her feedback in a timely manner in online PBL	74 (90)
It was not hard for me to interact with my colleagues in online PBL	74 (90)
The interactions with my instructor and colleagues to organize tasks and share ideas were the same in online PBL as they would have been in a real class setting	60 (73.2)
The interactions with other team members were not hard and I was able to communicate with other teams and the whole class to share some points/discuss ideas in online PBL in the same manner as it would have been in a real class setting	36 (44)

As for the recommendation to use PBL and JiTT as instructional strategies in the online setting, most of the participants highly recommended the use of both instructional methods as they were enjoyable, can be easily done using available technology and learning platforms, and provide more flexibility in terms of time and place for learning encounters. However, three themes emerged as concerns for the use of PBL in the online mode. The first was related to the learning climate (learning places) that was described as unusual and non-conducive for learning (such as cafeterias, coffee shops, and homes). The second was related to the lack of social interactions, which might hinder the development of social skills and collegiality among team members. The third was related to internet connectivity.

4.6. Interpretation of Findings

This study aimed at assessing the impacts on learning and skills of two SCL instructional learning strategies, PBL and JiTT, in an online setting and their implementation challenges.

Results of this study showed that online PBL and JiTT are as effective as face-to-face LBL on short-term knowledge acquisition and retention, as demonstrated by the absence of a significant difference between the scores on the quizzes and percentages of students passing the quizzes for the modules taught using the three instructional strategies. Moreover, based on the results of the test scores, online PBL and JiTT had significant positive impacts on long-term knowledge acquisition and retention, in addition to critical thinking and problem-solving skills, when compared to the LBL method. These impacts were maintained across the various course disciplines and study levels. These results are similar to findings from other studies where PBL and JiTT were used in the physical classroom in a variety of courses delivered at various study levels [36,38,42,47–49,51–56]. These results can be explained by the underpinning pedagogy related to the used instructional strategies. Indeed, both PBL and JiTT are active learning pedagogies that engage students in deep learning through thinking, investigating, discussing, and creating. They also provide students with multiple opportunities for deep engagement and interaction with the learning content. Furthermore, applying new knowledge to solve problems helps students organize knowledge, make connections, and develop a deeper understanding of the course material. In other words, they promote a deep approach to learning, which was reported to improve long-term knowledge acquisition and retention, and enhance critical thinking and problem-solving skills as well [8–10,50,57–60]. In contrast to active learning, passive learning holds the student to absorb the information that is usually presented in the form of lectures. This type of learning promotes a surface approach to learning, which was reported to enhance the abilities of students to recall facts rather than to have meaning to what they learn.

Therefore, this method promotes a surface approach to learning. It also induces convergent thinking, where a given question typically has only one right answer and therefore enables students to perform well in knowledge-based quizzes administered shortly after the lecture, as observed in the current study [5].

Further, the results of this study suggest that these instructional strategies maintain their effectiveness in terms of impacts on learning and critical thinking and problem-solving skills in the online learning setting. This result is further supported by a limited number of studies that compared online PBL with PBL delivered in the physical classroom setting [60–64].

Moreover, students' self-perceived impacts on learning the subject matter and critical thinking and problem-solving skills correlated well with their performance on their final exams. This finding reflects well that these methods work well online and are still able to highly engage the student in the learning of the subject matter, critical thinking, and problem-solving activities. This result is additionally confirmed by the responses to the interview questions where students reiterated the ability of these instructional strategies to engage them in the learning process, help them in learning the subject matter, and develop their critical thinking and problem-solving skills.

Moreover, the results of this study revealed that both PBL and JiTT were perceived by the students to have positive impacts on their learning and skills in the five survey domains:

learning the subject matter, intrinsic interest in learning the subject matter, preparedness level, critical thinking and problem-solving skills, and personal skills. This result was variably reported in the literature where some studies showed positive and higher impacts of online PBL on learning and skills, whereas one study showed lower impacts of online PBL when compared to face-to-face PBL [61–64]. Moreover, even though the self-perceived impacts on learning and skills were positive for the general cohort of students, the junior cohort had significantly lower self-perceptions than the senior cohort in the following two survey domains: intrinsic interests in learning the subject matter and preparedness level. This finding might be multifactorial. The first factor may be related to the increased cognitive efforts associated with SCL instructional strategies, which greatly negatively affect students' motivation and engagement in learning [65]. Another factor may be related to the students' course enrollment motivation [66,67]. The reasons motivating students have a powerful influence on their intrinsic interests to learn the subject matter and perceptions of the importance of the subject matter for their future careers. Indeed, most of the junior students enrolled in human biology and genetics courses because these were designated as general university-required courses for certain majors. Therefore, they may basically have limited interest in learning the subject matter and insights into its usefulness. Thus, they are less able to self-assess the impacts of the teaching pedagogy on their motivation to learn and on preparing them for future careers. A final factor could be that junior students are unfamiliar with such active learning instructional strategies and, therefore, may not be able to appreciate all their short-term and long-term benefits [68].

Although the use of PBL and JiTT as instructional strategies was perceived to positively impact students' learning and skills, their implementation was coupled with many challenges from the students' point of view.

Firstly, the use of these instructional strategies in the online setting was perceived to impose heavy workloads on the students. Indeed, it is well reported in the literature that both SCL strategies and online education pose additional workloads for students [5,18,69]. Hence combining both methods would have resulted in the perception of increased workloads.

Perceived workloads were reported to influence the students' approaches to learning, making them more inclined towards the surface approach to learning. Therefore, this challenge should be addressed carefully when considering the implementation of SCL instructional strategies in online education. Workloads might be adjusted through close coordination between the courses that are delivered at the same study level, on the one hand, and through varying the types of active learning activities (use a combination of low-stakes and high-stakes active learning strategies) within the same course. Calculating students' workloads in hours is also a recommended strategy. This strategy would help in planning appropriately the course activities and tasks so that they will not be imposing heavy workloads on students.

In addition, some students reported having difficulties managing their time to complete assigned tasks on time at an appropriate performance level. This finding could be attributed to differences in the learning abilities of students, where quick and moderate learners might complete assigned tasks more easily at a more rapid pace than slow learners [70]. Despite that time management issues were also reported in courses delivered using traditional learning methods in the classroom physical settings, they are more critical when online SCL strategies are employed. Indeed, the students' actual learning in active learning strategies depends significantly on their level of engagement in the assigned tasks. Moreover, the lack of physical interaction in the online setting makes it difficult for the instructors to keep all students engaged at the same level and to pay attention to each student's learning needs. Therefore, appropriate planning of activities and student monitoring would be effective strategies to help all students achieve their learning goals.

Likewise, internet instability was reported as the main challenge for the online implementation of synchronous PBL and JiTT sessions in both the survey responses and student interviews. This was described in previous studies that tackled online education in general [69,71]. Since communication, interactions, and collaborations among learners are considered as core characteristics of these methods [5], internet instability impacts on learning should not be overlooked.

The lack of learning climate and socialization were also reported among the implementation challenges. Learning climate plays an essential role in the students' academic life because it significantly influences their learning processes [72]. Indeed, in contrast to the classroom physical setting, in the online setting, learning can occur in places that are not conceived for that purpose, such as cafeterias, homes, and cars. Therefore, when present in such places, students' mindsets will not be making connections to learning. Further, these places may be noisy and full of distractions, which might disturb the students' learning processes.

Moreover, in the online setting, students are deprived of building rapport with classmates [69]. All these factors might have implications for the students learning in the online setting. Hence, there is a need for educators to take into consideration these factors when designing their online learning modules to optimize students' learning experiences. The use of blended learning may also help address these challenges.

Lastly, similar to other studies, the use of these instructional strategies and online education seems to be better appreciated by students when working in small groups rather than in large groups [73–76]. This might be explained by the fact that working in small groups provides the students with a conducive and collaborative learning environment. In addition, it facilitates student adaptation to new learning environments and pedagogies. The use of blended learning may help address this challenge as well.

4.7. Limitations and Opportunities

This study has many strengths, including the selection of the SCL instructional strategies to be tested, the use of a mixed design research method, the use of the in-person LBL method as a standard instructional strategy for comparison, the use of the tested instructional strategies in multiple courses that are delivered at different study levels (junior and senior), and being among very few studies that addressed assessing the impacts of online SCL strategies on student learning and skills. The study also has limitations. First, there was no direct comparison between the same SCL instructional methods when used in the physical classroom setting and when used in the online setting. Second, the implementation challenges survey did not address challenges related to information technology (IT) skills.

Indeed, the students who were enrolled in the courses belonged to Generation Z, which is recognized as the first social generation to have grown up with access to the Internet and portable digital technology from a young age. Members of Generation Z are considered as information technology adepts. Moreover, their IT skills and computer literacy were further developed by online education that was implemented during the COVID-19 pandemic.

Moreover, students were able to report challenges related to their IT skills during the interview. In addition, no observations were conducted by the instructors or the researchers during student-led sessions and/or teacher-led sessions. No formal feedback was collected from instructors on the implementation challenges. Indeed, this study aimed to assess the effectiveness and challenges from a student perspective, and many meetings were conducted between the researchers and instructors to optimize the student learning experiences. Finally, only female students participated in this study. This might limit the generalization of the findings since males and females might have differences in learning method preferences and views.

Despite these limitations, this study yielded important information that can inform educational planners and academicians on effective instructional strategies that can be applied in online education in times of crisis. In addition, future research can build on the key issues and limitations identified in this research.

5. Conclusions

Despite the abundance of data showing the effectiveness of PBL and JiTT on learning and skills in the physical setting, limited data exist on their usefulness in online education.

This study showed that, based on the test scores, JiTT and PBL, when used online, were as effective as face-to-face LBL in promoting short-term learning and more effective than face-to-face LBL in promoting long-term learning, problem-solving, and critical thinking skills (research questions A, B, C, and D). In addition, based on the self-perceived impacts on learning and skills survey and interview responses, these instructional methods, when used online, were perceived to promote students' critical thinking and problem-solving skills; students' motivation for learning; and students' communication, collaborative and independent learning skills (research questions D, E, and F). Moreover, the main challenges for the online implementation of these methods that were revealed by the survey responses and interviews were internet instability, lack of a learning climate, and lack of socialization. Interviews highlighted two additional challenges related to workloads and time management (research questions G and H).

In conclusion, this study demonstrated that these methods, when used online, had positive impacts on students' learning and skills, and that these impacts were consistent across various disciplines and study levels. Therefore, PBL and JiTT can be considered as effective teaching/learning strategies that might be used in various disciplines and study levels in online education. Moreover, the findings of the present study shed light on the need for future studies that focus on comparing the same SCL learning strategy when used in different education modes (physical, blended, and online), and on identifying factors that would address identified challenges to optimize the students' learning experiences in the online setting.

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Article

Developing Students' Attitudes toward Convergence and Creative Problem Solving through Multidisciplinary Education in Korea

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Abstract: Given the rapid speed at which digital transformation has progressed, social or scientific problems that are difficult to solve using knowledge gained from the existing segmented academic paradigm have emerged. To solve these problems, the need for talent convergence has increased, and Korea has begun to provide convergence education, starting with science, technology, engineering, art, and mathematics (STEAM) education. Convergence education is defined as "education to cultivate knowledge that can solve problems creatively and comprehensively by raising interest and understanding of convergence knowledge, processes, and the nature of various fields related to science and technology". However, STEAM education faces several difficulties. To overcome these limitations, science, mathematics, and informatics convergence education (SMICE) has been studied, but verifying the effectiveness of SMICE has been difficult. Consequently, this study analyzes the effects of SMICE on middle-school students' attitudes toward convergence (ATC) and creative problem-solving (CPS) abilities. The subjects of the study were 50 middle-school students who received SMICE and general software (SW) education, and students' subsequent changes in attitude are analyzed. The results show that students who received SMICE improved their ATC and CPS abilities. In particular, participants' ATC and CPS scores were higher than those of students who received general SW education. Through this, a multidisciplinary education model is developed focusing on science, mathematics, and informatics, and proves the educational effect of the developed model when applied to classes.

Keywords: multidisciplinary education; interdisciplinary; convergence education; attitude toward convergence; creative problem solving; integrated curriculum; STEM; STEAM education

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1. Introduction

1.1. The Need for Multidisciplinary Education

With the development of science and technology, industries, society, and the shape of life have rapidly changed and, to a certain extent, this has never been observed before [1,2]. Although quality of life and convenience on average have increased, problems, such as global warming, unemployment, the gap between the rich and poor, and infectious diseases, have also worsened [2]. Since these problems involve social or natural phenomena, they are highly complex, and some studies on these problems have attempted to integrate solutions from different fields [3]. This is because solving such problems using traditional methods has been very difficult or impossible [4,5]. These phenomena have caused the development of basic science to be unable to keep up, blurring the boundaries between natural science and engineering and promoting convergence between the humanities and social sciences. As such, technoscience has risen in popularity and prevalence [4,6,7]. Thus, the convergence of different disciplines and fields is needed to solve problems; several disciplines must be integrated together, as the traditional academic sub-disciplinary paradigm has become obsolete and unable to address modern issues [3].

Accordingly, various countries have implemented education programs or curriculum changes to cultivate convergent literacy, which is the ability to solve problems creatively by converging knowledge from heterogeneous disciplines [7,8]. South Korea introduced convergence education into its curriculum to foster convergence talent [9,10]. Convergence education is not a recent concept; it has long been studied under the name of integrated education [8]. "Integration" means creating a new completeness that the object did not originally have by combining or connecting the object to be integrated. Therefore, integration in education means producing a new educational effect that subjects have not previously experienced based on the interrelationship of various subjects [11–13].

Jacobs (1989) found that when an integrated curriculum was applied, the ability to solve complex problems occurring in modern society could be cultivated, the interrelationship between subjects could be increased, and education using real-life topics was possible in class. Therefore, the application of an integrated curriculum in schools can increase students' interests toward learning [11,14].

Inclusive education has been actively studied to understand the educational effect of an integrated curriculum [15]. Jacobs (1989) suggested a hierarchy of integration—fragmented, connected, nested, multidisciplinary, interdisciplinary, and trans-disciplinary—according to the type of integration [14,16–20]. Ingram (1979) further studied the types of integration in an integrated curriculum, presenting qualitative and quantitative approaches as forms of structural integration. In an integrated curriculum, a quantitative approach involves creating a new totality by presenting and integrating several subjects or disciplines simultaneously. Meanwhile, a qualitative approach reorganizes subjects or disciplines by integrating them into common elements [21,22].

1.2. History of Multidisciplinary Education in Korea

As various types of integrated education curricula were studied and educational effects emerged, integrated curricula began to be introduced in Korea. The third curriculum in Korea (1973~1981) not only sought to conceptually integrate subjects and knowledge, but also focused on the integration between educational content and methods. The fourth curriculum (1981~1988) began to pursue the integration of knowledge and personal and social values. Accordingly, integrated curricula emerged, such as science, technology, and society (STS). This trend continued until the fifth, sixth, seventh, and 2007 revised curricula. Regarding the differences in the type of integration, the fourth curriculum integrated textbooks, while in the fifth and sixth curricula subjects were the center of integration. Such an integration was summation integration, where several subjects or textbooks were integrated simultaneously [21–23]. Efforts to foster an interdisciplinary and transdisciplinary integration continued with the seventh curriculum [22,24]. However, teachers' perceptions of the integrated curriculum was negative, and problems emerged with the curriculum and its realization. In the 2009 revised curriculum, STEAM education was actively introduced to foster convergence talents [25].

1.3. Limitations of STEAM Education in Korea

South Korea also introduced science, technology, engineering, art, and mathematics (STEAM) education in "The Second Basic Plan for Developing and Supporting Science and Technology Talent" [1,9]. STEAM education was introduced not only to achieve convergent literacy, but also because of an unusual phenomenon in Korea (and other countries) called the PISA paradox. The PISA paradox occurs when students have a high academic achievement in international evaluations, such as the Programme for International Student Assessment (PISA), yet their confidence and interest in science are very low [26]. To solve this problem, STEAM education was designed to cultivate students' interests in, knowledge of, and attitudes regarding science by converging knowledge from various subjects and integrating creative design and an emotional touch [1,8].

In 2011, Korea introduced STEAM education focused on convergent literacy and creative problem-solving skills in elementary, middle, and high schools to foster creative and convergent talents [9]. In addition, Korea presented creative convergence talent as a human resource in its 2015 revised national curriculum, an adapted curriculum meant to revitalize convergence education [27]. Recently, to revitalize convergence education through the 2022 revised curriculum, the restructuring of subjects, new development of convergence elective subjects, and high-school credit system were introduced [28].

However, despite the worthy aims of STEAM education, there have been many difficulties with its implementation in schools. For example, Lim (2012) found that STEAM education focuses only on convergence without discussing the core concepts or practices that are the basis of convergence, so the integration of various subjects is random. It was found that, in practice, teaching convergence in STEAM involves each subject area of STEAM rather than teaching creativity through convergence [7,27,29]. Furthermore, it was revealed that since classes are centered on textbooks available in the school, textbooks have been developed to teach independent subjects rather than convergence. Thus, the convergence of the concepts or practices of various subjects in STEAM education cannot be truly achieved. Accordingly, convergence in STEAM education is not truly interdisciplinary or transdisciplinary; rather, it is multidisciplinary [15,29].

Sim et al. (2015) argued that the definition of convergence in STEAM education was too ambiguous, so convergence between subjects was not properly achieved. Their results showed that convergence education was conducted by focusing only on students' interest levels and convergent thinking skills without properly presenting to them competencies or key concepts. Additionally, STEAM education could not be activated due to the gap between the purpose of STEAM education and academic achievement and the methods of evaluation in the curriculum. Lastly, Sim et al. (2015) pointed out that to provide STEAM education, a teacher who understands STEAM education and teaches by converging knowledge of various subjects is needed, but there is a lack of teachers with adequate experience [8].

1.4. Apperance of Science, Mathematics, and Informatics Convergence Education

Looking at the problem of STEAM education in Korea, it was not possible to focus on gaining wholeness through the convergence of subjects. Therefore, education was conducted in the form of presenting several subjects simultaneously, such as a quantitative approach in integrated education, which caused difficulties in effectively conducting education [1,8,21,25,30]. As a solution to these problems, convergence education through convergence between subjects with similar characteristics and competencies emerged [30,31].

Convergence education in its various forms has also been studied to solve associated problems in the school domain. Lee et al. (2018) proposed education through convergence between subjects with similar characteristics or competencies [32–34]. Prior studies have also determined that problem-solving processes in science, mathematics, and informatics subjects were similar, so research was conducted on education that converged science, mathematics, and informatics subjects [31]. Meanwhile, with the implementation of the *Science, Mathematics, and Informatics Education Promotion Act* in Korea in 2018, the foundation for science, mathematics, and informatics convergence education was established, and SMICE was introduced in schools [32]. Accordingly, Lee et al. (2018) developed a SMICE program for middle- and high-school students, and Kim and Lee (2021) analyzed the effects of the SMICE program on middle-school students' computational thinking [32–34]. Although the effectiveness of SMICE has been verified through previous studies, there was a limitation in that only computational thinking ability, which is a core competency of the informatics subject, was measured. When analyzing the effects of convergence education, it is important to measure students' competency in the converged subject, but it is also necessary to analyze the creative effects of education through convergence [32,35]. Therefore, SMICE's effects on students should be verified based on its competencies and goals, and assessing students' competency in only a specific subject can replicate the problems of existing convergence education.

Therefore, based on the previous studies, this study analyzes the educational effects of SMICE. The subjects of the study are middle-school students, and the core competencies resulting from SMICE and the educational effect through convergence are analyzed. The research subjects are divided into two groups, and the educational effect of SMICE is verified through different treatments for each group.

2. Materials Related to Science, Mathematics, and Informatics Convergence

2.1. Science, Mathematics, and Informatics Convergence Education Materials

To introduce SMICE into schools, Korea developed teaching and learning materials for middle- and high-school students. To create these materials, research was conducted. A research team that included professors and teachers specializing in science, mathematics, and informatics education was formed, and one science, one mathematics, and one informatics teacher was required to form a team for each theme [34].

A review of the literature revealed that many convergence education programs centered on specific subjects have been developed. For example, a mathematics-oriented STEAM education program, a technology-oriented convergence education program, and an art-oriented STEAM education program have been developed [7,36–39]. Many educational program researchers have concentrated on a specific subject, and the content of other subjects has been included to teach students about a specific subject [7,29]. Therefore, rather than convergence education, such programs emphasized teaching the content of several subjects together while focusing primarily on teaching one subject. In this form, convergence education caused more time and cognitive burdens, even if the learner was taught the same amount of educational content. Furthermore, there was no significant difference in educational effects [29]. This was one of the problems that prevented this type of convergence education from being integrated into schools. To prevent this problem, this study configured a program that included one science, one mathematics, and one informatics teacher at the same school level in the program development process. Thus, topics could be analyzed and approached in multiple ways from the perspectives of science, mathematics, and informatics subjects without being biased toward specific subjects [8]. Furthermore, the teaching and learning materials developed were reviewed in the same way.

2.1.1. Competency of SMICE

In Korea, the goal of the SMICE programs is to cultivate effectively the talent highlighted in the Korean curriculum. With the advancement of information and communication technology, changes in politics, the economy, and employment, and climate change, Korea's demand for creative convergence talents has spread. Accordingly, the 2015 revised curriculum defined a creative convergence talent as "a person who can create new knowledge and create new values by converging various knowledge with humanities imagination, science, and technology creativity, and the right personality". To cultivate these creative convergence talents, the curriculum was revised to focus on core competencies. Although the Korean curriculum prior to 2015 focused on the "knowledge transfer" that students should know through education, the revised 2015 curriculum emphasized the importance of "competence" in future society rather than "knowledge". Competency is not just knowledge, but also the ability to express knowledge by integrating knowledge, skills, attitudes, and values. Accordingly, in the 2015 revised curriculum, the talent and core competencies for creative convergence talent were defined, and the subject competencies for cultivating talent were defined for each subject [40].

Previously, convergence education curricula focused on teaching the same content, and only the time required to achieve the same academic results increased. However, SMICE aims not only to cultivate students' science, mathematics, and informatics capabilities, but also to obtain educational effects through convergence education. Therefore, the competencies in science, mathematics, and informatics subjects were analyzed based on the revised 2015 curriculum.

In the revised 2015 curriculum, "problem-solving" and "creativity convergence" were presented as competencies in math. "Problem-solving" is defined as "the ability to explore solution strategies using the knowledge and functions of mathematics in problem situations and to solve a given problem by selecting the best solution". "Creativity convergence" is defined as "the ability to produce and refine new and meaningful ideas in various ways and functions based on mathematical knowledge and functions, connect, and converge various mathematical knowledge, functions, and experiences, or other subjects or real-life knowledge, functions, and experiences with mathematics". In addition, "inference", "communication", "information processing", and "attitude" were presented as math competencies [31,41,42].

"Scientific thinking", "scientific inquiry", and "scientific-problem-solving" were presented as science competencies. "Scientific thinking" refers to the "thinking necessary in the process of exploring the relationship between scientific claims and evidence", and "scientific inquiry" is defined as "the ability to acquire new scientific knowledge or construct meaning by collecting, interpreting, and evaluating evidence in various ways such as experiments, investigations, and discussions". "Scientific problem-solving" means "the ability to solve personal or public problems using scientific knowledge and scientific thinking". "Scientific communication ability", "scientific participation", and "lifelong learning ability" were also presented as science competencies [31,43,44].

Lastly, "computational thinking" was presented as a competency in informatics. In the curriculum, "computational thinking" means "the ability to understand real-life and various academic problems and apply solutions creatively using the basic concepts, principles, and computing systems of computer science" and includes "abstraction", "automation", and "creative convergence ability". In informatics, "informatics culture literacy" and "cooperative problem-solving ability" were also presented as subject competencies [31,32,45,46].

Science, mathematics, and informatics are adjacent subjects, so the relevance between the three subjects is greater than that of other subjects [13]. However, in the curriculum, there were similar competencies across science, mathematics, and informatics, but competencies existed according to the characteristics of the subject, which differed by subject. Therefore, to create teaching and learning materials that reflect all science, mathematics, and informatics competencies, it was thought that at least 10 sessions per theme were required, and the cognitive burden of learners would consequently increase. In addition, since learners have to learn various content and engage in different activities in the process of cultivating subject competency, it was thought that inefficient education would be provided, as had been the problem with existing convergence education [8,29,32,34]. Thus, similar competencies across the science, mathematics, and informatics subjects were explored, and the corresponding competencies were synthesized to newly define curriculum competencies for SMICE.

Science, mathematics, and informatics emphasize problem-solving; science has "scientific problem-solving skills", mathematics has "problem-solving skills", and informatics has "computational thinking". Although the curriculum competencies of the three subjects were different, the common goal was to cultivate the ability to solve problems according to the characteristics of the subjects. Therefore, problem-solving was included in all three subjects as a competency that emphasized the importance of convergence education, a sentiment echoed in the revised 2015 curriculum [8,32,40]. Accordingly, "problem-solving" was selected as the core competency of convergence education for transitional correction. In addition, SMICE's problem-solving steps for each subject are composed of "analysis", "design", "execution", and "evaluation".

2.1.2. Type of SMICE

Subsequently, a new type of SMICE program was developed. In the previous convergence education program, it was necessary to learn new content for convergence education. Therefore, even if classes had the same learning goal, convergence education required more class hours for students to learn new content than in general teaching and learning classes [29].

Sim et al. (2015) found that there was a limit to providing convergence education in schools due to the lack of class time. The teacher also had to retain the number of hours to proceed with the convergence education in the curriculum. To solve these problems and to prevent learning from being inefficient, an educational program for middle-school students was configured for students to experience convergence based on the knowledge they had learned in the elementary-school curriculum [8]. Furthermore, high-school students could experience convergence with the knowledge they had learned in the middle-school curriculum [34].

Therefore, a new type of convergence education was proposed to overcome the problems with existing convergence education. It was developed with a convergence of subject knowledge (CSK), problem-solving in real life (PSRL), creative activities curriculum, and free semester (CACFS) as types of SMICE. CSK was constructed in the form of students solving problems by converging their previously learned subject knowledge. PSRL involves conducting activities to solve problems by converging existing knowledge for greater learning outcomes in science, mathematics, and informatics. Lastly, CACFS was configured for students to experience convergence problem-solving through team projects. CSK, PSRL, and CACFS are composed of systematic steps that can be adapted according to the educational contexts of Korea. The types of SMICE were developed for selection and use according to learners' levels and the purpose of convergence education [33,34]. The troubleshooting steps for each type are shown in Table 1.

Table 1. Problem-solving process in SMICE [32–35].

Type	Analysis	Design	Execution	Evaluation
CSK	Understanding Problems Learn Content for Design and Solving	Problem Decomposition Modeling Algorithmic Design	Simulation Programming	Test Application
PSRL	Understanding Problems Problem Analysis	Problem Decomposition Pattern Recognition Modeling Algorithmic Design	Simulation Programming	Prototype Test Application
CACFS	Understanding Problems Problem Analysis	Problem Decomposition Pattern Recognition Modeling Algorithmic Design	Simulation Programming	Prototype Test Evaluation Application

2.1.3. SMICE Themes

Subsequently, the new SMICE themes were derived. To derive themes, teams consisting of science, mathematics, and informatics teachers were formed. Each team brainstormed and derived themes according to the goals, competencies, and types of SMICE, as well as the characteristics of science, mathematics, and informatics. From this, 51 topics that could be introduced to middle and high schools were derived. The validity of the themes was analyzed based on the characteristics of the 2015 revised curriculum, tangible suitability, and the type of SMICE. Through this, nine themes of convergence education suitable for middle- and high-school students were derived. The topics derived are shown in Table 2.

Table 2. Themes and learning objectives of SMICE for middle- and high-school students [32–35].

School Level	Type	Theme	Learning Objective
Middle school	CSK	Development of rock search program using selection	Using the selection structure, a program to find rocks suitable for conditions may be written.
		Calculate the area of a fan-shaped figure	Understand the relationship between the center angle and the area of the fan shape and create a program to find the area of the fan shape.
		Curling game using friction force	Understand the frictional force as a cause of interfering with the movement of an object and to create a curling simulation program.
	PSRL	Carbon footprint calculator	A carbon footprint calculation program can be created using variables and various operations.
		Time-speed graph	Understanding that the situation of various changes can be graphically represented and draw a time-speed graph that can be changed at will.
		Moving of particles	Create simulation software that expresses the diffusion motion of gas molecules.
	CACFS	Brick-breaking game with gravity	Create a game software that uses gravity to break bricks.
		Carpet pattern design with GeoGebra	Understand the nature of the floor plan and the movement of the figure and design the desired carpet pattern.
		Water-cycle process	Understand the causal relationship between the change in the state of water and the entry and exit of thermal energy, and to make software that simulates the circulation process of water.
High School	CSK	Find the representative value	Create a program that finds representative values using arrays and functions.
		Factorization calculator	Understand the principle of factorizing any quadratic equation; you can make a factorization calculator.
		DNA information search	Understanding how amino acids are made from DNA and create a protein synthesis program.
	PSRL	Vehicle safety distance calculator	Create a program to find the safe distance of a car using the selection structure.
		Create math icons	Create the math icons using the graph of the equation of the figure and the function
		Forecasting particulate matter	Understanding the scientific standards of fine dust forecasting and create a program that outputs forecast grades and behavioral tips according to the concentration of fine dust.
	CACFS	The secret of a three-point shot	Algorithms for solving problems in the field of life science can be written in cooperation.
		Create a color wheel	Understand the principle of color change and create a color ring using a function in which the brightness of red, green, and blue lights changes.
		Nature's choice of antioxidant-tolerant creatures	Create simulation software that implements the motion of a horizontally thrown object.

2.1.4. Example of SMICE Program

Based on the learning objectives in Table 2 and the problem-solving step in Table 1, a SMICE program was developed (Figure 1 (the original is Korean, but in this paper it is presented with a translation into English)). SMICE programs for middle- and high-school students were developed, respectively, and for each SMICE, three types of convergence were developed: CSK, PSRL, and CACFS. The central and adjacent subjects were determined for each subject, and adjacent subjects were integrated for students to learn the central subject [34].

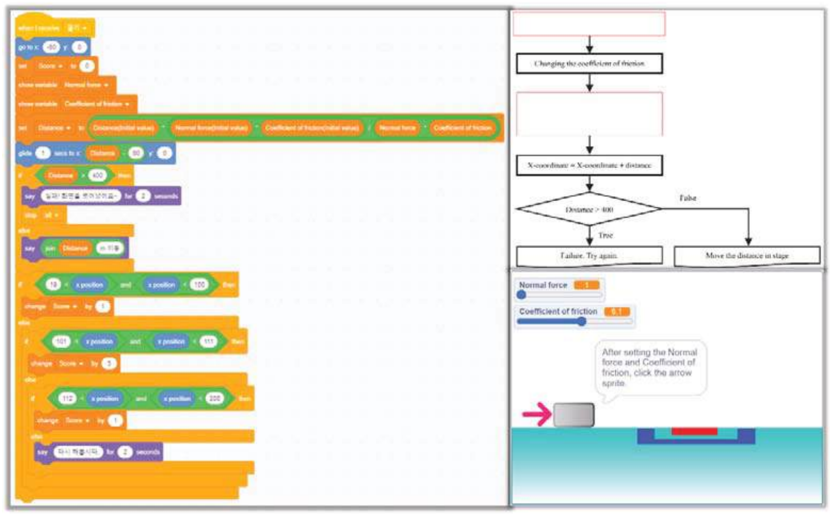

Figure 1. Example of SMICE program (curling game using friction force) [33–35].

For example, in relation to the "curling game using friction force", the convergence type is CSK, and informatics, mathematics, and science subjects were integrated around "friction force". In the "analysis" stage, news articles with the keywords "curling" and "sports simulation" were read to motivate the subjects. Next, an activity to understand the problem was presented by examining the factors affecting the distance the stone moves during curling.

In the "design" stage of the problem-solving process, to move the curling stone to the desired position, the relationship between the friction force, weight, and moving distance was identified, and core element extraction, problem decomposition, the pattern between elements, and modeling experience were conducted. In addition, students conducted activities to express modeling results using algorithms to make them a program.

In the third step, "execution" involved implementing algorithms through programs using scratches. Students designed screens to simulate the weight of the stone, friction force, and distance in a programming development environment (block-based programming environment, scratch) and programmed sprites representing curling stones to determine distance according to weight and friction force. Students came to understand the science, mathematics, and informatics content by executing and implementing the learned content as programs.

The last step, "evaluation", was configured to simulate the developed program. In addition, the program was applied using the learned content. An educational program was organized for students to learn the science, mathematics, and informatics content and foster problem-solving skills through the process of addressing topics that are common in real life [34].

2.2. Methods

2.2.1. Overview

In this study, the educational effects of SMICE on middle-school students in Korea were analyzed. Korean middle schools were selected for sampling, and the research subjects were recruited. A test tool was selected for the analysis of the educational effects of SMICE. Next, SMICE was administered to middle-school students, and the test tool was used before and after administration. Finally, by analyzing the results of the tests, the effects of SMICE on middle-school students were determined.

2.2.2. Participants

The participants were seventh graders attending middle schools in Korea. To ensure the same treatment, students attending one school were selected. The total number of subjects was 50, and these were divided into the experimental (n = 23) and control groups (n = 27). The participants included 30 boys (60%) and 20 girls (40%), and the gender ratio was almost similar for each group.

As the importance of computational thinking has increased, it has become an active educational focus [47]. Representatively, the United States developed a framework for computer science education at CSTA and provides opportunities to understand the principles of computer science and experience coding through platforms, such as Code.org. In addition, computer science education is being conducted to help students develop computational thinking skills, produce artifacts, and experience troubleshooting using block-based programming languages (e.g., Scratch). The UK has also added computing as a subject in its new curriculum and is providing computing education for elementary-, middle-, and high-school students. For example, the UK is actively conducting education using physical computing boards (e.g., microbit) and is also strengthening teacher competency through the teacher community [47,48].

In Korea, computer science education was conducted as part of the "informatics" subject in the curriculum. However, in the 2009 revised curriculum (2012–2017), informatics education was not conducted in all schools, but rather taught according to the schools' or students' curricular choice. As the importance of computational thinking skills increased, education targeting computational thinking skills became mandatory in elementary and middle schools in the 2015 revised curriculum (2018–2024) in order to activate informatics education. In Korea, computing thinking skills are taught in practical subjects in elementary schools, while computational thinking skills are taught in information subjects in middle schools [47,49].

Since the subject of computational thinking is different in elementary and middle schools, there is no collective term to refer to it, and it is not possible to conduct education on computational thinking with the same goals in elementary and middle schools. Therefore, similar to computer science education in the United States and computing education in the UK, Korea refers to computational thinking skills education as SW education. MOE (2014) defined it as education intended to nurture creative and convergence talents with computational thinking. To promote SW education, Korea has focused on the development of teaching materials, leader and research software schools, and teachers' research groups [47–50].

As such, Korea provides computing thinking skills education in elementary and middle schools under SW education. Elementary schools have 17 h of compulsory SW education, while middle schools have 34. The students who participated in this study were first-year middle-school students who completed the 2015 revised curriculum. Therefore, they had undergone SW education in elementary school [49,50]. In the Korean elementary school curriculum, the development environment for block-based programming languages and procedural thinking, operation, sequential structure, selection, and repetition are learned. Subsequently, students design and produce a program [51,52].

SW education in Korea consists of experiences and activities related to computational thinking in elementary school, understanding of computer science concepts in middle schools, developing practical artifacts and experiencing convergence with other subjects in high schools [50].

The subject of the current study is informatics education in the regular curriculum. In Korea's middle-school curriculum, the informatics subject is mandatory, and students must complete 34 h of classes. Informatics in Korea's middle-school curriculum consists of the following areas: "informatics culture", "data and information", "problem-solving and programming", and "computing systems". Here, the core competencies include "computational thinking", "informatics culture literacy", and "cooperative problem-solving." [52].

The experimental part of this study was conducted in the second semester of 2020 (September–December). In 2020, Korean schools were online and offline due to COVID-19. Therefore, students first experienced informatics education conducted online and offline simultaneously. Because they are part of the middle-school informatics curriculum, "problem-solving and programming" and "computing system" were assessed as part of this study. "Problem-solving and programming" is an arena for learning computational thinking and consists of abstraction, algorithms, and programming. Students experience "understanding problems" and "decomposition" under the umbrella of "abstraction" and learn "understanding algorithms" and "expression of algorithms" under "algorithm". In programming, "input and output", variables, operation, and control structures are learned, and projects that enable students to experience abstraction, algorithms, and programming are conducted. The "computing system" component allows students to learn about computing systems, such as hardware and software, and to experience physical computing [34,52].

2.2.3. Treatments of Experimental and Control Groups

Treatment in this study was conducted as part of the middle-school curriculum in Korea. The Korean middle-school curriculum consists of "subject education (Korean language, social studies/ethics, mathematics, science/technology home economies, art (music/art), English)", "elective subject education", and "creative hands-on activity". Subject education teaches subjects determined by the subject domain, whereas elective subject education involves selecting the desired subjects for each school. Elective subject education includes the environment, foreign languages (e.g., Spanish, German, and Chinese), healthcare, and careers and occupations. Finally, creative hands-on activities are activities outside of the subject that enable students to practice knowledge in a complementary relationship with the subject and support the harmonious development of mind and body [49,53].

Creative hands-on activities include autonomous, club, volunteer, and career activities. They are operated autonomously by each school according to the educational needs and developmental stages of the students in each area. In middle schools, creative hands-on activities focus on establishing one's identity, promoting an attitude of living with others, and actively exploring one's career path [54].

The treatment in this study was a creative hands-on club activity in middle schools. In club activities, students are guided on themes, and they can apply for a club activity on a topic they are interested in. The teacher then manages the club for one semester on a previously announced topic. In this study, a club was formed with the theme of SMICE and coding, and the treatment was carried out for students who applied to the club activity. Therefore, all the students who participated in the study were receiving SW education through subject education, but each group received additional treatment through club activities.

Treatment was conducted differently for each group: the experimental group was given SMICE and the control group was given general SW education. The experimental group was treated with an over-correction convergence education program under the themes of "curling games using friction", "moving of particles", "time-speed graph", and "drawing board for fan shape". The experimental group experience took three hours for each theme and underwent a total of 12 h of education [33,34]. The control group engaged in the same programming activity as the experimental group, but rather than proceeding with "analysis", "design", and "evaluation", they explained and produced the principles of the program presented in "execution". Additional application tasks were also performed. This made it possible to compare the effects of SW education and SMICE.

The students who participated in the treatment had received SW education in elementary school and were receiving SW education in middle schools. Although the SW education received in elementary school may vary based on the teacher, the SW education provided in this treatment was conducted by a single teacher, so the same education was experienced.

The teacher who performed the treatment received teacher training for SMICE and consulted with the researcher about the treatment process and class plan. The teacher training focused on understanding the necessity of SMICE, exploring the teaching–learning structure by curriculum and topic, and practicing with teaching–learning materials. Since the teacher who performed the treatment was an informatics subject teacher, training on the programming language was not performed separately.

This treatment was conducted simultaneously online and offline due to COVID-19. Accordingly, the teachers were supported so that there were no difficulties in the process of teaching online.

2.2.4. Questionnaire

CPS and ATC were used to analyze SMICE. SMICE was developed to improve students' problem-solving abilities, which is a common core competency in science, mathematics, and informatics subjects. Therefore, CPS was used to analyze SMICE. The test tool for measuring CPS used the creative problem-solving profile inventory (CPSPI) developed by Lee et al. (2014). CPSPI derived factors suitable for middle-school students in Korea based on previous studies on CPS. The factors in the test tool were "problem-finding and analysis", "generating ideas", "execution plan", "execution", and "persuade and communicate", with a total of 39 questions. Items were derived from each factor, and the reliability and validity of the test tool were verified. The question responses were on a 5-point Likert scale. The Cronbach's alpha for the test tool was 0.73–0.83 [55].

Unlike in general SW education, convergence was included in CPS. Therefore, a test tool was used to examine the changes in convergence among the study subjects. In this study, the test tool for ATC developed by Shin et al. (2014) to measure attitudes toward convergence to analyze the effects of convergence education was used. In the test tool, attitudes were analyzed as cognitive, emotional, and behavioral factors, from which the ATC factor was derived [26,56,57]. Cognitive factors are related to individual perceptions that affect attitude formation. Therefore, relevance (personal and social) was presented to measure the students' knowledge of convergence and their comprehensive conceptual perceptions. The emotional factor refers to individual emotions or feelings about convergence, and interest was derived as an emotional factor based on the existing attitude test tool. Lastly, behavioral factors refer to the "behavioral tendency" to proceed with an action, which is necessary to reflect confidence or efficacy for behavioral practice. Thus, self-efficacy was derived as the behavioral element of the ATC [58–60]. Items were developed based on the derived factors, and the validity of the contents of the test tool, the validity based on the implications, and the validity of the internal structure were analyzed [61]. The Cronbach's alpha of the test tool was 0.86–0.91, and its validity was verified through the structural equation and the Rasch model. The test tool developed through the study was designed to respond to a total of 23 questions on a 5-point Likert scale [26]. The test tool used in this study is shown in Table 3.

Table 3. Test tool for the effect analysis of SMICE [26,55].

Test Tool	Constructs	Items	Cronbach's Alpha
CPSPI	Problem-finding and analysis	9	0.80
	Generating ideas	8	0.83
	Execution plan	10	0.76
	Execution	5	0.73
	Persuade and communicate	7	0.81
ATC	Knowledge	4	0.87
	Personal relevance	5	0.91
	Social relevance	4	0.90
	Interest	5	0.86
	Self-efficacy	5	0.86

3. Results and Discussion

3.1. Creative Problem-Solving Ability

In the pre-test, there was no statistically significant difference in CPSPI between the experimental group ($M = 3.08$, $SD = 0.60$) and the control group ($M = 3.06$, $SD = 0.53$) ($t = 0.15$, $p = 0.88$). Even after an examination of the detailed factors, there were no significant differences in problem-finding and analysis ($t = -1.07$, $p = 0.29$), generating ideas ($t = -0.40$, $p = 0.69$), execution plan ($t = 0.35$, $p = 0.73$), execution ($t = 1.51$, $p = 0.14$), and persuasion and community ($t = 0.20$, $p = 0.84$). Since the study subjects were taught under the same curriculum in one school, there was no significant difference in CPSPI.

In relation to the changes based on the treatment, the control group showed an improved CPSPI in the post-test ($M = 3.37$, $SD = 0.51$) compared to the pre-test ($M = 3.06$, $SD = 0.53$). In addition, the difference in CPSPI between the pre- and post-tests was statistically significant ($t = -2.46$, $p = 0.02$). In the detailed factors, significant improvements were found in execution ($t = -2.57$, $p = 0.02$) and persuasion and communication ($t = -2.09$, $p = 0.05$). Thus, it was confirmed that middle-school students who received general SW education improved their CPSPI by focusing on execution as well as persuasion and communication.

In the experimental group, the CPSPI of the post-test ($M = 3.77$, $SD = 0.62$) was improved over the pre-test ($M = 3.08$, $SD = 0.60$), and the difference was statistically significant ($t = -3.21$, $p < 0.01$). Significant post-test improvements were also shown in problem-finding and analysis ($t = -3.49$, $p < 0.01$), generating ideas ($t = -2.87$, $p = 0.01$), execution ($t = -2.78$, $p = 0.01$), and persuasion and communication ($t = -2.68$, $p = 0.01$). However, in the execution plan, the post-test results ($M = 3.85$, $SD = 0.87$) showed improvement over the pre-test results ($M = 3.22$, $SD = 0.88$), but there was no statistically significant difference ($t = -2.01$, $p = 0.06$).

The post hoc test showed that the CPSPI of the experimental group ($M = 3.77$, $SD = 0.62$) was higher than that of the control group ($M = 3.37$, $SD = 0.51$). Additionally, there was a statistically significant difference in CPSPI between the experimental and control groups ($t = 2.47$, $p = 0.02$). Therefore, it was confirmed that the CPSPI of the experimental group was higher than that of the control group. In relation to each factor, only problem-finding and analysis ($t = 2.71$, $p < 0.01$) as well as execution ($t = 2.55$, $p = 0.01$) showed significant improvement. Regarding other factors, the experimental group showed higher post-test scores than the control group, but there was no significant difference (as observed in Figure 2).

In summary, there was no difference in CPSPI between the experimental and control groups in the pre-test, but both groups showed improvements in CPSPI after treatment. Accordingly, the result of the post-test was that the experimental group had a higher CPSPI than the control group, and the problem-finding and analysis as well as execution factors in the CPSPI of the experimental group were higher than those of the control group. Persuasion and communication improved in both groups, but no significant difference was found in the post-test. Therefore, there was no difference in effect according to treatment. "Generating ideas" improved only in the experimental group, but no significant difference was found in the post-test. Therefore, the treatment yielded no significant improvement. In both groups, the execution plan did not show any significant improvement.

Therefore, it was confirmed that general SW education also influenced the improvement of CPSPI in middle-school students. However, SMICE was more effective in developing CPSPI among middle-school students than general SW education. In particular, SMICE improved middle-school students' problem analysis, decomposition, problem definition, abstraction (problem-finding and analysis), and idea or algorithm (execution) programming abilities [46,55]. Thus, it was confirmed that SMICE was effective in the development of CPSPI for middle-school students.

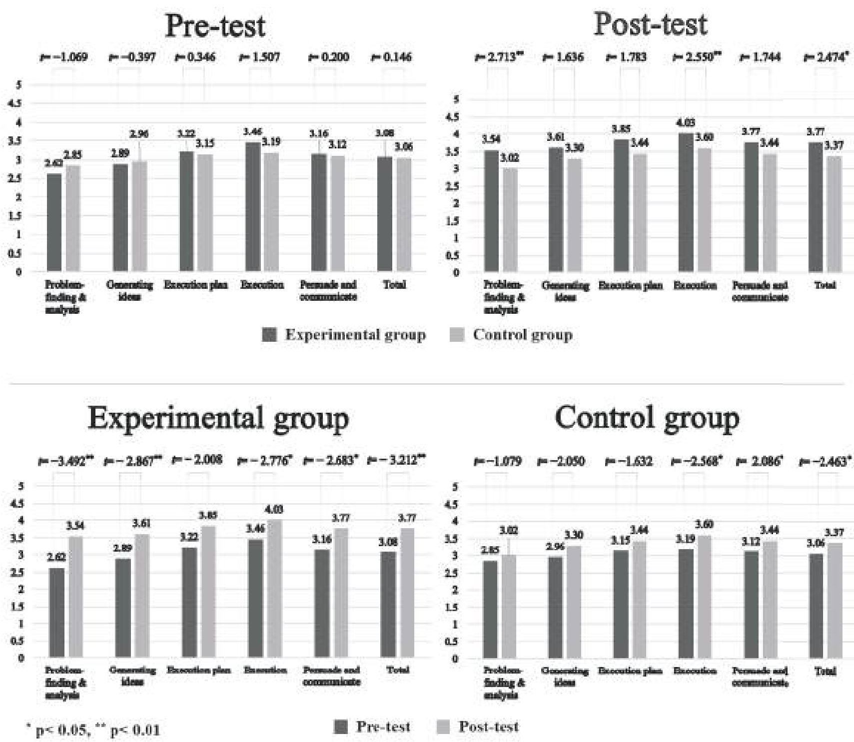

Figure 2. Changes in CPSPI according to treatment.

However, it should be noted that there was no significant difference between "generating ideas" and "persuasion and communication", and that there was no change in the "execution plan". An execution plan is a factor related to an algorithm because an execution plan is a process of evaluating, improving, and writing an idea in detail. However, there was no significant improvement following either general SW education or the over-correction convergence education program. Informatics in the Korean middle-school curriculum includes an understanding and expression of algorithms in problem-finding and programming. In addition, for the treatment, the content was written in the designed flowchart so that the algorithm worked properly. The content confirmed that there is a limit to the development of algorithm competency among middle-school students and that improvement is necessary to enhance their algorithm competency [32,46,55].

3.2. Attitude toward Convergence

In terms of ATC, there was no statistically significant difference between the experimental (M = 3.09, SD = 0.65) and the control (M = 3.23, SD = 0.49) groups in the pre-test (t = 0.93, p = 0.36). There was no significant difference in knowledge (t = −1.33, p = 0.19), personal relevance ($t = -1.38$, $p = 0.17$), social relevance ($t = 0.88$, $p = 0.38$), interest ($t = 0.03$, $p = 0.97$), and self-efficacy ($t = 0.04$, $p = 0.97$). Thus, it was confirmed that there was no significant difference in the ATC of middle-school students before treatment.

Looking at the change according to treatment, the post-test ($M = 3.12$, $SD = 0.48$) decreased in the control group compared to the pre-test ($M = 3.23$, $SD = 0.49$). However, the difference between the pre- and post-tests was not statistically significant ($t = 0.84$, $p = 0.41$). The increase/decrease in the detailed factors was different for each factor. However, the difference between the pre- and post-tests for all factors was not statistically significant. Therefore, it was confirmed that there was no change in attitudes toward convergence among middle-school students who received general SW education.

In the experimental group, ATC improved in the post-test ($M = 3.63$, $SD = 0.71$) compared to the pre-test ($M = 3.09$, $SD = 0.65$), and the difference between the pre-test and the post-test was statistically significant ($t = -2.48$, $p = 0.02$). In addition, in knowledge ($t = -3.18$, $p < 0.01$), personal relevance ($t = -2.26$, $p = 0.03$), and social relevance ($t = -2.19$, $p = 0.04$), the post-test values were better than in the pre-test. The difference between the pre- and post-tests was found to be significant. Therefore, it was confirmed that middle-school students who received SMICE improved their convergence attitude, focusing on knowledge, personal relevance, and social relevance. However, no significant change was observed in interest ($t = -1.26$, $p = 0.22$) or self-efficacy ($t = -1.71$, $p = 0.10$).

In the post hoc test, the experimental group ($M = 3.63$, $SD = 0.71$) had a higher ATC than the control group ($M = 3.12$, $SD = 0.48$), and the difference between the two groups was statistically significant ($t = 3.00$, $p < 0.01$). Regarding all factors in ATC (knowledge ($t = 2.39$, $p = 0.02$), personal relevance ($t = 2.14$, $p = 0.04$), social relevance ($t = 2.75$, $p = 0.01$), interest ($t = 2.52$, $p = 0.02$), and self-efficacy ($t = 2.25$, $p = 0.03$)), the experimental group showed higher values than the control group, and the difference between the two groups was also significant. From this, it can be confirmed that the improvement in ATC in the experimental group was significant. Therefore, it can be confirmed that SMICE affects the development of middle-school students' ATC. However, although interest and self-efficacy improved in the experimental group, there was no significant difference. Therefore, there is a limit to interpreting the difference in interest and self-efficacy in the post-test as the effect of SMICE (as observed in Figure 3).

The test tool for ATC measures knowledge and relevance (cognitive factor), interest (emotional factor), and self-efficacy (behavioral factor) in relation to convergence. The study's results confirm that SMICE only improves cognitive factors related to fusion. To solve problems through convergence, students need to change their attitudes and practices based on their knowledge of convergence [61]. In this study, attitude change was made based on the knowledge of convergence, but it was found that it did not affect students' self-efficacy or interest in practice.

According to Oh et al. (2012), convergence researchers cultivate meta-knowledge about convergence based on their own knowledge of convergence [62,63]. To cultivate meta-knowledge of convergence, it was necessary to understand the necessity and relevance of convergence and its effects according to the context and situation emphasized by PISA [26,60]. Therefore, it was necessary to understand the individual and social relevance of convergence. In this study, SMICE was shown to be effective in improving both personal and social relevance. Therefore, it was confirmed that the problems outlined in the literature could be solved, and the educational effect appeared to show that science, mathematics, and informatics are subjects that can converge [8,29]. It was further shown that the type and theme of SMICE were suitable for convergence education.

However, there was no significant change in interest in convergence (emotional factor). Murayama et al. (2013) found that intelligence is an important factor for instantaneous achievement, but not an important factor for long-term academic achievement [64]. They also found that motivation is an important factor in long-term academic achievement. In this study, it was confirmed that SMICE was effective in achieving the short-term achievement of convergence. However, to cultivate convergence literacy in the long run, it is necessary to improve students' interest in convergence. In addition, self-efficacy is required for students to practice actions based on knowledge of convergence [58,60]. However, there was no development of self-efficacy regarding convergence in this study. SMICE formed a problem-solving phase based on students' capabilities in the three subjects, but there was a limit to improving efficacy expectations regarding convergence [58,60,65].

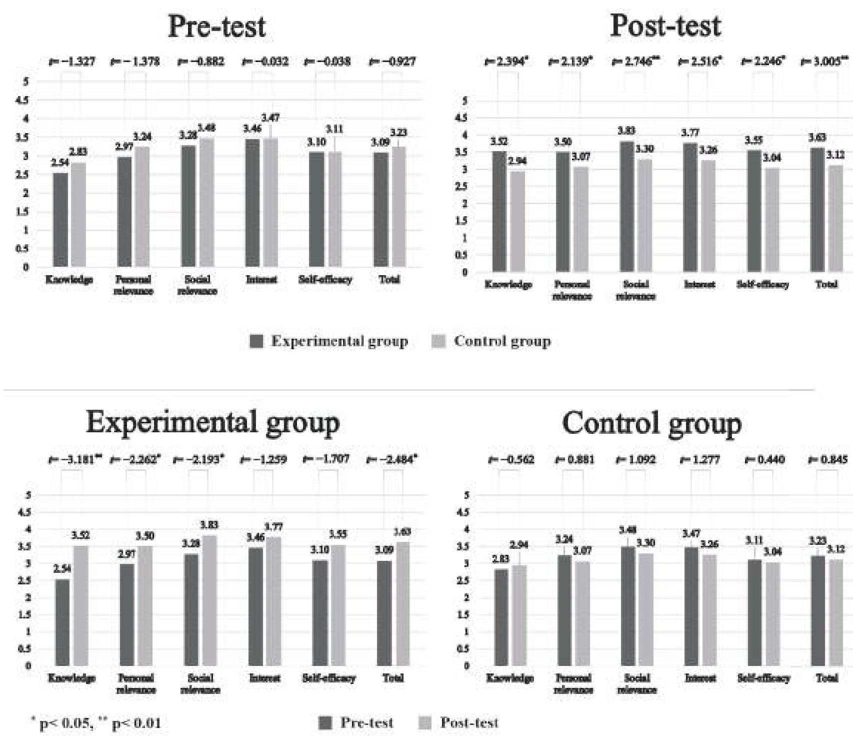

Figure 3. Changes in ATC according to treatment.

The study revealed the direction of convergence education. In previous studies, convergence education focused on presenting the contents of several subjects [8,29,36–39]. However, in this study, convergence education was designed based on subject competency. Applying convergence education in this direction to middle-school students in Korea resulted in improved CPS and ATC. Thus, it is necessary to consider a qualitative approach to integrated curriculum, such as competency-oriented convergence, rather than theme-oriented or subject-centered convergence, which have been widely studied in existing convergence education [11,19,21,33].

SMICE is a specialized form of education in Korea. Korea introduced STEAM education into the national curriculum to promote convergence education by combining subjects and coding (e.g., SMICE) [8,29,32,33]. Recently, as the importance of artificial intelligence (AI) education has increased, policies regarding AI convergence education have being actively implemented. Although teachers agree on the importance of AI, they have been unable to determine a clear direction for teaching AI education and supporting AI convergence education. In this study, a method for converging coding with other subjects was presented [7,51]. Further research is needed to explore ways to conduct convergence education involving AI in information subjects.

4. Conclusions

Since 2011, Korea has been actively conducting convergence education, led by STEAM education, to nurture convergence talent. However, convergence education cannot be activated effectively due to the difficulties encountered in schools. Previous studies have indicated that the problem with convergence education in Korea is that it focuses on "convergence". For example, choosing a subject to teach, such as ordering a salad at a salad shop, and presenting the contents of several subjects is considered convergence. Since the contents of various subjects are presented, many contents can be learned, but no wholeness (educational effect) through the convergence of subjects could be expected. This is equivalent to the quantitative approach in an integrated curriculum. In order to solve this problem, there has been a movement to introduce theme-centered convergence education. However, even in theme-centered education, the contents of various subjects related to the theme are presented. Therefore, it takes the same form as the existing quantitative approach to integrated curriculum.

Convergence education does not present several subjects. However, it is necessary to converge subjects to produce an educational effect, similar to the qualitative approach of an integrated curriculum. Therefore, this study pursued the convergence of science, mathematics, and informatics subjects based on the qualitative approach. Accordingly, competencies related to science, mathematics, and informatics subjects were analyzed, and problem-solving ability was determined using the competencies of the three subjects as common competencies. Themes for developing common competencies were derived, and educational programs were developed. It is meaningful that the convergence education was centered on competency rather than on the form in which the contents of various subjects were presented, as in existing convergence education. This represents a qualitative approach to integrated curriculum, and it is different from the convergence approach to education that is prevalent in Korea.

Middle-school students who received SMICE improved their CPS, and middle-school students who received general SW education also improved their CPS. Therefore, there was a difference in the development of CPS according to teaching–learning, even if the same programming task and the same amount of time were given. The SMICE program developed in this study was effective in developing the CPS of middle-school students. Furthermore, it was confirmed that SMICE effectively influenced the development of CPS, which is a focal competency of SMICE.

Convergence yielded new effects or synergistic cooperation by converging heterogeneous disciplines to solve social phenomena or natural problems that cannot be solved by academic sub-disciplines. In this study, it was expected that new educational effects would emerge through the convergence of science, mathematics, and informatics subjects. Therefore, the change in ATC was examined as the effect of creativity that would appear through subject convergence. The results show that there is no change in ATC following general SW education, but middle-school students who received SMICE improved their ATC. This confirmed that SMICE was effective in improving middle-school students' ATC. Thus, when education that combines science, mathematics, and informatics subjects was conducted, middle-school students better understood the knowledge and the relevance of convergence.

In this study, the educational effect of SMICE was verified, but the following limitations existed. The first was the research subject. The SMICE program was developed for middle- and high-school students. However, this study was only conducted on middle-school students. Therefore, it is also important to conduct a study on high-school students to analyze the effects of SMICE.

The next limitation was the type of SMICE. In this study, "curling games using friction force", "moving of particles", "time-speed graph", and "calculate the area of a fan-shaped figure" were developed in a modular form and were used for treatment. For each topic, "curling games using friction force" and "calculate the area of a fan-shaped figure" fell under CSK, and "moving of particles" and "time-speed graph" fell under PSRL. Therefore, CACFS-related modules were not used in the treatment and the types were not the same for each theme. SMICE programs were developed to foster problem-solving skills, but there are differences in the difficulty or activities in the steps for each type. Therefore, the effects of SMICE may vary depending on the subject used in the study. In this study, online and offline classes were conducted simultaneously due to COVID-19. Therefore, themes were selected and used for treatment. In future work, it is necessary to analyze in depth the effects of the types of SMICE.

In addition, those who acquired general SW education were set up as the control group to analyze the effects of SMICE. SMICE was developed to overcome the limitations of existing convergence education programs. Therefore, it is necessary to analyze the differences between general convergence education and SMICE and derive the educational effects according to the type of convergence in education. However, there are many types of convergence, and it is difficult to develop and apply educational programs on the same theme and with the same educational objectives. Therefore, in this study, the task of developing a program corresponding to the same theme was conducted, but there was a difference in the process of performing the task (experimental group: convergence vs. control group: rote skill and application in programming). Therefore, it is necessary to study ways to clarify the difference between existing convergence education and SMICE.

In this study, ATC was used as a test tool to examine the educational effects of SMICE. Previous studies have found that ATC and convergence attitudes are different, and it is necessary to cultivate a *convergent* attitude while having a *convergence* attitude. This means that the convergent attitude is a higher competency than ATC. The study confirmed that SMICE is effective in improving ATC. Therefore, it is necessary to investigate the effect of SMICE on convergence attitudes.

Finally, this study confirmed that SMICE was effective in improving CPS and ATC, but not all factors under CPS and ATC showed significant improvement. However, there was a limitation in that the experiment was difficult to conduct due to the unprecedented situation of COVID-19. Therefore, based on the results of this study, it is necessary to improve SMICE programs for middle-school students and verify their educational effects.

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Article

Students' Emotions and Engagement in the Emerging Hybrid Learning Environment during the COVID-19 Pandemic

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Abstract: Due to the COVID-19 pandemic, classes in schools acquired a hybrid learning model. Students took their classes both in person and, at other times, remotely. However, students are currently facing situations that they are not familiar with after a period of two years of confinement due to the COVID-19 pandemic. This emerging model of learning, to which the students had to adapt, not only impacted on their emotions during learning but also influenced their perceptions of their abilities and skills in being able to perform adequately in a situation of uncertainty, which also influenced the degree of academic engagement that they had. This study applied the structural equation modeling technique, using PLS-SEM software, to a sample of 194 students. The results show that their self-efficacy to act in a situation of vulnerability was affected, which is why their negative emotions increased and their positive emotions decreased. This in turn influenced the degree of engagement and effort they invested in developing a school activity.

Keywords: self-efficacy; emotions; academic engagement; hybrid learning; higher education; COVID-19 pandemic

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1. Introduction

During the pandemic, classes in schools were taught using a hybrid learning model, which involved students receiving classes that fluctuated between face-to-face and online periods. This model, which is called a hybrid [1], consists in dividing the total number of students into two blocks. The first block of students attended school to take their classes in person, while the second worked remotely. This hybrid model is an emerging adaptation that had to be implemented given the sanitary conditions [1].

This model is also called emergency remote education, according to Hodges et al. [2], as it was an emergency response to a situation in which the main measure was confinement; therefore, its effectiveness cannot be compared to other educational processes that were designed from the very beginning to be provided online [3]. The main difference is that e-learning or online education was created so that students could build their knowledge based on their individual learning experiences, supported by electronic media [4].

The hybrid learning model with which IPN higher education institutions have worked in Mexico City is an emerging adaptation in which the students of a group coexist simultaneously in different spaces [5]. For one week, half of the group studied in the physical classroom, and the other half was connected to classes in a virtual room; in the following week, the situation was reversed.

During this unexpected situation at the time of the COVID-19 pandemic, the students were affected academically, financially, physically, and psychologically [6].

Faced with the situations presented by this emerging hybrid environment, the students were caught up in a carousel of emotions, both positive and negative [7,8]. The negative emotions included anxiety [8,9] about the possibility of catching COVID-19 while traveling between home and school or at the school itself [10] and anger due to not being able to hear or take the entire class during the weeks in which they were learning remotely because of the failures of the school's internet connection [9,10]. Another negative emotion that the students may have experienced was boredom during online classes due to the aforementioned technical problems related to the lack of a fast internet connection [11].

Fortunately, positive emotions also arose, such as the joy of obtaining a satisfactory grade or the hope of reaching a planned level of success and the pleasure of seeing their classmates in physical form again [12]. These emotions play a fundamental role in student motivation, learning, and performance [13–16] and, crucially, in the degree of engagement with their learning [17].

This emerging model of learning, to which the students had to adapt, not only impacted their emotions during learning but also influenced their perceptions of their abilities and skills in being able to perform adequately in a situation of uncertainty; we are all born with the need to feel effective in our environment [18].

This raises the following questions: to what extent did the hybrid model of learning affect the students' efficacy in performing their schoolwork and what emotions prevailed? To what extent did self-efficacy and emotions affect school engagement?

Therefore, this study explored how the students' degree of self-efficacy when performing in a situation of uncertainty may have influenced their emotions and their degree of engagement with their studies. This research is important as it provides empirical evidence that analyses the effects of the COVID-19 pandemic on the essential constructs for school success, such as academic feelings, self-efficacy, and academic engagement.

1.1. Academic Emotions, Engagement, and Self-Efficacy

Several theories have been proposed to study the interrelationships between motivation, engagement, and self-efficacy, and two of them have been given particular attention. The first is the control–value theory by Pekrun [19], which provides an approach to exploring emotions in achievement environments such as the academic context. This theory implies that students' emotions can be affected by fostering their perceptions of competence and control. It is beneficial for schools because shaping educational environments properly can contribute to changing emotions in such a way that students know how to use them to their advantage.

The second theory is the expectancy–value theory of motivation by Eccles [20] and Pintrich [21], which analyzes the role of motivation in the performance of goals or tasks. The authors propose two main components as the foundation of this theory. The first plays a crucial role in determining school performance and refers to students' beliefs about their ability to perform their schoolwork and whether they have control and are responsible for their performance. This component is called expectative and includes self-efficacy and beliefs about the control of their learning. The other component is called value and includes extrinsic and intrinsic motivation towards an objective and the value the student gives to a task.

The emotional state of students is directly related to the involvement that they have with their learning activities. Emotions are feelings towards a situation, thought, or person, which are distinguished by being real or unreal [22]. Among the positive emotions that students can experience are fun, enthusiasm, enjoyment, satisfaction, and vitality. Negative emotions can include boredom, frustration, anxiety, depression, or anger. Emotions during the learning process play a fundamental role in students' motivation, learning, and school performance [13–15] and in the level of engagement that they show with their education [17]. In this study, positive emotions included enjoyment, enthusiasm, amusement, pride, and interest. Negative emotions included boredom, disinterest, frustration, sadness, and anxiety.

In defining school engagement, first Skinner and Belmont [23], then Fredricks et al. [24], and later Reschly and Christenson [25] found that academic engagement is a meta-construct that includes emotional, behavioral, and cognitive engagement. Regarding emotional engagement, the affective, positive, or negative responses that students manifest in the development of academic tasks are evident [24]. The opposite behavior to engagement is the lack of interest, disaffection, or detachment that students may have towards academic work. When a student presents this kind of behavior, they are capable of manifesting negative emotions such as frustration, boredom, anxiety, depression, or anger, as well as passivity, distraction, or mental disconnection [18].

Regarding behavioral engagement, González et al. [26] pointed out that this refers to the time, attention, and effort that students invest in their academic process, that is, in the resolution of assigned tasks and in their learning environment in general. On the other hand, Reschly and Christenson [25] and Reschly [27] commented that behavioral engagement is the level to which a student participates in academic, social, or extracurricular tasks involving attention, concentration, and persistence [18].

Cognitive engagement is the mental effort that students put into their learning process [26]. Student engagement is high when using sophisticated cognitive strategies, such as self-regulation or metacognition [28]. Some metacognitive actions involve learning to plan, monitor, and regulate learning, according to what was pointed out by Ramirez-Arellano et al. [29]. Planning allows students to have knowledge about the way in which the problem will be addressed, while monitoring helps students to understand the problem and monitor its evolution and finally regulate or control their learning [30].

Martin et al. [31] commented that one of the primary factors in understanding the level to which students have to get involved and take responsibility for their educational work is motivation. There are several authors who have analyzed this relationship and verified the effects of motivation on academic engagement [32]. In the case of Wang and Eccles [33], they confirmed that motivation affects student engagement, which they divided into emotional, behavioral, and cognitive engagement.

In the expectancy–value theory, [20,21,34] have proposed that within the motivation component, self-efficacy is an essential element in determining school performance and refers to the students' beliefs about their ability to accomplish school tasks. In this regard, Sun et al. [35] found that there is also a positive relationship between self-efficacy as a component of motivation and academic performance.

Self-efficacy is defined as the confidence that a person has towards their ability to achieve an objective in a specific situation, and it is also considered fundamental for a student to achieve school goals and to be able to face the different situations that arise during their life [36].

In the school environment, the effects demonstrated by a student's self-efficacy in meeting goals are crucial as the perception that the student has about their capacity and ability to solve the situations that arise is decisive [37]. Likewise, the control that students have over emotional reactions to success or failure is a strong predictor of effort and persistence in student activity [18].

It has been found that self-esteem, self-efficacy, and expectations are some of the elements that could be involved in student engagement, which in turn would have a considerable effect on the quality and level of engagement [38]. On the other hand, Skinner et al. [18] pointed out that every person innately has the need to feel effective within the environment in which they work, and the more that students, within their school environment, feel this sense of dominance, the better the quality of their involvement is.

Even today, inconsistent results are shown regarding the effects of self-efficacy and academic engagement in hybrid and face-to-face environments [39].

This section provides the theoretical foundation on which this research proposes a hypothetical model (see Figure 1) to study the relationships between self-efficacy, emotions, and academic engagement. The theoretical bases for each relationship are presented in the following section.

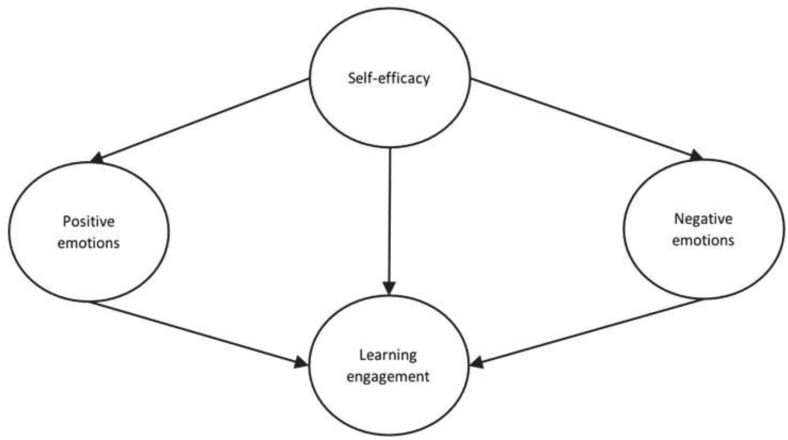

Figure 1. Hypothetical model of causal relationships.

1.2. Related Work

This section presents previous research concerning the effects of self-efficacy and emotions on students' engagement with their schoolwork.

Self-Efficacy and Its Relationship with Emotions and Academic Engagement

Within the academic field, it has been found that emotions during learning are positively related to motivation, learning strategies, and academic performance [40]. Other researchers have found that positive or negative emotions directly impact cognitive and learning strategies differently. For example, if students feel amused or curious about what they are learning (positive emotions), then they will use learning strategies such as self-regulation and critical thinking [14,40].

Similarly, it was found that fun (a positive emotion) is related to motivational beliefs and self-regulation strategies, which in turn were shown to have effects on the level of current and future engagement that the students demonstrated [17]. Another study also suggested that the effects of fun are essential for the adoption of online assessments for mathematics instruction [41].

Thus, positive academic emotions impel students to feel more engaged in schoolwork [42]. This was also observed in the study by Carmona-Halty et al. [43], who surveyed high school students in order to observe the effects of academic engagement and its role as a mediator between students' emotions and performance. Their findings showed that academic engagement mediates the link between positive emotions and academic performance. In addition, the authors added that increasing students' positive emotions is a challenge for educators and parents.

In contrast, negative emotions minimize the use of self-regulation strategies and promote external guidance/help [14,44,45].

Similarly, the research of Tze et al. [45] showed that when students feel bored it impacts on their motivation and learning strategies, with the greatest effect on their performance. Likewise, the study by Marchand and Gutierrez [15] demonstrated evidence of the strong negative effect of anxiety on the use of learning strategies.

Therefore, negative academic emotions could negatively on students' achievements, making it more difficult for students to be engaged in their learning activities [46]. For example, in a longitudinal study on adolescents, Salmera et al. [47] analyzed the effects of self-efficacy as a component of personal resources and school burnout (as feelings of inadequacy) on academic engagement. Their results showed that self-efficacy had a positive relationship with academic engagement and a negative association with burnout.

Additionally, one year after the beginning of this study, it was observed that academic engagement was negatively associated with school burnout.

King et al. [48], in a cross-sectional and longitudinal study, explored the effects of positive and negative emotions on academic engagement and its counterpart, academic disengagement. Their results proved that students with high levels of positive emotions were more engaged in their learning. Conversely, students with high levels of negative emotions reported higher disaffection. It was also observed that students who experienced positive emotions were more willing to strive for higher levels of engagement in their school.

Furthermore, in the context of the COVID-19 pandemic, through a longitudinal study Zhang et al. [49] explored the role of adaptability, academic emotions, and school engagement. Their results showed that academic engagement was positively correlated with positive emotions (such as enjoyment) and negatively correlated with negative emotions (such as anxiety, fear, and boredom).

Regarding motivation, it has also been found that there is a positive relationship between motivation and fun and a negative relationship between motivation and boredom [50]. Negative emotions decrease aspects related to intrinsic motivation. However, they increase extrinsic motivation, helping students in a certain sense, as this encourages them to avoid failure [14].

Another researcher, Pellas [51], who analyzed the effects that self-efficacy had on academic engagement in online education courses at a university, found that students who presented high levels of self-efficacy also reached high levels in the use of cognitive strategies and self-regulation. Likewise, it was found that self-efficacy was a significant predictor of the emotional engagement of those involved. As previously mentioned, it can be confirmed that self-efficacy in a given domain is essential to experiencing positive emotions, such as the enjoyment of that domain [17].

Likewise, other studies have found similar results, which explain that self-efficacy impacts on academic engagement [39] and learning performance [52]. Salmela-Aro and Upadyaya [47], when conducting a longitudinal study with adolescent students, also found that there is a positive linear relationship between self-efficacy and academic engagement; they point out that the level of self-efficacy that is attributed to a student influences the level of engagement and effort invested in developing an activity.

This was shown more clearly in the study by Heo et al. [39], who analyzed the relationship between self-efficacy and school engagement in students with and without symptoms of depression. The results showed a direct relationship between self-efficacy and school engagement in non-depressed students.

The research carried out by Borrachero et al. [53] analyzed the emotions of graduate teachers towards science teaching, finding that when teachers believed in their own ability to learn certain content, their positive emotions increased. Moreover, when teachers did not consider themselves capable of learning such content, their negative emotions increased.

2. Materials and Methods

2.1. Data Collection

A sample of 194 students from a higher education school was obtained, with ages ranging from 18 to 24. The students were pursuing a bachelor's degree in computer science engineering. The surveys were anonymous and answered by Google Forms (Google, Mountain View, CA, USA). All the students were invited to participate in answering the questionnaire; they were informed of its objective and that the data collected would be used exclusively for research purposes. The students' consent was requested to participate in the study, and all agreed to participate [54].

The questionnaire was distributed to the students on a regular day of classes; those in the physical classrooms answered on their mobile phones, and those taking classes online answered from home. It was applied at the end of March 2022, three months after starting their semester in the hybrid model, so that they could express their feelings about this model before returning to the face-to-face model; due to the sanitary conditions, they were to return to face-to-face classes in May 2022.

The sample size was five cases per variable observed in the low limit and ten cases per variable observed in the upper limit [55].

2.2. Instruments

The positive and negative emotions of the students were assessed using the Student Engagement and Disaffection in School (SED) instrument [18]. Positive emotions (PE) included enjoyment, enthusiasm, amusement, pride, and interest. Negative emotions (NE) included boredom, disinterest, frustration, sadness, and anxiety. The answers were evaluated using a 5-point Likert scale, where 1 meant totally disagree and 5 meant totally agree.

As the expectancy–value theory of motivation was included [20,21,34], we adopted the Motivated Strategies for Learning Questionnaire (MSLQ) instrument by Pintrich et al. [34,56]. This instrument includes self-efficacy (SE) as the motivational factor. Eight items were used and were evaluated with a 7-point Likert scale, where 1 was totally disagree and 7 was totally agree. Examples of self-efficacy for learning included "I'm certain I can understand the most difficult material presented in the readings for this course" and "I'm confident I can do an excellent job on the assignments and tests in this course".

Both instruments, the SED and the MSLQ, have been validated previously in the educational context [29,57,58].

To assess learning engagement (LE), the Schreiner and Louis [59] Engaged Learning Index instrument was implemented, using ten items. This instrument also evaluated the responses using a 5-point Likert scale, where 1 meant totally disagree and 5 meant totally agree. This instrument has been validated in previous research, such as in the study by [39], for example. To use this instrument, translation into Spanish was carried out and it was reviewed by a group of academics and a professional translator. When all the professionals had given their approval, the instrument was applied at the school where this study took place. This instrument included items such as "I can usually find ways of applying what I'm learning in class to something else in my life" and "I feel energized by the ideas that I am learning in most of my classes".

Likewise, as the instruments were measured with different Likert scales, all the factors were standardized [60].

2.3. Analysis

The proposed model was analyzed using the structural equation modeling (SEM) statistical technique, using the partial least squares method (PLS_SEM) and using SmartPLS version 3 software (SmartPLS GmbH, Oststeinbek Germany). This technique is particularly useful for small sample sizes and makes better predictions when compared to the covariance-based technique CB-SEM [61]. In addition, the PLS-SEM technique does not require statistical assumptions such as data normality and sample size; so, it is considered a non-parametric SEM technique. The PLS-SEM technique has been used for both confirmatory and predictive research [62].

Utilizing a PLS-SEM technique is a two-tier process. The first tier involves calculating the measurement model or outer model. This model can include reflective or formative indicator variables. The difference between the two measurement approaches lies in the causal priority between the constructs and their indicator variables. In this study, reflective measures were used as the indicator variables of each construct are competitive with each other and represent manifestations of the construct [63].

The second tier consists in estimating the relationship among the constructs in the structural model or inner model. The links between the constructs are hypothesized according to theoretical reasoning [64].

As the measurement model evaluates the quality of the relationships between indicator variables and their underlying constructs, there were some criteria to validate. The construct validity was verified using Cronbach's alpha (A); for many researchers, values greater than 0.70 are considered acceptable [65].

The composite reliability (CR) and the average of variance extracted (AVE) evaluated the convergent validity; values greater than 0.7 are considered acceptable for CR and 0.5 for AVE [66].

The discriminant validity is verified when the values of the diagonal that represent the square root of the AVE values of each construct are greater than the values below them, which represent the values of the correlations between the constructs [67].

The indicator reliability shows how much of the indicator's variation can be explained by the construct. Hulland [68] suggested that empirical studies can include loadings smaller than 0.4 in a PLS-SEM model or, as Hair et al. [66] mentioned, larger than 0.5.

The value of Cronbach's alpha, CR, and AVE, as well as the Fornell–Larcker discriminant validity criterion (shown later), are indicators of the goodness of fit of the proposed model [69].

The structural model was estimated by assessing collinearity issues, the path coefficient significance level, the level of determination coefficient R^2, the effect size f^2, and the predictive relevance Q^2.

If two or more constructs (as independent variables) of the structural model are highly related, there is a multicollinearity issue, and it is observed when the variance inflation factor (VIF) coefficient is higher than 5 [66]. The goodness of the path coefficients was tested by the bootstrapping technique and t-statistics [70].

The R^2 reflects the level of the construct's explained variance and can take values between 0 and 1. For social science research, the following thresholds are applied: weak (0.25), moderate (0.50), and substantial (0.75) [71].

The effect size f^2 shows the change in R^2 when a certain (exogenous) construct is omitted from the model. According to Cohen [72], the effect sizes of 0.02, 0.15, and 0.35 are small, medium, and large, respectively.

The Q^2 value assesses the predictive accuracy of the structural model. Stone [73] and Geisser [74] suggest using the Stone–Geisser test. The predictive relevance should be positive and with values higher than zero [75].

3. Results

3.1. Descriptive Statistics, Reliability, and Validity

The proposed model was analyzed using the structural equation technique, and the validity of the constructs was verified. The measurement model evaluated the construct reliability, convergent validity, discriminant validity, and indicator reliability. In order to achieve validity, five observed variables were removed from the learning engagement (LE) construct, and four observed variables from the negative emotions (NE) construct. No observed variables were removed from the self-efficacy (SE) and positive emotion (PE) constructs.

The observed variables and their factor loadings, including Cronbach's alpha, composite reliability (CR), and the average variance extracted (AVE) of the constructs involved in the proposed model, are shown in Table 1.

The reliability of each construct (construct reliability) was evaluated using Cronbach's alpha (A). Values greater than 0.70 were obtained; so, these values were considered acceptable. The convergent validity was also evaluated using the values of the composite reliability (CR) and the average variance extracted (AVE). Values greater than 0.7 for CR and 0.5 for AVE were observed; so, it was considered that construct validity was reached. The factor loadings show values higher than 0.4 [68], reaching indicator reliability.

Table 2 shows the discriminant validity of the measurement model, in which it is observed that the AVE values (on the diagonal) are greater than the values of the square root of the correlations between the constructs (the rest of the values). Therefore, discriminant validity was reached.

Table 1. Cronbach's alpha, composite reliability, and average variance extracted of the proposed model.

Construct	A	CR	AVE	Observed Variable	Factor Loadings
Self-Efficacy (SE)	0.908	0.926	0.611	SE1	0.742
				SE2	0.809
				SE3	0.814
				SE4	0.696
				SE5	0.820
				SE6	0.688
				SE7	0.849
				SE8	0.819
Positive Emotions (PE)	0.779	0.894	0.532	PE1	0.517
				PE2	0.690
				PE3	0.787
				PE4	0.841
				PE5	0.769
Negative Emotions (NE)	0.865	0.894	0.517	NE1	0.793
				NE2	0.814
				NE3	0.634
				NE4	0.621
				NE5	0.823
				NE6	0.754
				NE7	0.619
				NE8	0.658
Learning Engagement (LE)	0.761	0.842	0.521	LE1	0.749
				LE2	0.511
				LE3	0.814
				LE4	0.696
				LE5	0.797

Table 2. Discriminant validity.

	Self-Efficacy	Positive Emotions	Negative Emotions	Learning Engagement
Self-Efficacy	0.782	−0.441	0.506	0.456
Positive Emotions		0.729	−0.483	−0.609
Negative Emotions			0.719	0.697
Learning Engagement				0.722

3.2. Causal Model or Structural Model

Figure 2 shows the results of the proposed model. These results demonstrate that the relationships between the constructs are statistically significant.

The results show that there is a direct and significant relationship between self-efficacy and academic engagement. Relationships between self-efficacy and positive emotions and self-efficacy and negative emotions were also observed. It was noticed that both emotions influence academic engagement. It was observed that the significance levels of the path coefficients were all significant (*** $p < 0.001$).

Hair [66] suggests that the VIF values should be lower than 5. The results show that the inner VIF values were NE (1.516), PE (1.399), and SE (1.443). Therefore, collinearity among the constructs was not an issue.

The determination coefficient R^2 of the construct learning engagement was 0.58, which is considered medium; for the negative emotions, it was 0.256, and for the positive emotions, it was 0.195, both of which are considered small [71]. This means that PE, NE, and SE were able to explain more than half the variance in the learning engagement construct.

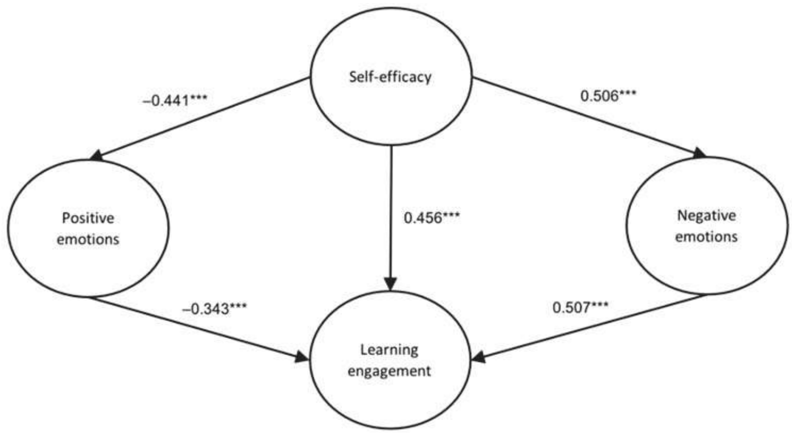

Figure 2. Resulting causal model *** $p < 0.001$.

The effect sizes f^2 of the structural model show the values of NE (0.407) and PE (0.202), which, according to Cohen [72], are large and medium, respectively. It was also observed that the SE construct had no effect on learning engagement as its value (0.015) was less than 0.02.

To evaluate the predictive accuracy of the structural model, the Q^2 value of the endogenous constructs was used. The results show values of LE (0.289), NE (0.127), and PE (0.099), all of which are positive and higher than zero [75].

4. Discussion

During the health conditions imposed by the COVID-19 pandemic, in which an emerging hybrid teaching model was established, the manner in which self-efficacy influenced positive and negative emotions was analyzed, along with how these, in turn, have impacted the academic engagement of higher education students. Self-efficacy should be understood as the perception or judgement of students about their ability to complete school tasks.

Various studies have found the significant role that emotions play in the learning process [14,50,76,77]. The results show that self-efficacy has an impact on positive and negative emotions. As can be seen in Figure 2, there is a causal relationship between self-efficacy and negative emotions, which means that when students do not consider themselves capable of learning certain academic content, their negative emotions increase; that is, the low values of self-efficacy mean that students do not feel they have the skills and abilities to pass their subjects [53], which is why they feel anxious, stressed, distracted, and bored. This was also shown in the investigations by Sinatra and Taasoobshirazi [78] and Ramirez-Arellano et al. [29].

Additionally, it was found that there is a negative causal relationship between self-efficacy and the emotions of enjoyment, enthusiasm, and fun (positive). That is, when students do not believe in their own ability to learn the content of the subject, their positive emotions decrease, which could imply that students who feel less able to complete a school task have a decrease in their positive emotions and, therefore, that they might feel uninterested in the class [29]. As mentioned, it can be confirmed that self-efficacy in a given domain is essential to be able to experience positive emotions, such as the enjoyment of that domain [17].

What leads to the reflection on how the emerging hybrid teaching model has influenced the self-efficacy of the students during the uncertain conditions of the COVID-19 pandemic is the fact that they felt stressed, worried, and anxious about getting COVID-19 on their way from home to school and at the school itself. In the week during which students had to attend their online classes, feelings of anger or frustration were evident as a consequence of not being able to clearly hear their class due to failures caused by the school internet from which the teacher transmitted. Likewise, the students felt bored in their online classes due to the same technical problems caused by an inadequate internet signal. Therefore, it can be assumed that the described problems interfere with the skills that the students must have to be able to attend and complete all school activities, consequently increasing their negative emotions.

The results also show the effects of negative and positive emotions on academic engagement. Research has been conducted that confirms that emotions predict academic engagement [51] and school performance [14]. Emotions are an essential aspect of the academic career of students, and they can vary over time [79]. During the health emergency, the students' emotions may have fluctuated due to the stress and anxiety caused by the environment of uncertainty about possible infections.

It has been proven that negative emotions are related to poor grades [80]; the fact that students experience emotions of stress, anxiety, worry, or boredom causes them to feel uncommitted to their learning, affecting their behavioral and cognitive engagement [81]. This was also observed in another study that showed that stress in students affected their degree of academic engagement [29]. Therefore, it is necessary to foster positive self-efficacy beliefs in students, which should be promoted to reduce negative emotions.

Conversely, if students feel enthusiastic and interested, these feelings cause a higher degree of engagement [53]. Therefore, it is vital to introduce motivating factors that promote enjoyment, enthusiasm, and fun in such a way that they manage to encourage a high degree of behavioral and cognitive engagement in students.

Other studies have found that self-efficacy influences the degree of academic engagement [39]. This research has also found a direct causal relationship between self-efficacy and academic engagement. When students show low levels of self-efficacy, this could imply that they are not very engaged with their homework and school activities. Conversely, high levels of self-efficacy have been shown to influence the degree of commitment of the students to their studies. Therefore, students who have a positive perception of the fact that they are capable of successfully carrying out their school activities will be more committed.

This was also observed in the research by Salmela-Aro and Upadyaya [47], who found a positive linear relationship between self-efficacy and academic engagement in adolescent students, pointing out that the level of self-efficacy that is attributed to a student influences their degree of engagement and effort invested in developing an activity. This implies that practices and academic activities that stimulate positive self-efficacy beliefs in students should be encouraged; this in turn will increase their motivation, performance, and skills when performing their school activities [58,82]. This encourages universities to apply support and tutoring models, especially for students in their first year at university, to develop skills such as autonomy, digital competence, and self-regulation [83].

5. Conclusions, Limitations, and Future Research

5.1. Conclusions

During the health emergency caused by the COVID-19 pandemic, universities had to implement an emerging hybrid teaching model, combining face-to-face classes and online classes. Within this new situation, students experienced feelings of uncertainty due to the fact that they were facing situations of possible contagion or technical problems due to the poor internet signal from the place where teachers transmitted classes. These problems affected the abilities and skills of the students in performing adequately in an uncertain situation. When students do not consider themselves capable of learning certain content, their negative emotions increase, and consequently, they feel anxious, stressed, distracted, and bored. Conversely, more motivated students feel more skillful in completing a school task; they feel interested in the class, enthusiastic, and even have a sense of fun. Emotions such as stress, anxiety, worry, and boredom cause students to feel less engaged in their learning. In response to this problem, the abilities and skills of students should be stimulated by providing the appropriate technical conditions and continuing to promote preventive measures to avoid contagion, all with the aim of reducing their negative emotions in order to help build positive self-efficacy beliefs in the students.

It can be concluded that the conditions of uncertainty in the hybrid learning model, which was implemented due to the health emergency, have affected the level of self-efficacy that is attributed to a student. This, in turn, has influenced the degree of engagement and the effort that students invest in developing an activity.

5.2. Limitations of the Research

The study had the limitation that it was only carried out in an IPN engineering school because the other IPN schools continued the semester online due to a large number of infections in the city. Therefore, a small sample size was obtained.

5.3. Future Research

As a continuation of this study, future research could focus on factors related to the work of tutoring the students who showed little engagement with their schoolwork by monitoring the tutoring for a semester and measuring the impact at the end of it.

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Promoting STEAM Education in Primary School through Cooperative Teaching: A Design-Based Research Study

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Abstract: The COVID-19 pandemic has highlighted the importance of students' information literacy, computer skills, and research competencies for self-regulated learning and problem solving. STEAM education, with interdisciplinary knowledge building and higher-order thinking development as its main purpose, is considered essential for students' sustainable development in the post-pandemic era. However, STEAM education in China's K-12 schools is facing several problems, such as insufficient qualified teachers, unsustainable development, and difficulty in achieving meaningful discipline integration. To address these problems, this study proposes an innovative STEAM education model supported by cooperative teaching and theories of project-based learning and collaborative learning. After two iterations of design, evaluation, and revision, the proposed STEAM education model and a set of instructional design principles were validated. The resulting model features a multi-teacher cooperative strategy, detailed and diverse scaffolding, familiar themes for students, the integration of STEAM education into formal curricula, and extended instruction hours. The study results suggest that cooperative teaching can facilitate meaningful discipline integration and can alleviate the STEAM faculty shortage. This study produced five proven instructional design principles for conducting STEAM education supported by cooperative teaching in primary schools.

Keywords: STEAM; STEM; design-based research; cooperative teaching; China

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1. Introduction

STEAM (science, technology, engineering, arts, and mathematics) [1] is derived from STEM [2,3], with the discipline of arts added, and focuses on cultivating learners' comprehensive abilities and core literacy, aiming to nurture excellent talent resources to support the development of modern society [4]. STEAM can be defined as "education for increasing students' interest and understanding in scientific technology and for growing STEAM literacy based on scientific technology and the ability to solve problems in the real world" [5]. In this study, STEAM is used as an umbrella term for both STEM and STEAM education as defined here.

The potential of STEAM education has been acknowledged worldwide, receiving growing attention from both educational researchers and practitioners. Many researchers have studied the construction of STEAM education, including teaching modes, methods, strategies, and education design [6]. For example, Stanford University's d. loft STEAM education combines STEAM education with design thinking, requiring students to develop feasible solutions to solve local, national, and global problems after learning the basics of STEAM [7]. Kopcha et al. [8] designed a STEAM education program using robots to develop students' computational thinking. Zhang et al. [9] described a STEAM education innovation with different schools carrying out different activities. The research findings in general support the value of STEAM education and report various benefits, such as increased collaboration, enhanced creativity, and the development of scientific inquiry skills [10,11].

Despite its many alleged benefits, STEAM education faces a persistent challenge: STEAM education is difficult to implement and sustain in primary schools, and lacks meaningful interdisciplinary integration [3]. There are several possible reasons: first, qualified teachers for STEAM education are in high demand [12]. At present, most primary school teachers are subject-based [13,14], are only experts in their own subjects, and do not have a comprehensive understanding of all of the content knowledge needed for STEAM education. If multiple teachers are responsible for STEAM teaching, it can lead to patched teaching, in which instructional content is forced together without emphasizing the underlying connections. It is difficult to guarantee the project experience of students in STEAM education as well as teaching effectiveness. Second, the design and implementation of STEAM education is too dependent on researchers, and is not sustainable. Most the current STEAM education has been designed and developed by researchers, and researchers even carry out practical teaching. An obvious problem is that STEAM education ends at the end of the research project. School teachers do not learn how to design and implement STEAM education, and they cannot continue to carry out STEAM education in schools. Third, STEAM education usually exists in the form of comprehensive practice-style education or after-school expansion education, and is not integrated into the formal curriculum of the school. This leads to a lack of attention from teachers and a lack of enthusiasm from students, which leads to difficulty implementing STEAM education in schools.

This study suggests that cooperative teaching may be an effective way to solve these problems. In this study, we propose a teaching model for STEAM education based on the concept of cooperative teaching. To simplify the model's name, we coined the term *Co-Teaching STEAM* to refer to the model throughout the paper. Cooperative teaching means that two or more teachers are jointly responsible for teaching the same student group [15]. Teachers work together to develop a teaching plan, engage in ongoing communication and feedback during the teaching process, and ultimately evaluate students' performance together [16]. The use of cooperative teaching can effectively avoid separation between disciplines, ensure the integrity of the STEAM teaching process, and enable students to experience a complete project process. In addition, in cooperative teaching, each teacher is only responsible for what they are good at and does not need to master all of the knowledge of STEAM education, which provides a solution to the problem of insufficient teachers in STEAM education. However, there is a lack of case studies on effective instructional design principles for cooperative teaching in STEAM.

This study employed a design-based research approach to explore effective instructional design principles for implementing STEAM education in the primary school context. More specifically, we sought to answer the following research questions:

1. What are the benefits and limitations of co-teaching STEAM education?
2. What are the effective instructional design principles of co-teaching STEAM education?

2. Theoretical Framework

The theoretical framework for designing co-teaching STEAM education is informed by the theories of PBL, collaborative learning, cooperative teaching, and scaffolding.

2.1. PBL

Project-based learning (PBL) is a systematic teaching and learning method which engages students in complex real-world tasks that result in a product or presentation to an audience, enabling them to acquire knowledge and life-enhancing skills [17]. PBL emphasizes student-centered and group collaborative learning, requiring students to explore real-life issues, and students' inquiry activities are challenging and constructive [18]. During the PBL learning process, students work together in groups to conduct problem-oriented independent inquiry and to summarize what they have learned through review and reflection to improve group work [17]. STEAM education revolves around a real problem, involving students in small groups conducting research and then communicating the results with their peers [18].

PBL is an appropriate STEAM teaching method, permits the integration and application of STEAM discipline knowledge [19–22], and can provide students with the learning context and problems of knowledge construction and group collaborative inquiry. A good example of STEAM education supported by PBL is the Mars Education Program developed by Arizona State University in the United States, which is divided into four areas, each of which consists of a series of thematic education units that form a curriculum plan covering grades K-12. This includes project activities such as creating models of the solar system, designing rockets, and developing vehicles [23].

2.2. Collaborative Learning

Collaborative learning refers to a learning mode in which students work in groups of two or more to mutually search for understanding, solutions, or meanings or to create a product [24]. Collaborative learning is defined as "the instructional use of small groups so that students work together to maximize their own and each other's learning" [25]. Collaborative learning allows students to work together to explore, constantly find and solve problems, and build knowledge in the process. It is this reciprocal interaction between students in the collaborative learning process and the respect they develop for others' perspectives that enables the exchange of knowledge and the co-construction of meaning to occur [26], enhancing the development of problem-solving, reasoning, and learning [27]. In addition, role allocation in collaborative learning enables students to make different contributions to the team, and can promote positive interdependence among group members.

Collaborative learning is important for STEAM education for several reasons: first, tasks in STEAM education often involve multiple disciplines, and collaborative learning helps to reduce the difficulty of tasks by breaking them down and allowing group members to make different contributions. Second, multiple intelligence theory holds that each student has their own area of strength in intelligence [28]. In STEAM education, collaborative learning is adopted, and the group members have advantages in different intellectual fields, which helps students to conduct independent collaborative inquiry and complete project tasks. Third, in most cases the equipment used for STEAM education is limited, and in order to ensure educational equity, it is necessary to use the device in groups in order for students to adopt a collaborative learning approach.

2.3. Cooperative Teaching

Cooperative teaching refers to a teaching mode in which teachers of multiple subjects form a teaching team, collaborate in teaching design, and maintain continuous communication and feedback in the teaching implementation process to break the disciplinary barriers and improve the teaching effect [16]. The critical feature is that the teachers simultaneously teach for a planned and scheduled part of the instructional day. The essential philosophy undergirding the arrangement is that all teachers are responsible for all students. Cooperative teaching allows teachers to pool their unique perspectives and individual strengths to enable educational changes and reforms that would not otherwise become feasible and sustainable [29].

Cooperative teaching has great potential for STEAM education thanks to its subject integration. This type of teaching task is often beyond the capacity of a single teacher, because most subject teachers are only experts in their own subjects and cannot undertake the teaching tasks required for complete STEAM education [12]. Therefore, it is necessary for teachers from several different subjects to participate in the teaching of STEAM education. A classic example of cooperative teaching is the Synchronous Delivery Classroom described by Luo et al., where experienced Art and Music teachers from urban schools worked closely with rural teachers to deliver quality education to rural students. [30]. However, this is cooperative teaching in an online context; similar examples in face-to-face STEAM context have rarely been reported in the literature.

2.4. Scaffolding

In the field of learning, scaffolding refers to temporary support for tasks that learners may not be able to complete themselves [31]. When learners complete learning tasks beyond their own abilities, the assistance which more knowledgeable people provide to help them is called scaffolding. [32,33]. Scaffolding is necessary for student-centered education for the following reasons: first, research has consistently shown that when students lack prior domain-specific knowledge, they experience problems attempting to solve even well-structured problems [34]. Second, authors have suggested that a learner's cognitive load is reduced with the aid of scaffolding and that this allows the learner to perform parts of a task that he or she would otherwise not be able to perform [35,36]. Third, research findings suggest that the effectiveness of PBL largely depends on whether adequate support for learners is provided, especially for younger students who lack self-regulated learning skills [37,38]. Therefore, it is necessary to provide sufficient scaffolding for STEAM, which is known to be a student-centered and inquiry-based instructional innovation.

2.5. Theoretical Assumptions for Design

On the basis of a literature review, we summarize seven theoretical hypotheses of STEAM education design based on the three dimensions of strategy, task, and process, as shown in Table 1.

Table 1. Instructional design decisions for co-teaching STEAM education.

Dimension		Design Decisions	Description	Theoretical Assumption	Supporting Literature
Task Design	P1	Disciplinary integration	Integrate science, math, technology, arts, and other disciplines into a single task to promote interdisciplinary skills.	Cooperative teaching	[19,20]
	P2	Choose familiar and authentic themes	Tailor task themes to reflect real-life experiences and problems	PBL	[7,39]
Strategy Design	P3	Providing adequate scaffolding and tools	Provide various scaffolding (e.g., worksheets, discussion notes) to facilitate collaboration.	Scaffolding	[35,40]
	P4	Divide students into groups	Students are divided into all-boys, all-girls, and mixed groups for task completion.	Collaborative learning and PBL	[24,25]
	P5	Implement student-centered activities	Promote knowledge construction and meaningful dialogue through shared inquiry.	PBL	[41]
Process Design	P6	Multi-teacher cooperation	Collective teaching by various subject teachers through cooperative lesson preparation.	Cooperative teaching	[15,16]
	P7	Integration into the formal curriculum	Making STEAM part of formal curriculum by assigning its units to related subject classes.	Cooperative teaching	[42,43]

3. Initial Design

Based on the integrated STEAM instructional design principles identified in the literature, we propose the initial design of co-teaching STEAM, as shown in Figure 1. The implementation design process is divided into four stages: preparation, design, enforcement, and display and evaluation. We designed the co-teaching STEAM course by integrating the knowledge of science, technology, mathematics, and arts. The complete course consists of three lessons.

The first lesson focuses on introducing the project and creating scenarios. The science teacher first introduces the scientific knowledge related to myopia, helps the students understand the causes and harms of myopia, and then guides the students to design a questionnaire on the status of myopia, distributed to the whole school's students after class to investigate the status of myopia. The theme of myopia is chosen because it is relevant to students: there is a high rate of myopia among grade six students, and students are familiar with and interested in the theme.

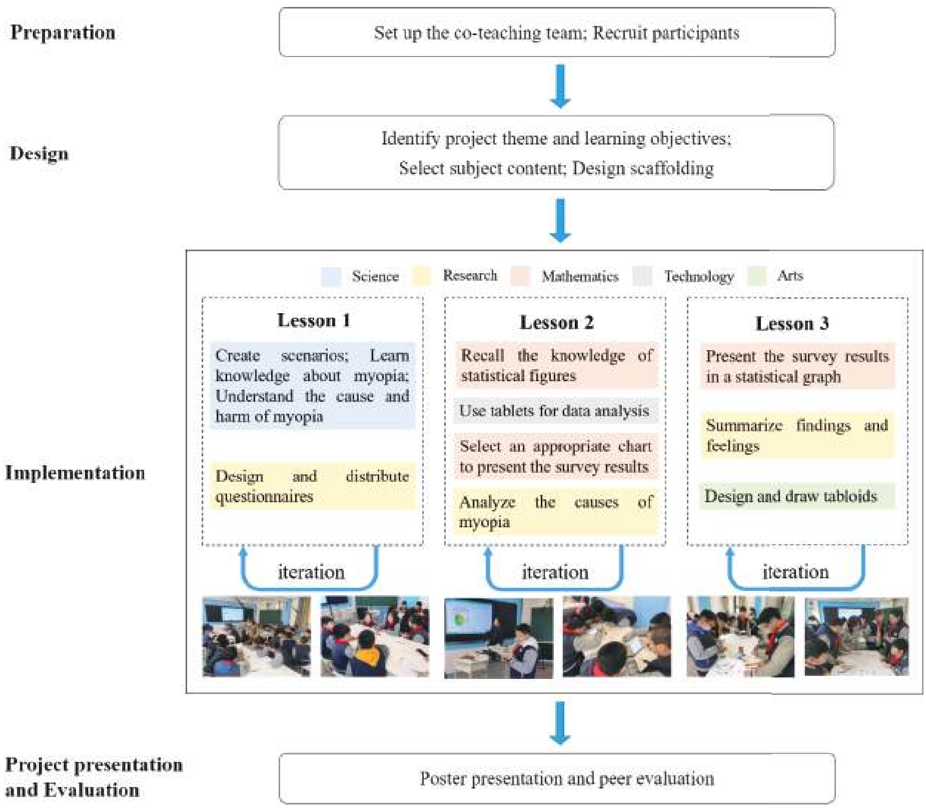


Figure 1. The initial instructional design.

The second lesson is mainly to analyze the results of the questionnaire data. At the beginning of the class, the math teacher guides students to recall the relevant knowledge of the statistical graph, and then the students use a tablet computer to explore independently in groups. The students' main tasks include selecting the appropriate statistical graph to present the survey results, analyzing the possible causes of myopia based on the survey results, summarizing the findings, and sending a group representative to present the findings on stage.

The main task of the third lesson is to design a research poster. Students design posters in groups, present research findings in statistical charts, and use artistic treatments to apply artistic design to the work. Then, through the design, the statistical chart, research conclusions and findings, and final results are presented in the posters, and students add frames, pictures, and other decorations. Finally, the students' group works are displayed in the school and self-evaluation and mutual evaluation are carried out. This lesson is facilitated by an art teacher.

4. Methodology

4.1. Design-Based Research

DBR is a systematic approach that improves educational practices through iterative analysis, design, development, and implementation [44]. It has three cornerstone principles: collaboration with practitioners to solve complex problems in real contexts; proposing plausible solutions to these complex problems based on learning and teaching theory using modern technological means; and implementing solutions in real teaching environments, improving by iteration, and defining new design principles [44]. Therefore, we adopted a design-based research study to verify the effectiveness and feasibility of the design principles over various iterations. We implemented two iterations, collected various types of data for reflection and evaluation, and made improvements to the design. In this way, we hope to contribute to the design and implementation of STEAM education.

4.2. Research Context

The study was conducted at W Primary School in Wuhan, Hubei Province. In order to improve the teaching and incorporate advanced teaching concepts, this school has launched STEAM education; however, due to the lack of systematic teaching design and professional guidance, the previous STEAM education simply combined various subjects and eventually became patched teaching, which failed to achieve the purpose of promoting the integration of disciplines and all-round development of students. We were commissioned by the school and strongly supported by school leaders and teachers to carry out this study.

The teaching practice was carried out in the smart classroom of W Primary School, which adopted a "scattered" seating arrangement and had seven to eight workspaces set up according to the number of students. Each workspace was equipped with two tablet computers. A total of 91 randomly selected sixth grade students participated in the study, with a ratio of about 7:5 boys to girls, aged between 11 and 13 years old. Due to time conflicts and other reasons, 86 students participated fully in the study. In class, six or seven students formed a group, and students in each group sat together, which was conducive for students to carry out group research and complete project tasks together. In order to connect the courses and ensure the integrity of the project, all teachers and teaching support staff were in an observation room for each class. Figure 2 shows the classroom used for this study.

(a) (b)

Figure 2. STEAM learning environment: (**a**) video screenshot of the teaching process and (**b**) students using tablet computers for data statistics and analysis.

4.3. Data Collection and Analysis

This study collected three types of data to evaluate the instructional design: observational data based on video recordings, semi-structured interviews with the students, and commentary from the teachers.

Videos were recorded for each lesson to facilitate subsequent descriptive analysis and critical reflection on the teaching implementation process. Informed by the coding manual of Saldaña [45], we mainly used four types of coding techniques to analyze the classroom videos: (1) structural coding, featuring a list of a priori topical codes such as cooperative teaching, collaborative learning, and interdisciplinary integration; (2) process coding using gerunds to connote sequential teaching and learning actions such as attention grabbing, task description, lecturing, practice, interaction, and presentation; (3) emotion coding labelling learning experience in terms of positive (e.g., curious, engaged, proud, pleased, etc.) and negative (distracted, indifferent, confused, etc.) emotions; and (4) evaluation coding using tags of "+", "−", and "REC" to indicate strengths, weaknesses, and suggested revisions to the STEAM design.

Another important data source was semi-structured interviews with the students. After each class session, we purposefully selected 6–8 students to participate in interviews based on their classroom performance. The semi-structured interview outlines normally comprised the following six aspects: basic student information, interdisciplinary knowledge, perception of collaboration, role allocation, scaffolding, and the performance of both group and self. Additionally, we collected comments from the teachers during class preparation and post-class debrief. The commentary data reflected the teachers' evaluation of and reflection on the STEAM design and implementation. They provided valuable insight for continually refining the STEAM resources, activities, and sequence. The semi-structured interview questions are listed in Appendix A.

5. Results

5.1. First Lesson

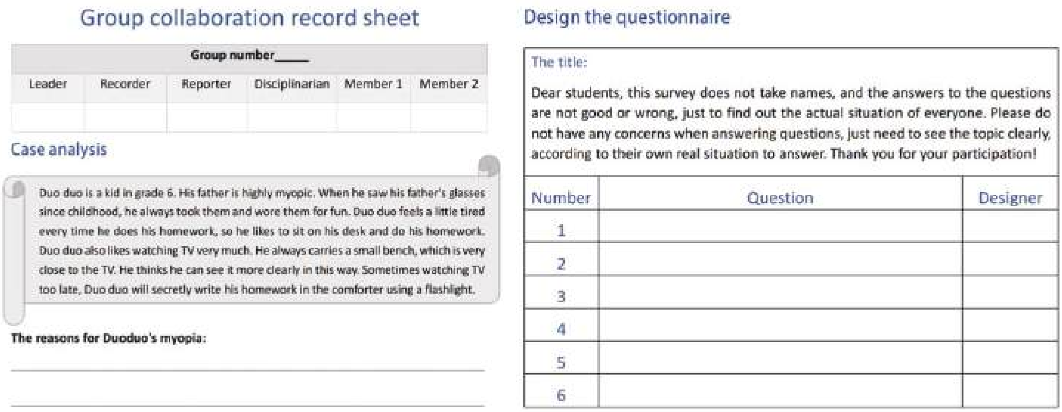
5.1.1. First Iteration

On the whole, the lesson went according to our expectations. The classroom atmosphere was good, students were active in answering questions, and the group discussion was full of enthusiasm. The science teacher first introduced the theme of myopia with riddles, videos, and pictures to let students understand the impact of myopia. After the presentation, the teacher provided a case study, and the students had enough time to discuss and explore this. Then, based on the previous exploration, the teacher guided students to design a questionnaire about the status of myopia.

However, we found some problems with the implementation of the course. First, we found that the course content seemed too easy for the students. The students in grade six already knew what behaviors might cause myopia and had common knowledge about the harms of myopia. Several students gradually lost interest in the class. Second, in the process of discussion, some students actively expressed their opinions, while others were often silent and did not participate in the discussion. In addition, with no clear assignment of tasks, discussions sometimes descended into confusion. As commented by the science teacher, "the students liked to argue, and no one kept order in group work nor recorded the results of group discussion." Third, it seemed that the final report of the group was not related to the discussion content. The reporter only expressed their own opinion without integrating the opinions of the group members, which led to a lack of participation and sense of achievement for other members; the reporter may not have remembered what the other panelists said. In addition, since the results of the discussion were not recorded, statements from different groups were repeated. Fourth, due to the lack of relevant types of course experience, most students just took this lesson as an activity class and did not understand the entirety of the STEAM project or understand the project process.

5.1.2. Reflections on Instructional Design

In view of the problems found in the first iteration, we made the following modifications to the instructional design. First, we introduced the complete project process in class. We explained the complete project-based learning case so that students could understand that they were participating in a complete project. The first lesson presented the basic knowledge, learning, and investigation of the project. Second, in view of the problem that the content of the course was too simple, we added relevant information about the refraction and reflection of light and the principle of human eye imaging to stimulate students' thirst for knowledge. Third, we used role allocation to divide the group members into five categories (group leader, recorder, reporter, disciplinarian, and group member) to increase the positive interdependence among the group members and avoid confusion in the discussion. Fourth, we added scaffolding and provided a group collaboration record sheet (as seen in Figure 3) for each group to help students record the ideas of group members in a timely manner, integrate group opinions, and report the results of group discussion.


Group collaboration record sheet

Group number_____					
Leader	Recorder	Reporter	Disciplinarian	Member 1	Member 2

Case analysis

Duo duo is a kid in grade 6. His father is highly myopic. When he saw his father's glasses since childhood, he always took them and wore them for fun. Duo duo feels a little tired every time he does his homework, so he likes to sit on his desk and do his homework. Duo duo also likes watching TV very much. He always carries a small bench, which is very close to the TV. He thinks he can see it more clearly in this way. Sometimes watching TV too late, Duo duo will secretly write his homework in the comforter using a flashlight.

The reasons for Duoduo's myopia:

Design the questionnaire

The title:

Dear students, this survey does not take names, and the answers to the questions are not good or wrong, just to find out the actual situation of everyone. Please do not have any concerns when answering questions, just need to see the topic clearly, according to their own real situation to answer. Thank you for your participation!

Number	Question	Designer
1		
2		
3		
4		
5		
6		

(a) (b)

Figure 3. Group collaboration record sheets (translated version): (**a**) group collaboration record sheet for the first lesson and (**b**) part of the questionnaire design sheet.

5.1.3. Second Iteration

Compared to the first iteration, the second iteration went more smoothly. The science teacher first introduced the whole process of activities for the project, and helped the students understand with examples of project-based learning. In the knowledge explanation session, in response to the addition of the new information, the students showed great enthusiasm for learning. When we observed the videos of the class, we found that the frequency of students' minds wandering decreased significantly. In the interview, some students said that they were interested in the information about light reflection and refraction. "Although the reflection and refraction of light is the knowledge of junior high school, presenting it in the form of interesting videos can not only stimulate students' curiosity, but also expand their knowledge quickly", said the science teacher. In the group collaboration, the addition of role allocation and scaffolding made the discussion more efficient. Role allocation made every member actively participate in the discussion. For example, one group leader stopped two group members from chatting and invited them to express their opinions. In order to fill out the group collaboration sheet, the recorder took down the group members' opinions carefully, and the reporter combined the results of the group discussion when speaking. However, the students who had no speech task were not focused. In general, the effectiveness of group collaborative learning was greatly increased, the completion of group tasks was higher, and students had a clearer understanding of the purpose and significance of the whole project.

5.2. Second Lesson

5.2.1. First Iteration

In the second lesson, we introduced tablet computers as a tool for students to conduct data analysis. Before the beginning of the lesson, training on the basic operation of the tablet computer was carried out to eliminate the influence of prior knowledge differences and novelty effect. The teacher first showed the project process chart, explained the activity content of the lesson, and then led the students to recall the characteristics and application of different statistical charts. Next, the teacher asked a student to demonstrate how to use a tablet computer to generate statistics. After informing students of the group tasks and the location of the data resources, students began to use the tablet computers to conduct independent inquiry.

We found some problems in the process of course implementation. First, the teacher's teaching time was too long, resulting in the class running seriously overtime (75 min), and there was no time for presentation and reporting. Second, each group needed to analyze five problems. The task was too large, and some groups failed to complete the task. "Most groups did not complete the data analysis task, so I could not advance the class process," the math teacher said during the post-class debrief. Third, the scaffolding was not detailed enough. In the conclusion and discovery part of the task list, there was no hint; students did not know how to start and wrote a lot of irrelevant content, which impacted the learning effect. Fourth, some group members were busy with tablet computers and did not participate in the discussion. Other group members were unable to operate tablet computers and could not see the data, and they were not able to participate in the discussion.

5.2.2. Reflections on Instructional Design

In view of the problems found in the first iteration, we made the following modifications to the instructional design: first, we limited teachers' teaching time to fifteen minutes and eliminated the session for students to demonstrate how to use tablets. Students had already learned about statistical graphs, and the focus of the second lesson was on students' own exploration, so we provided as much time as possible for students. Second, we assigned different groups to analyze data from different segments, and each group independently selected three questions for analysis and exploration to reduce workload. Third, we further refined the task list and provided necessary hints and guidance in the form of triggering questions to ensure that students would head in the right direction. Fourth, we added the role of tablet operator to avoid future conflict between students fighting to use the tablets, allowing attention to be focused on task completion.

5.2.3. Second Iteration

On the whole, our improvement promoted the smooth and orderly progress of the class, and all class activities were mostly completed within the stipulated time. The reduction in teaching time did not affect students' exploration and collaboration, and provided students with enough practice time. Furthermore, limiting data analysis to a specific sample segment rather than the whole school reduced the workload and ensured that students could concentrate on completing group tasks. Providing students with the freedom to choose their own questions better modelled the student-centered education concept and improved students' enthusiasm. However, disputes arose due to different opinions. For example, one boy in group five insisted on choosing "the relationship between genetics and myopia", while the other group members agreed that it would be better to choose "the relationship between time spent using electronic products and myopia".

Moreover, by adding guiding questions on the scaffolding, students could direct their thinking and analyze the problems more deeply (as shown in Figure 4). However, this practice may have limited students' thinking to an extent. We found that different groups had a high degree of similarity in analyzing questions, which may be because students' thinking was confined to the guiding questions. Lastly, the increased the role of the operator made the division of collaboration clearer, exploration more efficient, and was more conducive to the completion of group tasks. After the operator used the tablet computer to generate the chart, they observed the chart and analyzed the data with other members to ensure that every member of the team participated in the discussion and expressed opinions, thus avoiding the problems of students competing to use the tablet computer and lack of communication.

Announcements

1. Use a tablet computer to generate graphs that are appropriate to the characteristics of the data.
2. The recorder fills in the survey record form according to the group discussion results.
3. The recommendation group representative reports the results.

Record form	
Survey grade	Grade one and grade two
Survey problems	Conclusions and Findings
Continuous use of the eyes for more than forty minutes	How do myopic students use eye circumstances? How do you feel about that? 56.52% of the students chose "occasionally", while 43.48% chose "often". Thoughts: More students chose "often", while fewer chose "occasionally". The myopic students at the lower learning level were less likely to use their eyes for more than 40 minutes.
Nearsightedness of parents	What is the difference between the myopia circumstances of the parents of myopic students and not myopic students? How do you feel about that? The myopia rate of parents of myopic students is high, and that of parents of not myopic students is low. Thoughts: Whether myopia is concerned with parents. (Myopia can be inherited)
Sitting correctly while reading and writing	What is the difference between the sitting position of myopic students and that of not myopic students? How do you feel about that? Myopic students are more likely to sit incorrectly. Thoughts: Myopia and sitting position have certain relation, we must standardize sitting position.

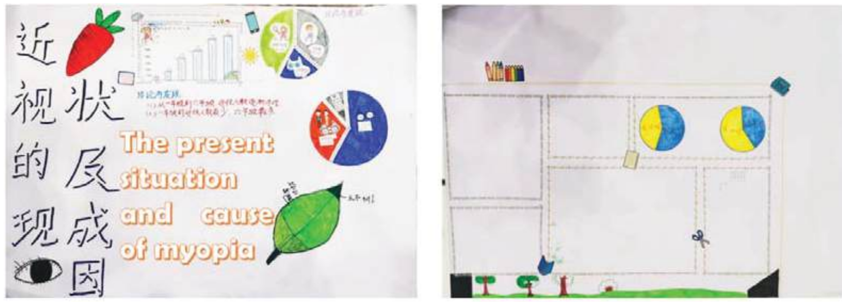
Figure 4. Group work record form for the second lesson (translated version).

5.3. Third Lesson

5.3.1. First Iteration

The third lesson, as a whole, followed our plan. The students showed great interest and most of them were able to focus on completing the group posters. The art teacher first led the students to recall the content of the former two lessons, then explained that this lesson was the last lesson of the project and that the main activity was to design a poster to display the survey results of the project. In order to provide a reference for the students to create posters, the teacher explained the design method of posters and the elements that should be included, and showed examples of finished posters. Next, the students began to design their own posters. At the beginning, all the students were enthusiastic and actively involved in the creation. After a period of time, only some students were working hard, while others began to play, and the whole class was chaotic. "I often have to maintain order to ensure the smooth progress of the class," the art teacher told us afterwards.

Although we learned from the experience of the first two classes and extended the length of this lesson, by the end of this lesson none of the groups had finished making their posters (as shown in Figure 5). We summarized the reasons as follows: first, the materials provided were not interesting enough. While we provided stickers, frames, and other decorations, they did not meet the needs of students. Most students chose to draw by themselves, which wasted time. Coloring and writing wasted a large amount of time as well. Second, although role allocation was conducive to the division of labor and collaboration in the group, it caused new problems; team members only focused on their own tasks, and did not help other members. The work of each member was linear, which affected the overall process on the group task. For example, we found many designated frame-painters became alienated during the collage creating process, distracted by irrelevant activities such as chitchat when it was not their turn to work.



(a) (b)

Figure 5. Student work in the first iteration: (**a**) the poster created by Group No. 8; (**b**) the poster created by Group No. 2.

5.3.2. Reflections on Instructional Design

In the second iteration, we made the following improvements to the instructional design of the third lesson: first, we added knowledge related to ring graphs into the teacher's explanation, provided a design case of a ring graph, and encouraged students to replace the pie graph with a ring graph so as to reduce the coloring area and save time. Second, we provided more abundant scaffolding, including tailored colored cardboard, faster coloring with thick pens, and designed artistic characters and statistical charts of coordinate axes to reduce the time occupied by simple labor and to help students concentrate on the design of the posters. Third, we emphasized the importance of teamwork and encouraged students to help each other instead of just being stuck in the tasks of their roles.

5.3.3. Second Iteration

After making improvements, the second iteration went well, and each team completed the design and production of posters within the specified time. The scaffolding we provided saved time and increased the efficiency of the posters. As several students said in the interview, "Colored paper and calligraphy help us a lot. We don't need to cut and write by ourselves, which saves a lot of time." After that, we exhibited students' works in the whole school. The group leader explained the design ideas and concepts of the group project, and different groups evaluated each other. Examples of the groups' work and the exhibition scenes are shown in Figure 6.

(a)

Figure 6. *Cont.*

(b)

Figure 6. Work presentation and group review scene: (**a**) examples of one group's works; (**b**) the group leader explaining the work of the group.

6. Conclusions and Implications

This study showed that cooperative teaching can be used to facilitate STEAM education in the primary school context. It was able to promote meaningful discipline integration and address the shortage of STEAM teachers. Based on its positive impact on STEAM education, five instructional design principles are put forward. The following section elaborates on those research findings. The findings contribute to scholarly research by proposing instructional design principles for STEAM education supported by cooperative teaching.

6.1. Benefits and Limitations of Co-Teaching STEAM Education

Based on this case study, we believe that the benefits of co-teaching STEAM education are characterized by the following two aspects. First, it can alleviate the severe shortage of STEAM education teachers. In the current educational environment, teachers are used to teaching by subject, and it is difficult to master multidisciplinary knowledge in a short time. Cooperative teaching allows teachers to focus their limited teaching preparation time on the subject knowledge they are familiar with in order to prepare more comprehensively for teaching. At the same time, continuous communication and collaboration between teachers in cooperative teaching ensures the integrity and consistency of STEAM projects and promotes meaningful discipline integration. Second, STEAM education in the form of cooperative teaching can arouse students' interest and promote teachers' professional development. As a student said in an interview, "I like this kind of class and hope to attend similar courses in the future," and "I like this kind of lesson very much, and different teachers make me full of expectations for each lesson." For teachers, the participation of teachers from different disciplines in the development and implementation of STEAM courses can make up for a lack of knowledge in other disciplines. "In the collaborative process, I have gained a certain understanding of other disciplines, which is also a kind of growth for me," one teacher said in the interview.

However, there are challenges with STEAM education supported by cooperative teaching which may hinder its adoption in the primary school context. First, this teaching mode places a lot of demands on teachers. They need to cooperate with each other, actively participate in curriculum development, and maintain continuous communication with each other. In addition, teachers are required to accept and embrace more advanced educational ideas. Second, it may affect normal course progress. While integrating STEAM education into the formal curriculum can increase the attention of teachers and students to STEAM and promote its development in primary schools, it may lead to failure to complete teaching tasks on time due to the occupation of class time and teachers' energy.

6.2. Implications for Instructional Design

Based on the research results, we propose the following five instructional design principles for implementing STEAM education supported by cooperative teaching in the primary school context:

1. Use cooperative teaching to solve the shortage of teachers in STEAM education. A big reason that STEAM education is difficult to implement in the primary school context is that it cannot achieve true discipline integration. On the basis of operability, cooperative teaching can maximize the integration of disciplines and promote STEAM education in primary schools.
2. Provide adequate and detailed scaffolding to support learners' collaborative learning. Well-designed scaffolding is essential for the smooth implementation of student-centered learning and collaborative inquiry, especially for young students with limited self-regulation skills. In our study, students were provided with example scaffolding to illustrate the project process and task requirements, guidance scaffolding to assist in the exploration task, and tool scaffolding to complete the group work.
3. Select practical problems that students are interested in and familiar with as the theme of the project, and control the difficulty and complexity of the task reasonably to enhance learning motivation and increase participation. This study took myopia, which is very familiar to students, as the project theme, integrated relevant knowledge of science, mathematics, technology, and arts disciplines into it, and allowed students to participate in a complete scientific research process. Through the different iterations, the content and timing of lessons and group tasks were adjusted.
4. Integrate STEAM education into the formal curriculum and put it into the curriculum schedule together with general subject courses. In this study, for example, the three lessons were all conducted in normal class hours rather than after-school expansion lessons. It has been proven that this reduces the workload of teachers and increases their enthusiasm to carry out STEAM education.
5. Appropriately extend the length of a single instructional session to meet the needs of teacher guidance, students' independent exploration, and communication evaluation. The third lesson of the study, which requires students to create posters, is more appropriate for a 90-min class than the typical 45-min class.

6.3. Research Limitations and Future Research Agenda

The current study has several limitations. First, the study was conducted in two classes from a single grade using a specific project task, and the findings might lack transferability to other educational contexts. Second, the research only carried out two iterations, and the instructional design needs to be improved. The specific operation mode and process for implementation for multidisciplinary cooperative teaching are not clear enough, and require further in-depth research. Third, the research results are entirely from qualitative data and lack any collection and analysis of quantitative data. Therefore, we suggest that future research should design more iterations to further improve the instructional design and determine the implementation steps and specific processes of STEAM education supported by cooperative teaching. In addition to processing qualitative data, quantitative data such as project scores could be collected to support future research results.

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Data Availability Statement: The data presented in this study are available from the corresponding author on reasonable request.

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Appendix A. Semi-Structured Interview Questions for Students

1. What's your name? Have you ever taken a STEAM course like this before?
2. In your opinion, what are the unique characteristics of this STEAM course? What makes it different from other courses such as math, science, and art?
3. What do you think of teacher cooperation in this course? What influence does it bring to your learning in the STEAM course?
4. What did you find most interesting about the whole project? What are the things that you dislike?
5. The course is in the form of group collaboration. What was your experience of working together with others? Which class yields the best collaborative experience?
6. During the project, what difficulties did your group meet in the collaboration process? Were these difficulties resolved successfully in the end? How was it resolved? (If not, what do you think are the reasons for failing to resolve it?)
7. Which learning mode do you prefer, learning with your group members or individually? Why is that?
8. What do you think are the differences between boys and girls in the collaborative learning process? Can you provide an example?
9. What do you think of the role assignment strategy? Did it help you work together on tasks? Can you provide an example?
10. What was your role in the design of the poster? How do you feel about your role? (The interviewer could ask further questions: On a scale of 10, how would you rate your performance in your assigned role?)
11. Do you think the learning materials such as collaboration sheets, task sheets, and charts provided by the teacher are helpful for the completing the project? What did you dislike about it?
12. Overall, are you satisfied with your group work? What do you think of your own contribution and the performance of other group members?
13. What subject content knowledge have you learned from participating in this STEAM course? Please elaborate.
14. What else have you learned from this STEAM course?

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Searching for Pedagogical Answers to Support STEM Learning: Gender Perspective

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Abstract: This article analyzes the results of a study on the situation concerning the educational achievements of girls and boys in the STEM field in Latvia. The study was conducted at the compulsory education level to understand the conditions in the learning environment that can predictably affect the academic achievements of girls. For the purposes of the study, a survey questionnaire was developed, which was filled out by 1847 students from the 7th–12th grades. The obtained results show which factors affect learning achievement in STEM subjects for students with low and high learning achievements in groups divided into boys and girls and which pedagogical activities can predictably improve STEM learning achievements. The research data confirm that there are differences in predicted learning achievements in groups of boys and girls with high learning achievements, depending on the pedagogical strategy used. Additionally, the results of the study confirm that the most significant factor for a predictable increase in learning achievements in the STEM field is students liking mathematics and, in the case of high learning achievements, them liking chemistry. An indicator that has a significant negative impact on academic achievement in STEM subjects is a dislike of physics, which appeared in the group of girls with low academic achievements. Liking other STEM subjects to improve student achievement did not appear statistically significant in any of the analyzed groups. This study is essential to supplement the knowledge base on gender differences in learning achievements in STEM subjects and is also important for the educational space of Latvia because the learning achievements of girls in the STEM field are lower in this country than it is for boys. The obtained results show which methods of pedagogical work have a higher impact on increasing the predicted learning achievements and also show potential future research directions.

Keywords: gender differences; STEM; learning outcomes; compulsory education; pedagogical methods

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1. Introduction

It is known that there are relatively few women in the field of STEM (Science, Technology, Engineering, and Mathematics) [1–3] and that girls generally have lower academic achievement in STEM subjects [4,5]. There are many studies in which researchers have tried to find answers that explain the fact that girls both have lower academic achievement in the the STEM field and are still not choosing to study it in depth. Some studies have found evidence that stereotypes play a big role [6]. As a result, girls develop a negative attitude toward mathematics and other STEM subjects and this attitude, in turn, affects girls' academic achievements and whether they will choose to learn in-depth knowledge related to this field. This attitude is formed under the influence of teachers and parents [7] because they are three times more likely to associate STEM sciences with boys than with girls and these beliefs are internalized by the children they are with on a daily basis [8]. The majority of girls have to face gender discrimination in one of its forms as early as their teenage years and, while this is most often from their peers, it is often also from adults with whom the children are together with on a daily basis—teachers, school staff, and even parents [7,9]. This experience can be of different levels of intensity, including when experiencing a stereotypical attitude, when faced with seemingly innocent comments about their appearance, and they can be offensive gestures or involve ignoring the female's expressed opinion.

2. Literature Review

Gender stereotypes have been found to affect girls who are considered gifted in STEM fields [10] because stereotypes in society can influence their choices and girls who do well in STEM have been found to choose a career in the humanities, life sciences, or social sciences instead of computer science, engineering, mathematics, or physics [6,11]. This is linked to regular expressions of microaggressions, which contribute to the fact that not everyone has equal access to STEM knowledge and contributes to the perception among girls that the STEM field is not for them [12,13]. The term "microaggression" was coined by Pierce (1970) [14] and, since then, there have been countless studies showing that it has a significant impact on underrepresented groups, which in the context of this study are girls in the STEM field. Both microassaults and microinsults accumulate and, over time, females begin to feel less capable in engineering because they feel marginalized, ignored, or even prevented from working on more serious projects in the STEM field [15]. The impact of microaggression on girls' choices is surprisingly high and it has been shown that girls exposed to microaggressions (compared to a control group) indicated a significantly lower desire to choose a career related to STEM [16,17].

Kessels (2005) [18] and Hannover and Kessels (2004) [19] concluded in their research that girls who like and are good at physics are considered more masculine and that the girls themselves perceived themselves as unpopular among boys. The boys' answers to the questions asked by the researchers also showed that they do not like girls who are interested in physics. Another study concluded that girls lose interest in STEM at the age of 10–15 [20]. The results of these studies may be one of the explanations why the break in girls' interest in the STEM field occurs precisely in adolescence, that is, when children begin to feel a romantic attraction toward each other, but there is no exact answer to the question of how to maintain this interest using pedagogical methods in the daily learning process.

Girls who believe that STEM is a subject for girls are better able to resist the discrimination and stereotyping they experience and this does not affect their motivation to study [21]. It is important to understand how to promote the development of motivation because it has been found that those students who have already developed a negative attitude toward STEM and who are indifferent to their learning achievements are no longer affected by various stereotypes [22]; these findings point to the importance of being purposeful in order to maintain this motivation toward STEM.

There are researchers who believe that apart from the influence of parents and educators, the surrounding environment is also important. For example, females who are in minority conditions showed a deficit in accuracy vis à vis females who were placed in same-sex conditions [23]. Additionally, setting the environment so that there are many references to the role of women, which can be expressed in the choice of learning materials or the colors of learning spaces and materials, can affect the learning achievements of girls [7,24]. One study experimentally demonstrated both that the pre-test information girls receive can lower their performance on that particular test and even that telling girls before the test that girls tend to perform lower academically on these types of tests can result in lower scores, but if such information is not provided before the test, then the results do not differ between boys and girls. This experiment also proved that negative self-esteem has an impact on academic achievement [22]. Similar conclusions were reached in another study, which found that boys and girls show equivalent learning results when their gender identity is not activated [25]. This evidence clearly shows that stereotypes have a huge impact on academic achievement and that girls' academic achievement can be identical and surely also superior to that of boys, so there is no biological basis for differences in academic achievement.

Sometimes there are ideas that it is necessary to organize the learning process differently for girls and that perhaps STEM lessons should be organized in gender-separated groups. However, such a division is opposed by the results of studies that confirm that working together in mixed-gender groups contributes to a more inclusive environment [26] and can reduce gender stereotypes [27], which is contrary to research that shows girls can achieve higher results if they can work in a single-gender group [23]. The only way to resolve this contradiction is to reduce stereotypes and microaggressions against girls in the STEM field because gendered groups contribute to the formation of stereotypes.

It is essential for educators to be aware of the possible influence of stereotypes on academic achievements in the group of girls, as well as of various manifestations of microaggressions, which gradually push girls out of the STEM field. It is essential to apply pedagogical work strategies that have a positive outcome to the learning achievements of all students because the teacher's pedagogical activity can be both a support point and can create barriers for girls' achievements in the STEM field [28–30].

The objective of the present research is to analyze the data obtained and understand which pedagogical methods predictably have the greatest potential impact to increase academic achievement in the STEM field. Initially, the article analyzes the relevant literature on girls in STEM, then it describes the methodology used, the research design, and the findings, then discusses what was learned. This paper adds to the literature in several ways. First of all, these data were obtained in one specific country where, until now, no studies have been conducted on the factors that can increase educational achievements in the STEM field and it is important to understand whether the results of the study resonate with those conducted in other countries. Second, it compares several groups of students: students with high and low academic achievements and high- and low-achieving boys and girls. These data will enable the modeling of pedagogical processes to remove barriers to girls entering the STEM field. The results of this study will expand the understanding of attitudes toward STEM, academic achievement, and the meaning of pedagogical work from a gender perspective.

3. Disclosure of Context

This article is based on data obtained from European Social Fund Project No. 8.3.1.1/16/I/002, "support for the implementation of national and international events for the development of educational talents", but it should be pointed out that it only analyzes the data that provide answers as to which pedagogical methods have the greatest potential impact on improving academic achievement among groups of high- and low-achieving girls and boys in the STEM field. The rest of the data will be analyzed in future articles.

4. Methodology

For the purposes of this study, a survey questionnaire was developed, which included questions about student demographics, their learning achievements in STEM subjects in the previous semester, what subjects the students like, which activities in the classroom they consider to have an impact on their learning achievements, and which pedagogical work methods they recommend teachers use to improve learning achievements in STEM subjects. The questionnaire was developed based on results of the literature analyses on aspects that influence learning achievements in STEM. In the first step, the questionnaire was piloted with a small group of students (N 114). After the piloting phase, the results were discussed in the project group to agree on necessary corrections of the questionnaire. After the piloting phase, the necessary changes were performed and the questionnaire was distributed to the students.

The purpose of this project was to analyze girls' learning achievements in physics and mathematics, but the boundaries of the research were expanded in the survey, for example, by providing the survey questionnaire to both boys and girls, including questions about a wide range of subjects, and sending it to all schools in Latvia. The data analysis takes into account not only the answers of girls with high academic achievements but also the answers of all girls and boys who participated in the survey. Regression calculations include not only mathematics and physics but also chemistry, computer science, programming, and biology. The data were obtained from 1847 students. Participation in the survey was voluntary and students could stop filling out the questionnaire at any time. Students from the 7th–12th grades were invited to participate in the study; there are two reasons for this. Firstly, schools start teaching such subjects as physics and biology from the 7th grade, prior to which they are included in the one subject of science. Secondly, 7th-grade students have reached the age of 13, which, according to the legislation in force in Latvia, is the age when a student can make an independent decision to answer the questions asked in a questionnaire if it does not require them to disclose sensitive information about the state of their health, family situation, etc. The data were analyzed to identify factors that have a statistically significant impact on academic achievement in STEM subjects by performing calculations both for the entire group of respondents and after dividing students, firstly, into groups with low and high academic achievements and, secondly, into groups of boys and girls irrespective of their academic achievements.

All ethical norms have been observed in the study and the anonymity of the respondents is guaranteed. The obtained data have been analyzed only in an aggregated form. The survey was administered through Google Sheets and the results were then transferred to SPSS for data calculation. The data calculation descriptive statistics and inferential statistics—regression analysis methods—were used to find out the extent to which the factors identified have an impact on learning achievement, which is the basis for further learning achievements.

5. Results

To be sure about the reliability of data, the Cronbach alpha was calculated for items used in the analyses and the results show that there is good internal consistency. It was 0.620 for the learning subjects that the students had to evaluate and 0.832 for the items that indicate different pedagogical strategies.

The questionnaire was filled out by 1847 students, of whom 1190 were girls and 657 were boys. Students could also choose the answer that they did not want to indicate their gender, but none of those who answered this question marked this option. The distribution of the number of respondents by their class group is even and there were 322 (17.4%) students from 7th grade, 426 (23.1%) from the 8th grade, 293 (15.9%) the 9th grade, 313 (16.9%) the 10th grade, 266 (14.4%) the 11th grade, and 227 (12.3%) from the 12th grade.

Students were asked to evaluate their attitudes toward different subjects on a 5-point Likert scale, where 1—I do not like it at all; 2—I do not like it much; 3—I am indifferent; 4—I like it; and 5—I like it a lot. The results of this evaluation show what subjects they prefer (see Figure 1) and these confirm that there are gender differences: girls mostly do not like physics and ICT and prefer arts, while boys mostly like sports and ICT.

The students were asked to evaluate the classroom environment by assessing what was offered to them that affected their desire to learn (see Table 1). The students had to rate their assessment using a 5-point Likert scale, where 1—it does not influence me at all; 2—it rarely influences me; 3—it sometimes influences me; 4—it influences me quite often; and 5—it influences me very often. It can be seen that girls in general evaluated all the proposed statements to be slightly more influential. Boys rated the opportunity to work in groups with their friends and the willingness of their classmates to learn higher than girls, but these differences are not statistically significant. The collected data show that the highest-rated factor was "the teacher helps me if I do not understand something" (M for girls = 4.61; M for boys = 4.32), which is not surprising since the teacher's role is to help students. The factor that has the least influence on the desire to learn is "if my classmates also want to learn a lot" (M for girls = 3.19; M for boys = 3.24).

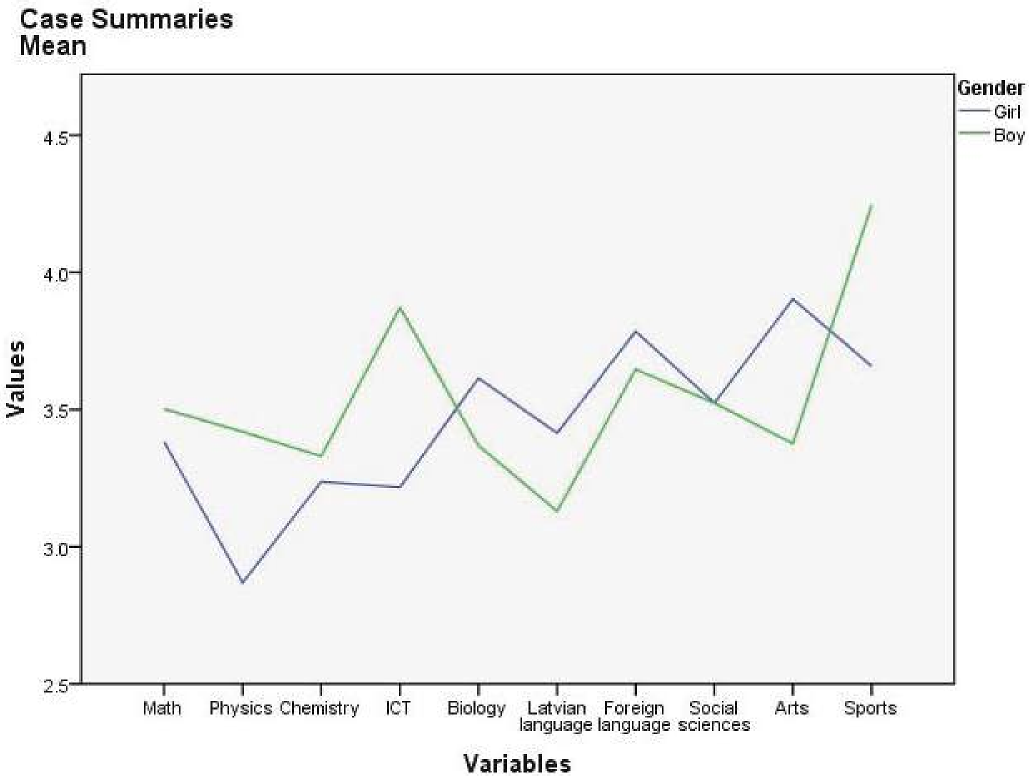

Figure 1. Students' attitudes toward learning subjects.

Table 1. Assessing factors affecting students' desire to learn.

	Girls		Boys		Total	
	Std. Deviation	**Mean**	**Mean**	**Std. Deviation**	**Mean**	**Std. Deviation**
The teacher conducts the lessons in an interesting way	4.40	0.790	4.17	0.901	4.32	0.838
The teacher comes up with various interesting activities	4.01	0.991	3.98	0.969	4.00	0.983
The teacher is fair to all students	4.38	1.446	4.10	1.035	4.28	1.321
The teacher is kind	4.37	0.843	4.06	0.947	4.26	0.894
The teacher helps me if I do not understand something	4.61	0.683	4.32	0.863	4.51	0.765
I am clear about how my work is evaluated	4.02	0.973	3.78	1.085	3.94	1.021
I can work individually	3.79	1.103	3.60	1.122	3.72	1.113
I can work in a group with my friends	3.84	1.143	3.91	1.115	3.86	1.133
I can work in a group with classmates of my own gender	3.24	1.401	3.32	1.338	3.27	1.379
I can work in different groups	3.50	1.207	3.50	1.187	3.50	1.199
I can succeed at what I do	4.33	0.870	4.05	0.967	4.23	0.916
If I can challenge myself with difficult tasks	3.50	1.144	3.56	1.084	3.52	1.123
If my classmates also want to learn a lot	3.19	1.281	3.24	1.239	3.21	1.266
If I know where to look for information	4.26	0.912	4.06	1.008	4.19	0.951

In the subsequent stage, students with high learning achievements in STEM subjects (math, physics, chemistry, and ICT), as well as biology, were separated, and these students were then subdivided into two groups: those whose grades in these subjects are 7.5 (out of 10) and below (students with low academic achievements) and those whose grades are 7.51 and above (students with high academic achievements).

The regression analysis includes questions about what subjects the students like, offering a choice of 10 subjects, and which of the 14 offered activities that take place in the classroom (see Table 1), in their opinion, affect students' learning achievements in STEM subjects.

Initially, the results of the group of students whose learning achievements in STEM subjects are lower than 7.5 were analyzed. The obtained results show that there are four statistically significant models that have an impact on the predicted learning achievements of students in STEM subjects. The ANOVA calculations show that all four models are statistically significant, but Model 4 has the greatest impact on increasing student learning achievements. The overall regression was statistically significant and results for the fourth model are as follows—R2 = 0.71, F = 4.132, $p \leq 0.043$.

As can be seen from regression analyses (see Table 2), the beta coefficient shows that the higher predictable outcome in STEM subjects is liking mathematics and the indicator "the teacher helps me if I do not understand something" in all models. In the fourth model, which has the most influential liking of mathematics, can increase learning achievements by 1.4, help of teachers by 2.12, and the possibility to succeed by 0.87. It can be concluded that students expect teachers to be kind, but it does not predict an increase in learning success. Students expect that teachers help them if they do not understand something, which is a strong predictor of learning success. This confirms that focused teacher support is needed more than just a kind personality, which does not support the learning of students whose learning outcomes are not high. In all of these models, liking mathematics emerges as a factor that predictably improves learning outcomes, implying that there is a strong emphasis on students being good at mathematics to predictably improve learning motivations across the STEM field.

Table 2. Coefficients_Low achievers_subjects_all students.

Model	Unstandardized Coefficients Beta	Standardized Coefficients Beta	Sig
(Constant)	5.169		0.000
Mathematic	0.140	0.170	0.000
The teacher helps me if I do not understand something	0.212	0.196	0.000
The teacher is kind	−0.129	−0.132	0.007
I can succeed at what I do	0.087	0.092	0.043

Next, regression calculations were performed for this group of students with low academic achievement in STEM subjects about the methods they would recommend teachers use and their predicted effects on academic achievement in these subjects. Students had to evaluate nine methods (group work, experiments, reading, etc.) on a scale from "never" to "all lessons" and the obtained results show that a statistically significant model for a predictable increase in learning achievement is "if teachers use individual tasks" and "if teachers ask us to analyze different examples". The overall regression was statistically significant and results for the second model are as follows—R2 = 0.33, F = 7.22, $p = < 0.007$. The R-square calculations show that the combination of such methods would predictably increase learning achievements in STEM subjects by 3.3%.

The beta coefficient shows that using "individual tasks", the assessment will increase by 1.25 points, and when using "analysis of examples", the assessment will increase by 1.26 points for the group of students with low learning achievements in STEM subjects (see Table 3).

Table 3. Coefficients_Low achievemers_suggestions_all students.

Model	Unstandardized Coefficients Beta	Standardized Coefficients Beta	Sig.
(Constant)	5.676		0.000
Individual tasks	0.125	0.121	0.005
Analysis of examples	0.126	0.116	0.007

Dependent Variable: Avg_5.

The next group analyzed was the students who have high learning achievements (over 7.5) in STEM subjects. In this group, two patterns emerge that predictably increase academic achievement, which are liking mathematics and chemistry. The ANOVA calculations show that both models are statistically significant and the R-square results show that for high-achieving students in the defined subjects liking mathematics and chemistry predictably increases their academic achievement in all STEM subjects by 7.6%, which confirms that the most important thing for high-achieving students to increase their learning achievements is liking the subject. The overall regression was statistically significant and results for the second model are as follows—R2 = 0.79, F = 16.212, $p = < 0.000$. No other indicators are significant in this group of students. Beta coefficients show that liking mathematics in groups of high achievers predictably increases grades in STEM subjects by 1.4 points, while liking chemistry predictably increases grades by 0.94 points (see Table 4). For this group, the activities taking place in the classroom are less important and the main driving force is their liking the subject, which means that the greatest emphasis in terms of pedagogical support should be placed on the stage when students develop an attitude toward one or another subject.

Table 4. Coefficients_High achievers_subjects_all students.

Model	Unstandardized Coefficients Beta	Standardized Coefficients Beta	Sig.
(Constant)	7.674		0.000
Math	0.114	0.184	0.000
Chemistry	0.094	0.171	0.000

Dependent Variable: Avg_5.

After performing regression calculations for the group of high-achieving students on the instructional methods they would recommend teachers use, the one that had a statistically significant effect on increasing academic achievement is reading; its predicted impact is 2.3%. The overall regression was statistically significant and the results for this model are as follows—R2 = 0.23, F = 13.586, $p \leq 0.000$. No other indicators are important for high achieving students.

The beta coefficients show that reading can predictably influence learning achievements in STEM for 1.15 points (see Table 5). This in turn demonstrates the importance of having appropriate learning materials for students to read to deepen their understanding of the subject.

Table 5. Coefficients_ High achievers_suggestions_all students.

Model	Unstandardized Coefficients Beta	Standardized Coefficients Beta	Sig.
(Constant)	8.133		0.000
Reading	0.115	0.156	0.000

Dependent Variable: Avg_5.

Next, the data of students were separated by gender and the group of girls with low academic achievement in STEM subjects was analyzed first. Here, again, the ANOVA calculations were performed to ascertain whether the data were statistically significant. Ten questions were included in the regression calculations, in which the students had to evaluate to what extent they like specific subjects and to what extent the activities taking place in the classroom influence the students. They expressed their assessments on a 5-point scale, ranging from "it does not influence me at all" to "it influences me a lot". The obtained results show that four models are statistically significant. The overall regression was statistically significant and the results for the fourth model are as follows—R2 = 1.25, F = 7.516, $p \leq 0.006$. However, interesting results emerge here, as in the strongest model, liking physics predictably affects academic achievement by 12.5%, but the beta coefficient shows that this liking for physics has a negative effect on predicted academic achievement in STEM subjects of 1.31 points for low achieving girls (see Table 6). This means that low-achieving girls dislike physics to a great extent, even to the point of affecting their academic achievement in all STEM subjects. According to the beta coefficients, a predictable increase in the results is for the indicators "the teacher helps me if I do not understand something" by 3.76 and liking mathematics by 1.48; these results are quite similar as for the general group of low achieving students where the help of teachers and liking of mathematics has a strong impact on predictable learning achievements. Similar to the case of the general group of students with low achievements, the negative effect is "the teacher is kind", where the predicted decrease in learning achievements in STEM subjects is 1.63 points, confirming that students understand that a teacher who helps them learn can increase their learning achievements, but they still believe that it is important for teachers to be kind.

Table 6. Coefficients_ Low achievers_subjects_girls.

Model	Unstandardized Coefficients Beta	Standardized Coefficients Beta	Sig.
(Constant)	5.231		0.000
The teacher helps me if I do not understand something	0.376	0.321	0.000
The teacher is kind	−0.154	−0.157	0.009
Math	0.148	0.188	0.001
Physics	−0.131	−0.155	0.006

Dependent Variable: Avg_5.

Next, the analysis turned to the questions where students had to recommend the frequency of the instructional methods used by the teachers on a 5-point Likert scale from "never" to "all lessons" and the obtained data show that in the group of girls with low learning achievements in STEM subjects, the model is statistically significant where "analysis of examples" and "individual tasks" are recommended. The overall regression was statistically significant and the results for the second model are as follows—R2 = 0.43, F = 5.287, $p \leq 0.022$. The predicted increase in academic achievements is 4.3% and the beta coefficients show that a predictable increase in STEM learning achievements for low achieving girls is by 1.53 points if the pedagogical strategy "analysis of examples" is used and by 1.34 points if "individual tasks" are provided (see Table 7).

A regression analysis of the group of boys with low learning achievements in STEM subjects, where the analysis includes the subjects that students like and classroom activities that students evaluate as important, was performed next, and the obtained results show that the statistically significant predicted learning achievements in STEM subjects are influenced by a liking for mathematics and the option "I can succeed at what I do". The overall regression was statistically significant and results for the second model are as follows—R2 = 0.64, F = 5.374, $p \leq 0.021$. Liking mathematics predictably increases learning achievement in STEM subjects by 4.5%, while "I can succeed at what I do" predictably increases it by 6.4%. The beta coefficients show that liking mathematics can predictably increase the results by 1.88 points and "I can succeed at what I do" by 1.44 points for low achieving boys (see Table 8) and these results are in line with a general group of low achieving students where the liking of mathematics and feeling that one can succeed were indicators with positive predictable influences on improved learning achievements.

Table 7. Coefficients_ Low achievers_suggestions_girls.

Model	Unstandardized Coefficients Beta	Standardized Coefficients Beta	Sig.
(Constant)	5.609		0.000
Analysis of examples	0.153	0.146	0.010
Individual tasks	0.134	0.130	0.022

Dependent Variable: Avg_5.

Table 8. Coefficients. Low achievers_subjects_boys.

Model	Unstandardized Coefficients Beta	Standardized Coefficients Beta	Sig.
(Constant)	5.130		0.000
Math	0.188	0.213	0.001
I can succeed at what I do	0.144	0.149	0.021

Dependent Variable: Avg_5.

When performing regression calculations for boys with low learning achievements in STEM subjects on the methods they would recommend teachers use, "individual tasks" appears as statistically significant. The overall regression was statistically significant and the results for this model are as follows—R2 = 0.14, F = 4.278, $p \leq 0.040$. The data of adjusted R2 shows that the predicted impact of this indicator is of 1.4%. The beta coefficient shows that the predicted impact of this indicator is 1.38 points for improved learning outcomes (see Table 9). These results are quite similar for the general group of low achieving students and also for the group of low achieving girls and it means that low achieving students can succeed in STEM learning if they are provided with individual tasks.

Table 9. Coefficients_ Low achievers_suggestions_boys.

Model	Unstandardized Coefficients Beta	Standardized Coefficients Beta	Sig.
(Constant)	5.946		0.000
Individual tasks	0.138	0.134	0.040

Dependent Variable: Avg_5.

Subsequently, data calculations were performed on girls with high educational achievements in STEM subjects. The regression analysis for this group includes subjects that students like and what happens in the classroom that students consider important. The obtained results show that five models to increase the predicted academic achievement in STEM subjects are statistically significant. The strongest predictive value is for the model is where high-achieving girls can work with classmates of their own gender. The overall regression was statistically significant and results for the fifth model are as follows—R2 = 1.46, F = 4.373, $p \leq 0.037$. The adjusted R2 results shows that predicted academic achievement in STEM subjects can improve by 13.4% for the fifth model. The beta coefficient shows that a predictable increase in STEM learning achievements in the fifth model is in the amount of 1.29 if these girls like math, by 1,08 if they like chemistry, by 1.01 if they can succeed in what they do and by 0.47 if they can work in their own gender group. The predictable decrease in learning achievements by 0.8 is if these girls work in different groups (see Table 10). In these results we can see the same pattern of results as it was in all groups that liking mathematics is a strong predictor of increased learning achievements; this has the same pattern as in the general group of students with high learning achievements that the liking of chemistry has a predictable influence, but indicators about working in particular groups are present only for girls with high achievements in STEM subjects.

Table 10. Coefficients_ High achievers_subjects_girls.

Model	Unstandardized Coefficients Beta	Standardized Coefficients Beta	Sig.
(Constant)	7.272		0.000
Math	0.129	0.229	0.000
Chemistry	0.108	0.210	0.000
I can succeed at what I do	0.101	0.139	0.005
I can work in different groups	−0.080	−0.166	0.003
I can work in a group with classmates of my own gender	0.047	0.114	0.037

Dependent Variable: Avg_5.

When performing regression calculations on girls with high academic achievements in STEM subjects on the methods they would recommend teachers use, "individual tasks" appears as statistically significant, with a projected 1.9% increase in academic achievement in STEM subjects. The overall regression was statistically significant and results for this model are as follows—R2 = 0.21, F = 8.255, $p \leq 0.004$. The beta coefficients also show that, for high achieving girls, the use of "individual tasks" predicts an increase in STEM learning achievements by 1.07 points (see Table 11). Such results are similar as for other groups where it was confirmed that individual tasks have a high predictable impact.

Table 11. Coefficients_ High achievers_suggestions_girls.

Model	Unstandardized Coefficients Beta	Standardized Coefficients Beta	Sig.
(Constant)	8.122		0.000
Individual tasks	0.107	0.146	0.004

Dependent Variable: Avg_5.

A regression analysis was also performed for the group of boys with high academic achievements in STEM subjects, which included the subjects that the students like and what happens in the classroom that the students consider important. The obtained results show that only one model (liking chemistry) is statistically significant for increasing the predicted academic achievement in STEM subjects. The overall regression was statistically significant and the results for this model are as follows—R2 = 0.19, F = 4.409, $p \leq 0.037$. The predicted increase in improved STEM learning achievements is 1.9%. The beta coefficient shows that the predicted increase in learning achievements for high achieving boys if they like chemistry is 0.99 points (see Table 12).

Table 12. Coefficients_ High achievers_subjects_boys.

Model	Unstandardized Coefficients Beta	Standardized Coefficients Beta	Sig.
(Constant)	8.071		0.000
Chemistry	0.099	0.158	0.037

Dependent Variable: Avg_5.

When performing regression calculations on high-achieving boys in STEM subjects on the methods they would recommend teachers use, "reading" emerges as statistically significant, with a projected increase in academic achievement in STEM subjects of 3.3%. The overall regression was statistically significant and the results for this model are as follows—R2 = 0.33, F = 6.710, $p \leq 0.010$. The beta coefficient confirms that the predicted improvement in STEM learning achievements for high achieving boys is 1.49 points if students are reading (see Table 13).

Table 13. Coefficients_ High achievers_suggestions_boys.

Model	Unstandardized Coefficients Beta	Standardized Coefficients Beta	Sig.
(Constant)	8.041		0.000
Reading	0.149	0.198	0.010

Dependent Variable: Avg_5.

6. Discussion

In almost all the analyzed groups, it can be seen that a liking for mathematics plays a statistically significant role in predicting an increase in academic achievement in STEM subjects. The only exception is in the group of boys with high academic achievements, where a liking for chemistry is the most influential model. This confirms that mathematics is a basic subject, the liking of which teachers should encourage because it has a positive effect on high learning achievements in other STEM subjects as well, which echoes the conclusions of other researchers [31].

For the group of all students with low learning achievements and the group of girls with low learning achievements in the STEM subjects, it is essential that "the teacher helps me if I do not understand something". For low-achieving boys, this is not a significant factor. In the group of all students with low learning achievements and in the group of girls with low learning achievements, "the teacher is kind" is statistically significant, albeit with a negative impact on learning achievement, which means that it is important for students to explain what they do not understand and learn in the process. They consider the teacher's kindness of little value if the teacher's desire to help in the learning process is not present. This feature is not significant for boys in any of the groups or for students with high academic achievements in STEM subjects. "I can succeed at what I do" is statistically significant for predicted improvements in academic achievement in STEM subjects in the group of all students with low academic achievements and boys with low academic achievements, as well as girls with high academic achievements.

Liking chemistry is a significant predictor of high academic achievement in all analyzed groups with high academic achievement in STEM subjects. The factors "I can work in different groups" and "I can work in a group with classmates of my own gender" are statistically significant models in the group of girls with high academic achievements, but working in groups without a gender division has a negative effect. This is interesting because when asking girls about what methods they would recommend teachers use, only one appears with a statistically significant pattern (using individual tasks), and this may indicate that girls want to work individually and take individual responsibility for their learning achievements. This may be because they have already experienced the effects of microaggressions on their academic achievements.

The importance of individual tasks to high learning achievements must be emphasized and this should definitely be taken into account when planning and organizing the pedagogical process in the classroom, where great emphasis is placed on group work. These results indicate that students still want to be individually responsible for the work to be completed and to understand the task individually.

A liking for physics is statistically significant in a model that predicts academic achievement in STEM subjects, but this factor has a negative effect on low-achieving girls.

This result is also very important when searching for the causes of such dislike. It is important to remember that in Latvia, physics is only taught as a separate subject from the 7th grade, which is also the lower age boundary for students involved in answering the survey. Therefore, we can conclude that those girls who have developed a dislike for physics most likely developed it before the 7th grade (13 years old). This indicates that it is important to think about how to teach physics to students at a younger age, promote students' understanding of it, as well as create an environment where girls feel safe and do not feel the effects of stereotypes and microaggressions. It should also be noted that a liking for physics does not have a significant effect on any of the other analyzed groups. Additionally, a liking for ICT or biology was not found to be statistically significant in any of the analyzed groups.

Of the students' recommendations to teachers about the methods that they use, "individual tasks" appeared as statistically significant in all the analyzed groups with low learning achievements and in the group of girls with high learning achievements, but it was not significant in the group of boys with high learning achievements. The "analysis of examples" tool is an essential recommendation for teachers, as it has a statistically significant role in predicting improvements in learning achievements in STEM subjects in the general group with low learning achievements and also in the group of girls with low learning achievements. On the other hand, there appears a statistically significant recommendation to use "reading" tasks more in the group of all students and in the group of boys with high learning achievements in STEM subjects. This means that boys with high academic achievements are aware of the need to read and delve into information in order to acquire new knowledge. This proves that it is essential to provide learning materials that students can read and discover new information about a subject for themselves. The results also confirm that a significant emphasis must be placed on mathematics in order to increase both students' interest in STEM subjects and learning achievements in this field, which will predictably increase the number of people who will choose to link their careers to STEM; research shows that increased requirements to learning achievements also have a positive effect on girls' involvement in the STEM field [32].

The results of the survey show that students wish to understand STEM subjects and they would like teachers to help resonate with the motivational development idea of the important role of self-efficacy [33,34] because it confirms that it is important for students with low learning achievements to feel they are succeeding, but this is not so important when students are already aware of the impact of their learning activities on learning achievements. The fact that this factor is significant for the group of high-achieving girls echoes the findings expressed by other researchers [35,36] regarding girls feeling more insecure about their academic achievements, so it is important for them to feel they are succeeding. The reason for this is probably related to the fact that they do not want to be exposed to various stereotypical comments or expressions of microaggressions from boys, which echoes the findings of other researchers that girls who perform well in the STEM field also feel the influence of stereotypes [10] and are able to perform better when working in a group of their own gender [23]. However, one should not assume the hasty conclusion here that these results indicate that it is necessary to divide students into gender-appropriate groups because such a division contributes to the formation of various stereotypes. It would be better to create environments where girls can act as equals in the learning process and not feel the influence of stereotypes or microaggressions.

The results of the survey confirmed that students do not wish that requirements to learning outcomes should be lowered. They are eager to learn more if there is pedagogical support, however, increased requirements for students' learning achievements must also be in synergy with the support provided by teachers if something is not understood, with the reduction in stereotypes and expressions of microaggression, and with the opportunity to perform tasks individually.

In the survey, the students could answer which profession they associate their future with and the data show that not only do a very small number of girls associate their future careers with the STEM field, but boys only rarely associate their career choice with STEM as well. This is an extremely worrying fact and it is necessary to start thinking immediately about how to change this ratio. It is undeniable that such changes cannot happen in a short period of time, but it is also unequivocally clear that steps must be taken in the Latvian education system in order to change the situation. These should be rapidly growing actions to ensure a wide range of educational activities that contribute to the growth of knowledge in the STEM field.

7. Conclusions

Mathematics is a basic subject, the liking of which strongly predicts high learning achievements in STEM for all students; teachers should encourage and aim to ensure this. For high achieving boys, liking chemistry has a significant positive predictor. For low achieving girls, a liking for physics statistically and significantly predicts lower academic achievement in STEM subjects and it means that particular pedagogical strategies (individual pedagogical support, individual work, and feelings of success) should be used to improve girls' attitude to physics. The liking of other learning subjects included in the model—namely, Biology and ICT—do not have a predictable impact on learning achievements.

A strong predictable influence on STEM learning achievements has teachers' support when students do not understand something in low achieving students' groups as well as "individual work", which means that low achieving students cannot be let aside and they need individual pedagogical support. Such strategies as different kinds of group work do not support higher learning achievements.

Teachers' kindness plays an important role in learning but has a negative predictable impact on learning achievements. This result breaks a stereotype that if teachers are kind to students they will be eager to learn.

Students need to experience success and it was proved by the results that show that a high predictable impact on low achieving students has the indicator "I can succeed in what I do".

In a group of low achieving students, the indicator "analysis of examples" has a significant predictable impact on higher learning achievements.

Only in a group of high achieving girls does the indicator "to work in the same gender group" show a positive predictable influence on higher STEM learning achievements.

8. Future Research Directions

In the next steps of the research, the researchers will analyze the impact of stereotypes on students' learning achievements as well as the impact of teachers' actions on the formation of stereotypes.

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Exploring Teachers' Perceptions of the Barriers to Teaching STEM in High Schools in Qatar

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Abstract: Understanding teachers' attitudes and perceptions of STEM teaching is a key pathway to enhance effective STEM teaching. Inarguably, teachers are the cornerstone of educational quality and play a central role in students' academic performance. Specifically, the pedagogical strategies teachers employ and their effective use in the classroom are strong determinants of students' enrollment or retention in STEM fields of study and eventual careers. This study sought to explore the experiences of high school STEM teachers in Qatar, focusing on the pedagogical approaches they utilize and the challenges they encounter, with the aim of delving into how these approaches and barriers affect the teaching of STEM in the country's high schools. The study's design is observational, with data collected using a survey of 299 secondary high school STEM teachers (11th and 12th grades). To attain the goal of this study, we examined the barriers perceived to impede engagement in effective STEM teaching from high school teachers' perspective. The study's findings pointed to the influence of student- and school-related factors in shaping STEM teaching. Significant differences were detected based on teachers' gender, grade level of teaching, age group, and university education. Logistic regressions revealed that teachers' demographic attributes, including age group and university education, affect their likelihood to use STEM pedagogies in class. This likelihood was significantly affected by student-related barriers and the learning resources/materials employed in classrooms. These findings postulate critical evidence in directing the development of successful STEM learning practices within Qatar's high schools.

Keywords: STEM education; high school; teacher education; STEM pedagogies; barriers

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1. Introduction

In the face of the many global challenges the world is facing and the risks they pose to the future well-being of humanity, science, engineering, and technology are key to understanding and solving the pressing problems. Through advances in science, engineering, and technology, human beings can now find solutions to many of the urgent ills facing humanity, including climate change, health-related problems such as COVID-19, food shortages, overpopulation, resource management, and various other ailments. To deal with the complexities of modern society, which are mainly due to human activity, a new set of core skills and knowledge is needed. Herein lies the importance of science and technology as catalysts of prosperity and sustainable development for the present and future generations.

In the context of Qatar, in recent years, leadership has placed the importance of transforming the country from a hydrocarbon-based economy to a knowledge-based society high on its national agenda. At the heart of this plan is the demand for federal capacity building. Against this background, the need for professionals in science, technology, engineering, and mathematics (STEM) fields in Qatar is considered to be in crisis by various education, government, and industry circles [1,2]. While the demand for STEM professionals in Qatar is very high, the number of citizens with the education and training required for sustaining the industries vital to its economy remains alarmingly low. The mismatch between education and the job market needs in Qatar has resulted in a very high proportion of unskilled and semi-skilled citizens presently employed in the public sector [3]. Consequently, the private sector has had to rely on foreigners to fill the gap in STEM professions. With a significant deficit in the number of young people studying and contemplating a career in STEM, Qatar will continue to rely heavily on expatriate labor.

Compounding the problems associated with high levels of foreign labor in Qatar is that most young and highly educated Qatari citizens hold credentials in non-STEM fields. The private sector, dominated by industries, offers only a few positions suitable for young Qataris who attain university education in a non-STEM area [4]. Moreover, there is strong evidence that many Qataris, especially males, do not intend or desire to pursue tertiary education [5], a trend with severe ramifications for attempts to create a sustainable local STEM human capital in the country [6]. Indeed, there is a lack of documented research investigating how these problems linked with the shortage of skilled professionals in Qatar and the broader Gulf Cooperation Council (GCC) region can be addressed effectively.

While substantial gains have been made in terms of equitable access to formal education and enrolment and literacy rates in Qatar [6,7], many are critical of the inability of Qatar's education system to produce highly skilled graduates that can contribute to the nation's development, prosperity, and well-being [8,9]. Despite decades of steady gains, Qatari women's participation in the labor force is still meager. Declining female participation continues to affect growth and development in Qatar. Exacerbating the job market demographic imbalance is the significant dependency on highly skilled professionals from foreign countries, as was stated previously. To improve the capacity of its skilled workforce in the labor market, concerted efforts are required to increase the number of men and women enrolled in disciplines associated with the knowledge economy on a par with developing nations.

STEM education is essential to the economic development of Qatar. While the country's national development strategy highlights the importance of STEM education for progress and development, the practical application of STEM education continues to face many challenges, especially in developing countries, such as the GCC states. Therefore, this study aims to investigate teachers' perceptions regarding salient barriers to STEM education in high schools in Qatar. The originality of our research lies in offering insights into such barriers from an Arab Middle Eastern perspective.

This paper is structured as follows. Section 2 reviews the relevant literature on STEM, synthesizing and critically evaluating research dealing with critical challenges to STEM education. Section 4 describes in detail the research design and the methods employed in this current study, including the data collection and the type of analysis used. Section 5 provides a detailed description of the study's results, focusing on the different factors that shape teachers' perceptions of STEM education. Finally, Section 6 provides a discussion of these results.

2. Review of Literature

With the increasing demand for professionals who possess the skills and knowledge that are key to economic growth and development, the onus rests with educational institutions to prepare students equipped with critical STEM skill sets. To enhance students' STEM-related capabilities, schools in particular need to improve their STEM education offerings and redesign their instructional pedagogies [10]. Not surprisingly, the urgency of STEM for national progress, security, and well-being triggered the launch of a plethora of educational reforms that many countries worldwide embraced to revamp STEM education for the economy.

Hsu and Fang [11] identified two distinct approaches adopted in STEM education. One is both interdisciplinary and transdisciplinary and treats the contents of the different STEM disciplines as integrated and interrelated components. The other employs a multidisciplinary instructional approach that views STEM discipline contents as a cluster or constellation of individual STEM fields of study. In previous research, Gomez and Albrecht [12] suggested using an interdisciplinary approach that anchors STEM instruction and education in pedagogy to prepare students for STEM-related career pathways.

As key catalysts in the education process, teachers can have a critical role in teaching STEM, affect students' educational achievement in STEM subjects and ultimately influence their interest in STEM fields of study and careers [13]. Students learning and practical experiences are determinant factors that enhance their STEM skills and knowledge. Indeed, alongside these experiences, teachers and quality STEM programs create ideal opportunities for developing students' talents and abilities in STEM domains [14].

The extant literature refers to the interplay between a host of individual (personal), environmental (contextual), and behavioral factors that act as either enablers or barriers to STEM teaching. For example, Nugent and colleagues [15] suggested various social (contextual), motivational (interest and self-efficacy), and instructional (teachers and teaching) factors that create adequate conditions for effective STEM teaching. Other research conducted by Margot and Kettler's [10] systematic review of research exploring the teachers' perception regarding STEM education noted six key barriers that thwart STEM teaching. These challenges are associated with the curriculum, pedagogy, assessment, teacher support, students, and structural systems.

Current debates on STEM education point to hindrances that impede the implementation of effective interdisciplinary modes of teaching STEM. Examples reported in the literature include teachers' beliefs, knowledge, and understanding of STEM [16,17]. Other examples include poor teacher preparation, lack of professional development for teachers, shortage of teachers, poor cross-disciplinary content integration, low student motivation, inadequate facilities, and inappropriate assessments [11,18]. Work by Wahono and Chang [19] indicated three main barriers facing STEM teachers: insufficient knowledge, difficulty applying STEM to some topic areas, and difficulty linking the different STEM topics.

For the purpose of this study, two main theoretical models provided a framework for our research: Bandura's social cognitive theory (1986) and Attribution Theory [20,21]. First, the social cognitive theory (SCT) is used as a theoretical lens that lends a rationale for considering individual and environmental (contextual or school-related) factors. This theoretical lens proved helpful in examining individual characteristics, including self-efficacy, a concept central to SCT [22]. Past research revealed the importance of self-confidence in classroom instruction and the teaching of science subjects [23,24]. Second, the attribution theory (AT), a well-known research paradigm in social psychology, helps to understand why a particular behavior or event occurs and attributes the specific causes to the occurrence. In other words, the AT serves to make sense of the social world and explain how individuals perceive the causes of daily life experiences. Therefore, based on the literature, this study hypothesized that high school STEM teachers face challenges in Qatar that affect their teaching process.

3. Research Questions

This study aims to address the following research questions:

1. What are the barriers identified by teachers as impeding STEM teaching in their classrooms?
2. What are the factors likely to influence teachers' use of STEM pedagogical approaches in their teaching?
3. Are there any significant differences pertaining to these barriers based on demographics, such as teachers' gender, age group, geographic location of the university they graduated from, and grade level of teaching?

4. Methods

Our study's design is observational, with data obtained using survey questionnaires to explore the experiences of high school STEM teachers in Qatar regarding the pedagogical approaches they use and the challenges they encounter. In so doing, the aim was to dig into the way these approaches and challenges affect the teaching of STEM subjects in Qatar's high schools. A cross-sectional survey was created based on two components: STEM teaching approaches and barriers to effective STEM teaching. To collect the data required for this research, a survey was administered physically and virtually over two months during the 2021 Spring Semester (March–April 2021). The survey was first administered using paper questionnaires (paper-and-pencil interviewing–PAPI). However, the response rate was low, and the researchers decided to also gather data using computer-assisted personal interviewing (CAPI).

4.1. Participants

The study was carried out in thirty-nine high schools across Qatar. These schools were randomly selected from local government schools (56.4%) and private schools (43.6%) in Qatar. Upon receiving approval from Qatar University's research ethics board (IRB), school board superintendents and teachers were contacted to allow the researchers to collect teacher data in their schools. With the exclusion of teachers who did not complete the entire survey, a total of 299 teachers participated in the study.

Table 1 illustrates teachers' demographic distribution, demonstrating their distribution by gender (54.5% males and 45.5% females) and age group, ranging from 31 to 40 (40.1%). More than half of the participants held a bachelor's degree (59.5%) and many more reported graduating from an Arab university outside Qatar (64.9%). Almost all were expatriates (96%). Although the bulk of teachers taught both grades 11 and 12 (45.8%), 25.8% taught grade 11, and 24.7% taught grade 12 exclusively. Science teachers made up the majority of respondents (45.8%), followed by mathematics teachers (30.1%), followed by engineering and technology teachers (8.7%). The remaining 15.38% taught multiple subjects (at least one STEM subject). Most teachers reported teaching between 11 and 20 h per week (65.6%).

Table 1. Teacher demographics (N = 299).

Variable	Sub-Categories	Percentage	N
Gender	Male	54.5	163
	Female	45.5	136
Age Group	30 or less	8.7	26
	31 to 40	40.1	120
	41 to 50	33.8	101
	51 or more	16.7	50
Nationality	Qatari	1.7	5
	Non-Qatari	96.0	287
Educational Qualification	Diploma	4.0	12
	B. A. degree	59.5	178
	Master's degree	32.8	98
	Doctorate/Ph.D.	2.7	8
Type of University	A University or College in Qatar	6.4	19
	An Arab University outside Qatar	64.9	194
	An American or European University outside Qatar	10.7	32
	An Asian or African University outside Qatar	17.4	52
Experience in Qatar	Less than one year	2.7	8
	More than one year to two years	10.4	31
	More than two years to five years	15.7	47
	More than five years to ten years	35.5	106
	More than ten years to twenty years	28.1	84
	More than twenty years	6.7	20

Table 1. *Cont.*

Variable	Sub-Categories	Percentage	N
Grade level of Teaching	Grade 11	25.8	77
	Grade 12	24.7	74
	Both Grades 11 and 12	45.8	137
Class size	10 or less	3.7	11
	11 to 20	34.1	102
	21 to 30	44.1	132
	31 or more	15.4	46
Teaching subject	Science	45.8	137
	Technology and Engineering	8.7	26
	Mathematics	30.1	90
	Multiple subjects	15.3	46
Teaching Hours in a week	10 or fewer hours per week	11.7	35
	11 to 20 h per week	65.6	196
	21 to 30 h per week	20.1	60
	31 h or more per week	1.0	3

4.2. Survey Instrument

The execution process consisted of three phases: (1) survey formulation, (2) survey piloting, and (3) survey execution.

Step 1: To develop the survey, we examined existing research on (a) STEM teaching [25–31]); (b) the role of teachers in STEM (e.g., [10,32–36]); (c) successful pedagogical approaches in STEM education (e.g., [37–40]; and (d) barriers to STEM teaching (e.g., [18,41–43]. Reviewing this literature allowed us to grasp the survey's target areas better and helped us understand general perceptions of STEM teaching as perceived by teachers and students, thus enabling us to develop items addressing the barriers and challenges teachers face when teaching STEM. A five-point Likert scale was used to grade 110 closed objects within five constructs as follows: Student-related barriers faced in teaching STEM, School-related barriers faced in teaching STEM, STEM-related pedagogical approaches, STEM-related teaching activities, and Factors affecting the decline of student interest in STEM. For each survey construct, teachers were given different response options depending on the type of question. These types included disagree-agree questions (strongly disagree = 1; disagree = 2; slightly disagree = 3; slightly agree = 4; agree = 5; and strongly agree = 6), frequency questions (never = 1; rarely = 2; sometimes = 3; often = 4; always = 5), percentage questions, rating questions (very poor = 1; poor = 2; fair = 3; good = 4; very good = 5), emphasis questions (none= 1; minimal = 2; moderate = 3; considerable = 4; heavy = 5), and importance questions (not important at all = 1; not important = 2; undecided = 3; important = 4; very important = 5).

Step 2: This step included testing the developed survey with two focus groups, one in Arabic and the other in English, to fine-tune the instrument. The focus group discussions aided us in addressing concerns we had regarding the wording of questions. This helped in rewriting and clarifying inadequately worded questions. The survey's primary goals were to collect (a) basic background knowledge, (b) systematic evidence of teaching approaches, and (c) structured evidence of the main challenges to effective STEM teaching.

Step 3: The questionnaires were distributed after receiving all signed consent papers from teachers and school authorities. Teachers were instructed to respond to the survey in English or Arabic. The average time it took for the participants to complete the study was between 13 and 17 min. Factor analysis was used to form constructs which measured important factors that would help answer the RQs of this study. This was performed using a principal component analysis and varimax rotation with a minimum factor loading criteria of 0.50. To guarantee adequate levels of explanation, the communality of the scale, which depicts the degree of variation in each component was evaluated. The findings indicate that all communalities were more than 0.50. The significance of the data, (χ^2 (820) = 6096.87, $p < 0.010$), indicated that factor analysis was appropriate. The Kaiser–Mayer–Olkin (KMO) and Bartlett's test of sphericity were used to confirm the sampling adequacy. The data was found to be suitable for factor analysis according to the KMO value which was 0.885. Results of the factor analysis are shown in Table 2.

Table 2. Factor loadings for the items in each construct.

Items	1	2	3	4	5
Student-related Teaching Barriers					
STB1	0.797				
STB2	0.827				
STB3	0.782				
STB4	0.616				
STB5	0.731				
School-related Teaching Barriers					
SCTB1		0.578			
SCTB2		0.625			
SCTB3		0.802			
SCTB4		0.852			
SCTB5		0.791			
SCTB6		0.692			
SCTB7		0.703			
SCTB8		0.621			
SCTB9		0.617			
SCTB10		0.697			
SCTB11		0.849			
SCTB12		0.877			
SCTB13		0.571			
SCTB14		0.599			
SCTB15		0.737			
SCTB16		0.794			
SCTB17		0.654			
SCTB18		0.715			
Teacher Pedagogical Approach					
TP1			0.637		
TP2			0.772		
TP3			0.696		
TP4			0.682		
TP5			0.756		
TP6			0.828		
TP7			0.771		
Teaching Activity					
TA1				0.678	
TA2				0.737	
TA3				0.751	
TA4				0.744	
TA5				0.728	
TA6				0.727	
Decline in Student's Interests					
DSI1					0.660
DSI2					0.675
DSI3					0.661
DSI4					0.797
DSI5					0.655

Further, Cronbach alpha (α) was used to assess the internal consistency of the reliability. The computed values of α for each survey construct are given in Table 3. According to researchers [44], alpha levels above 0.70 are regarded as reliable, whereas values greater than 0.90 are considered extremely reliable. The estimated alphas in this study revealed a reliable and very highly reliable scale.

Table 3. Cronbach's Alpha values for constructs in the teacher questionnaire (with examples of survey items).

Construct	No. of Items	Cronbach Alpha
Student-related barriers faced in teaching STEM *To what extent is your teaching affected by students' lack of interest? (Frequency choice)*	5	0.832
School-related barriers faced in teaching STEM *To what extent is your teaching affected by insufficient pedagogical support for teachers? (Frequency choice)*	24	0.967
Teacher's approach to STEM pedagogies *To what extent do you apply inquiry-based education? (Frequency choice)*	9	0.854
Teacher's STEM-related teaching activity *How often do you make students work in cooperative learning groups? (Frequency choice)*	12	0.824
Factors affecting the decline of student interests *How often do traditional methods of instruction encouraging rote memorization contribute to the decline of students' interest in your class? (Frequency choice)*	6	0.823

4.3. Data Analysis

4.3.1. Measures

The survey constructs were formulated as quantitative measures to represent important factors that would help answer the RQs of this study. These measures included student-related teaching barriers, school-related teaching barriers, teacher pedagogy, teacher activity, and a decline in student interests. The reason for the selection of these measures was because previous analyses revealed that though instructors favor STEM teaching, many instructional impediments hinder effective STEM teaching, including the curriculum, structural problems, concerns with students and evaluations, and a lack of teacher support [10,45]. Moreover, there is evidence that suggests that high-quality teachers significantly impact students' perceptions of STEM and, in many circumstances, student achievement [46]. Therefore, we consolidated our survey items into five measures to singularly represent the items they contain. For this, Likert-scaled survey items under each construct were coded into numbers, and then summed to obtain an overall score for the respective construct. Since Likert-type data are ordinal and only account for one score being higher than the other, and not the distance between the points, some of the measures required to be coded into dichotomous variables to represent the data as nominal categories (as explained below for each measure). These measures have already been validated in Section 4.2. Below are the details of the formulation of these measures.

Student-Related Teaching Barrier Score

The first measure used in this analysis is a student-related teaching barrier (STB) score. Teachers were asked to define the extent to which their teaching was affected due to various student-related issues. These issues comprised of the following: lack of required skills, lack of necessary knowledge, not having enough sleep, disruption in the classroom, and lack of interest. Teachers' answers on their perceptions of students were encrypted to dichotomous variables by allocating a score of "1" to responses that corresponded to "often" and "always" and a value of "0" to those with "never", "rarely" or "undecided". These five statements were then tallied to get a single STB score ranging from 0 to 5. This score indicated the collective magnitude of challenges teachers faced in their STEM teaching due to student-related issues.

School-Related Teaching Barrier Score

The second measure used in this analysis is a school-related teaching barrier (SCTB) score. Teachers were asked to define the extent to which their teaching was affected due to various school-related issues. These issues comprised of the following: technical support, STEM training and pedagogical support, curriculum and teaching hours, instructional materials and supplies, classroom adequacy, outdated school computers, school space organization, administrative and budget constraints, school environment, and support and interest from fellow teachers. Teachers' responses to these questions were encoded into dichotomous variables by giving "1" to responses that matched with "often" and "always" and a "0" to those which matched with "never," "rarely," or "undecided". These five statements were then added to get a single SCTB score ranging from 0 to 18. This score reflected the cumulative extent to which teachers faced challenges in their STEM teaching due to school-related issues.

Teacher Pedagogical Score

The third measure used in this analysis is a teacher pedagogical (TP) score. Teachers were asked to define the extent to which they used various pedagogical approaches on a scale ranging from (1) 0–20% to (5) 81–100%. These approaches comprised of the following: project/problem-based approaches, collaborative learning, peer teaching, flipped classroom, personalized teaching, integrated learning, and differentiated instruction. Teachers' responses were then encoded into numerical variables by allocating values from 1 to 5 to the range of percentages. Therefore, 0–20% was coded as 1, 21–40% as 2, 41–60% as 3, 61–80% as 4, and 81–100% as 5. Additionally, the scores of all the different pedagogies were summed to obtain a single TP score ranging from 1 to 35. This score reflected the extent to which teachers applied pedagogical approaches in STEM. The TP score was then used to formulate the likelihood of teachers using pedagogical approaches in STEM teaching. This was done by translating the TP score to dichotomies for use in the logistic regression model on the basis that the extent of using pedagogical approaches by teachers in classrooms should at least correspond to 50%. Therefore, an average score of 2.5 for the seven items pertaining to TP score could be considered as teachers having a high likelihood to use pedagogical approaches in STEM teaching. Hence, teachers with high TP scores greater than 18 out of 35 were coded as "1" and teachers with low TP scores below 23 were recorded as "0".

Teacher Activity Score

The fourth measure used in this analysis is a teacher activity (TA) score. Teachers were asked to define the extent to which they implemented activities beneficial for STEM teaching. This included their use of different type of materials (audio, visual, written), engaging students in group discussions, making students see connections between different disciplines, helping them consider alternative explanations, and encouraging students to provide explanations. Teachers' responses to these activities were then coded into numerical equivalents by giving a score of "1" to responses that matched with "often" and "always" and "0" to those which matched with "never," "rarely," or "undecided". Furthermore, the scores were summed to obtain a single TA score ranging from 1 to 6. This score showed the overall degree to which teachers used activities beneficial for STEM learning.

Decline in Student Interest Score

The fifth measure used in this analysis is a decline in student interest (DSI) score. Teachers were asked to define the extent various student-related factors contributed to the decline of students' STEM interests in the class. These factors comprised of the following: lack of confidence, negative perceptions of STEM-related careers, lack of parental and family involvement, facing difficulty in homework, and lack of use (or misuse of) technology. Teachers' responses to these various activities were then coded into numerical equivalents by allocating a score of "1" to responses that corresponded to "often" and "always" and a value of "0" to those with "never", "rarely" or "undecided". Further, the scores of all the different activities were summed to obtain a single DSI score ranging from 1 to 5. This score reflected how various student-related factors contributed to declining students' STEM interests.

4.3.2. Statistical Analysis

SPSS (Version 29) was used to analyze all the data. Descriptive statistics were used to show the distribution of the demographics of the teachers. Graphical scales were developed to represent the distribution of the measures formulated in Section 4.3.1. These measures were analyzed using means and percentages to answer the RQ1. Further, bivariate logistic regression models were built to analyze the RQ2 which included interval and ratio-scaled variables. Using this, the relative effect of various factors on the likelihood of teachers employing STEM pedagogies was investigated. These factors included teachers' school-related barriers, teaching activities, age group, university education, and teachers' use of resources and materials. Furthermore, teachers' use of various resources and materials on their likelihood to employ pedagogical practices in STEM teaching was also regressed. Lastly, various non-parametric tests were chosen to answer the RQ3 depending on the statistical measurement and distributions [47,48]. Non-parametric analyses were used to compare differences between teacher's demographical groups. In the case of two groups (gender, grade level of teaching) the Mann–Whitney U test was used to evaluate significant differences. The Kruskal–Wallis H test was used to explore significant differences between three or more groups (age group, geographic location of graduation university of teachers). If the Kruskal–Wallis test yielded statistically significant findings, Dunn's test was used to compare each independent group pairwise and check whether groups are statistically significant at some threshold. In addition, since the given value of significance may be appropriate for individual comparisons and not for the set of all comparisons, the Bonferroni correction was employed when performing the Kruskal–Wallis test.

5. Results

5.1. Teachers' Perceptions of STEM Teaching

The perceptions of teachers were evaluated using specified measures, as stated in Section 4.3.1. The results of these measures are discussed below.

5.1.1. Student-Related Teaching Barrier Score

Teachers were asked to rate the extent to which they faced student-related barriers. This was done by asking teachers if their teaching was affected by various student-related issues. These responses were summarized to achieve an overall STB score. The STB score ranged from a scale of 0 to 5, with 5 denoting a high degree of teaching barrier due to student-related factors. Figure 1 shows the distribution of the STB score.

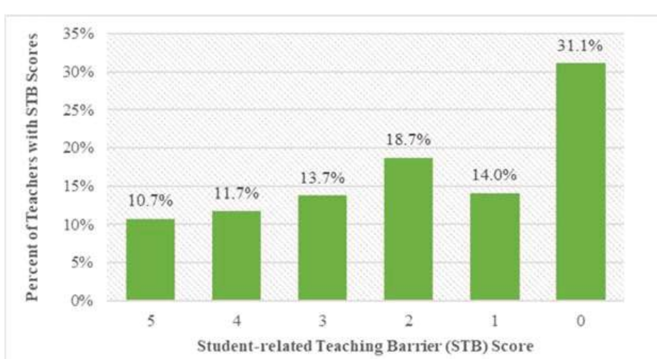

Figure 1. Student-related Teaching Barrier (STB) Scale.

The mean STB score was 1.93 (SD 1.72), indicating that there was no serious concern in the combined student-related barriers faced by teachers on an overall level. However, for further investigation into each student-related barrier individually, the teachers' responses were coded into two groups, having an extreme or high effect or low or no effect. The results are portrayed in Table 4. It was observed that almost half of the teachers were highly affected by students lacking the required skills (48.95%) and students not having enough sleep (48.09%). Moreover, 46% of the teachers reported that students lacked the necessary knowledge, which affected their teaching. Students' lack of interest and disruption in the classroom were reported to have an extreme or high effect on instruction by a lesser proportion of teachers, 36.11% and 22%, respectively. Therefore, these results indicate that, though teachers generally do not face student-related barriers on a macro scale, students' lack of skills, knowledge, and sleep significantly impacts STEM teaching in Qatar.

Table 4. Student-related barriers which affect STEM teaching in Qatar.

Student-Related Barrier	To What Extent Is Your Teaching Affected by the Following? (N = 299)	
	Extreme or High Effect (%)	Low or No Effect (%)
Students lacking the required skills	49.00	51.00
Students did not have enough sleep	48.10	51.90
Students lacking the required knowledge	46.00	54.00
Students' lack of interest	36.10	63.90
Students' disruption in the classroom	22.00	78.00

5.1.2. School-Related Teaching Barrier Score

Teachers were asked to rate how much they struggled with school-related issues. This was accomplished by asking teachers if school-related specific problems had an impact on their teaching. To get an overall SCTB score, the replies were added together. The SCTB score varied from 0 to 18, with a score of 18 indicating a significant teaching barrier due to student-related variables. Figure 2 shows the distribution of the SCTB score.

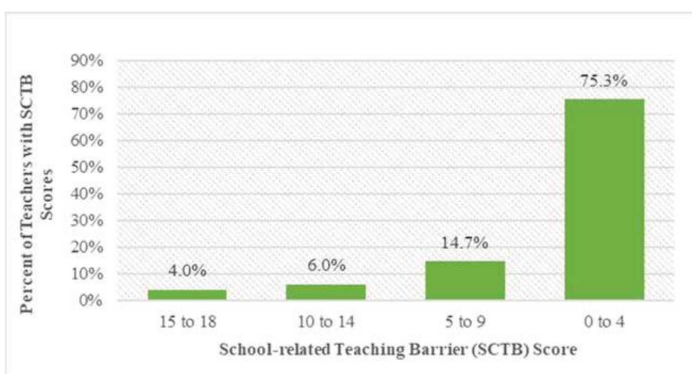

Figure 2. School-related Teaching Barrier (SCTB) Scale.

The mean SCTB score was 3.09 (SD 4.41), indicating that overall, student-related barriers faced by teachers were low. However, for further research into each student-related barrier separately, teachers' responses were divided into two groups with an extreme or high effect or low or no effect, as shown in Table 5.

Table 5. School-related barriers which affect STEM teaching in Qatar.

School-Related Barrier	To What Extent Is Your Teaching Affected by the Following? (N = 299)	
	Extreme or High Effect (%)	Low or No Effect (%)
Teachers have too many teaching hours	33.30	66.70
School computers out of date and/or needing repair	23.00	77.20
Classrooms are overcrowded	21.50	78.50
Administrative constraints in accessing adequate content/material for teaching	20.20	79.90
Teachers do not have adequate instructional supplies	19.20	80.70
Implementing the school's curriculum	18.60	81.30
Teachers do not have adequate instructional materials	18.60	81.40
School space organization (classroom size, furniture, etc.)	18.60	81.40
The school environment	18.10	81.80
Lack of pedagogical models on how to teach STEM	16.80	83.20
Understanding the curriculum	16.60	83.40
Lack of adequate training of teachers	16.30	83.60
Budget constraints in accessing adequate content/material for teaching	16.10	83.90
Insufficient technical support for teachers	16.00	83.90
Insufficient pedagogical support for teachers	15.10	85.00
Insufficient support from colleagues	13.20	86.80
Teachers' lack of interest	12.20	87.80
Lack of content in national language	9.40	90.50

5.1.3. Teacher Pedagogical Score

Teachers were asked to rate the extent to which they employed different pedagogical practices in their STEM teaching. Teacher's responses were combined to produce an overall TP score. The TP score ranged from 0 to 35, with the latter denoting a high use of STEM pedagogical approaches. Figure 3 shows the distribution of the TP score.

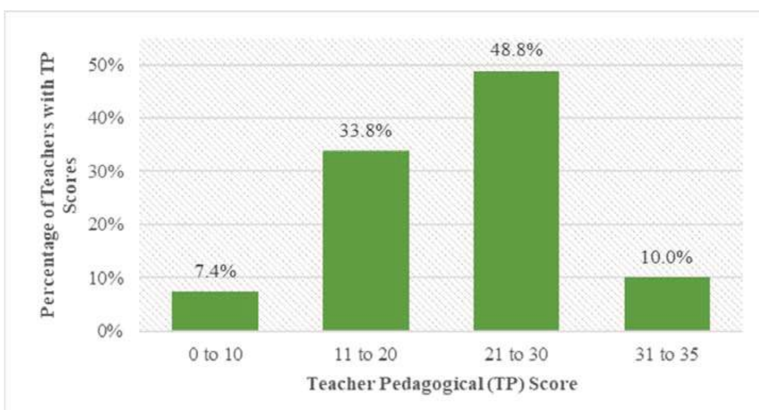

Figure 3. Teacher Pedagogical Score (TP) Scale.

The mean TP score was 21.45 (SD 6.88), indicating that overall, teachers employed pedagogical approaches to a reasonable extent. However, for the examination of each pedagogical approach individually, teachers' responses were divided into two groups having a high extent or low extent, as shown in Table 6.

Table 6. Pedagogical Approaches used in STEM teaching in Qatar.

Pedagogical Approaches	To What Extent Do You Apply the Following Pedagogical Approaches in Your Teaching? (N = 299)	
	High Extent (%)	Low Extent (%)
Collaborative learning	56.70	43.30
Integrated learning	51.90	48.10
Differentiated instruction	46.20	53.80
Project-/Problem-based approach	45.00	55.00
Peer teaching	44.80	55.30
Personalized learning	44.30	55.80
Flipped classroom	20.60	79.50

5.1.4. Teacher Activity Score

Teachers were asked to rate how often they used various teaching activities in their STEM instruction. Teacher's responses to these items were added together to generate a total TA score. The TA score varied from 0 to 6, with a score of 6 indicating extensive usage of activities in the classroom. Figure 4 shows the distribution of the TA score.

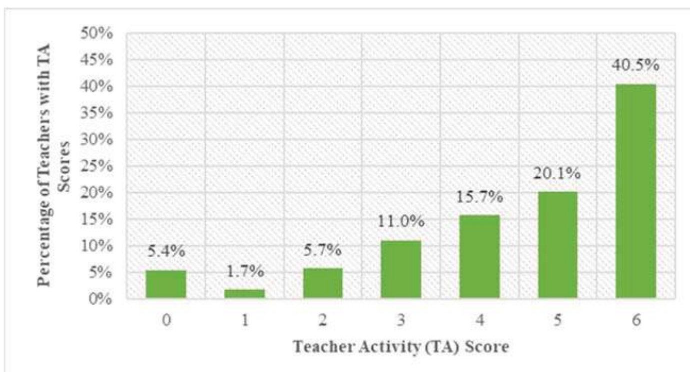

Figure 4. Teacher Activity Score (TA) Scale.

The mean TA score was 4.53 (SD 1.68), implying that on the overall level teacher's use of activities in their teaching was considerably high. For further research into each teaching activity, teachers' responses were divided into two groups having a high or low extent, as shown in Table 7.

Table 7. Teaching Activities used in STEM teaching in Qatar.

Teaching Activities	To What Extent Do You Implement the Following in Your Teaching? (N = 299)	
	High Extent (%)	Low Extent (%)
Engage the whole class in discussions	89.60	10.30
Use different type of materials (audio, visual, written)	87.30	12.60
Do group discussions with students	80.30	19.80
Help students see connections between different disciplines	79.80	20.30
Ask students to consider alternative explanations	67.00	33.10
Require students to supply evidence to support their claims	66.10	33.90

5.1.5. Decline in Student Interest Score

Teachers were asked to rate how various student-related factors contributed to the decline of students' STEM interests in class. The responses were totaled to arrive at a total

DSI score. The DSI score ranged from 0 to 5, with a 5 signifying a high decline in student interests. Figure 5 shows the distribution of the DSI score.

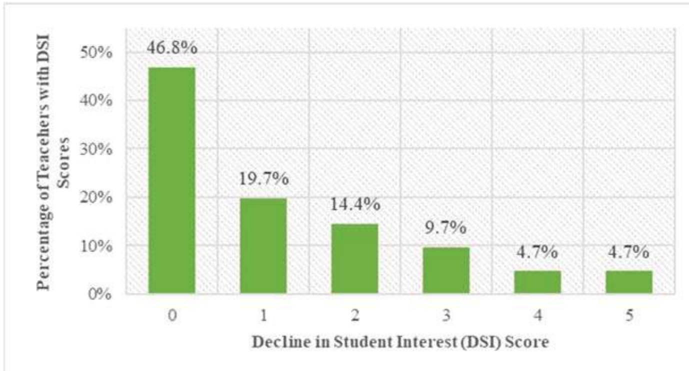

Figure 5. Decline in Student Interest (DSI) Scale.

The mean DSI score was determined to be 1.19 (SD 1.46), implying that the overall decline in students' interests due to student-related factors was not very concerning. However, for further investigation into each factor, teachers' responses were coded into two groups: either extreme or high effect or low or no effect. The results are portrayed in Table 8. It was observed that more than one-third of the teachers described a lack of parental and family involvement as a major factor in students' decline in STEM interests.

Table 8. Teachers' perception of the extent to which student-related barriers cause the decline in students' interest.

Student-Related Barrier	How Often Do the Following Factors Contribute to Declining Students' Interest in Your Class? (N = 299)	
	Extreme or High Effect (%)	Low or No Effect (%)
Lack of parental and family involvement	35.67	64.33
Lack of confidence	30.29	69.71
A negative perception of STEM-related careers	23.42	76.57
Lack of use (or misuse of) technology	22.10	77.89
Difficulty of homework	13.93	86.06

5.2. Factors Likely to Influence Teachers' Use of STEM Pedagogical Approaches

Regression analyses were performed to assess the parameters that affected teachers' perception of STEM teaching. Several bivariate regression models were built to predict teachers' likelihood to employ pedagogical approaches in their STEM teaching in connection with other measures and demographic factors.

5.2.1. Teacher's Student-Related Barriers, Teaching Activity, Age Group, and University of Graduation on Their Likelihood to Use STEM Pedagogical Approaches

A bivariate logistic regression model was built to ascertain whether factors are associated with the likelihood of teachers employing STEM pedagogical practices in their classrooms. These factors include STB score, TA score, nationality (Qatari or non-Qatari), age group, and graduated university. For this, the dependent variable was chosen to be the TP score, which was coded into dichotomies (TP score greater than 23 as "1" and TP score less than 23 as "0") to fit the regression model. The proposed regression model pointed to the chances of employing more pedagogical practices in STEM teaching (ODDS) = f(STB score, TA score, nationality, age group, and university level). Upon examination of comparing a complete regression model to an intercept-only model, the analysis was statistically significant (χ^2 (9) = 33.434, $p < 0.001$). The regression explained 15.5% of the variation of teachers who were likely to employ STEM pedagogies and correctly predicted 74.8% of all the cases. The regression also uncovered that teachers with high STB scores were marginally less likely to use STEM pedagogies than teachers with low STB scores (probability = 0.54).

Moreover, teachers with high TA scores were 1.3 times more likely to use pedagogical approaches in STEM teaching than those with low TA scores (probability = 0.58). Additionally, the age group of teachers was a statistically significant predictor of the likelihood of using pedagogical approaches in STEM teaching. Teachers younger than 50 were 2.182 times (on average) more likely to use pedagogical practices in their STEM teaching compared to those above 50 years of age (probability 0.68). Another interesting finding that the regression revealed was that the region of the university that teachers graduated from significantly affected their likelihood of employing pedagogical approaches in STEM teaching. Teachers from an American or European university were 6.07 times more likely to use pedagogical approaches in STEM teaching compared to teachers from Asian or African universities (probability = 0.86). Corroborating this, teachers from Arab universities were 1.896 times (on average) more likely to use pedagogical approaches in STEM teaching compared to teachers from Asian/African universities (probability = 0.65). Lastly, nationality was not statistically significant predictor of the likelihood of using pedagogical approaches in STEM teaching.

In summary, the results of this logistic regression showed that student-related teaching barriers faced by STEM teachers in Qatari schools significantly decrease their likelihood of using STEM pedagogies. Meanwhile, using STEM teaching activities in classrooms is a substantial factor in increasing the possibility of employing STEM teaching approaches. Further, their age group and university education were the main predictors of teachers' likelihood to use STEM pedagogies. While teachers under 50 were more likely to use STEM pedagogies, teachers from American or European universities were highly likely (probability almost 1) to use STEM pedagogical approaches. It should be noted that while the age group was found to be a significant predictor, teaching experience was not. Further, while university location significantly affected the likelihood of using STEM instructional approaches, nationality (Qatari/Non-Qatari) did not. The results are summarized in Table 9.

Table 9. Bivariate logistic regression of the relationship between STB score, TA score, nationality, age group, and university level on teacher's likelihood to employ pedagogical approaches in STEM teaching.

Variable	B	Wald χ^2	Sig.	Exp(B) (ODDS)	Probability
STB Score	−0.165	3.959	0.047	0.848	0.46
TA Score	0.314	14.161	0.000	1.370	0.58
Nationality	−1.409	1.383	0.240	0.244	0.20
Age Group	-	7.873	0.049	-	-
Age Group (30 or less)	0.579	1.140	0.286	1.783	0.64
Age Group (31 to 40)	1.087	7.794	0.005	2.964	0.75
Age Group (41 to 50)	0.588	2.380	0.123	1.800	0.64
University Level	-	8.410	0.038	-	-
University Level (University inside Qatar)	0.765	2.048	0.152	2.148	0.68
University Level (University outside Qatar)	0.497	0.600	0.439	1.643	0.62
University Level (American/European University)	1.805	7.192	0.007	6.079	0.86
Constant	−0.260	0.039	0.844	0.771	-

5.2.2. Teacher's Use of Resources and Materials on Their Likelihood to Employ Pedagogical Practices in STEM Teaching

A second bivariate logistic regression model was built to determine whether or not teachers' use of teaching resources correlated with their likelihood of employing STEM pedagogical practices in classrooms. Eleven teaching resources were explored in the regression. The hypothesized regression model was the likelihood of using more pedagogical practices in STEM teaching (ODDS) = f(paper-based materials, audio or video materials, presentations, robots, calculators, graphing calculators, computer-based simulations, STEM-specific software, data sets or spreadsheets, word processors, and online tools). A test of the full regression model compared to an intercept-only model was statistically significant (χ^2 (11) = 24.671, p = 0.010). The regression explained 11.3% of the variation of those likely to employ STEM pedagogies and correctly predicted 70.8% of all the cases. The analysis revealed that teachers who used online tools as a resource for their teaching were 2.4 times more likely to employ STEM pedagogies (probability = 0.71). Moreover, teachers who used conventional calculators (not graphing) when teaching their courses were statistically less likely to employ STEM pedagogies than the teachers who did not use traditional calculators (probability = 0.35). The remaining resources and materials were not statistically significant predictors of the likelihood of employing pedagogical approaches for STEM teaching.

These results reveal that online tools significantly affect the likelihood of teachers to use STEM pedagogical approaches in their teaching. Another interesting finding was that using traditional resources such as calculators decreased the possibility of teachers employing pedagogical techniques in their STEM teaching. This shows that online tools are more adaptable for teachers when using STEM pedagogical approaches. Further, from the other resources that were not statistically significant in the regression, one essential resource was the use of STEM-specific software. This is worrying as using STEM-specific software ideally should positively affect teachers' likelihood of using STEM pedagogies. The results are summarized in Table 10.

Table 10. Bivariate logistic regression of the relationship teaching resources and materials on teacher's likelihood to employ pedagogical approaches in STEM teaching.

Variable	B	Wald χ^2	Sig.	Exp(B) (ODDS)	Probability
Paper-based materials	0.225	0.540	0.462	1.252	0.56
Audio/video materials	0.115	0.086	0.770	1.122	0.53
Presentations	0.235	0.200	0.655	1.265	0.56
Robots	−0.515	1.064	0.302	0.597	0.37
Calculators	−0.639	4.424	0.035	0.528	0.35
Graphing calculators	0.596	2.996	0.083	1.815	0.64
Computer-based simulations	−0.117	0.170	0.680	0.889	0.47
STEM-specific software	−0.317	1.110	0.292	0.728	0.42
Data sets/spreadsheets	−0.588	3.776	0.052	0.556	0.36
Word processors	0.051	0.019	0.890	1.053	0.51
Online tools	0.882	10.095	0.001	2.417	0.71
Constant	0.616	1.431	0.232	1.851	-

A third bivariate logistic regression model was developed to determine whether teachers' use of learning resources for teaching challenging concepts correlated with their likelihood of having high teaching activity in classrooms. Four teaching resources were explored in the regression. The hypothesized regression model was the likelihood of using more pedagogical practices in STEM teaching (ODDS) = f(colleagues, educational and research journals, online resources, secondary textbooks). A test of the full regression model compared to an intercept-only model was statistically significant (χ^2 (4) = 17.477, p = 0.002). The regression explained 8.6% of the variation of teachers who were likely to employ STEM pedagogies and correctly predicted 77.5% of all the cases. The analysis revealed that teachers who used educational and research journals for teaching challenging concepts were 2.4 times more likely have a high teaching activity (probability = 0.71). Moreover, the use of online resources to teach challenging concepts showed a 2.1 times higher likelihood of having high teaching activity (probability = 0.68). The remaining resources and materials were not statistically significant predictors of teachers' likelihood of using pedagogical approaches for STEM teaching. These results indicate that using educational and research journals and online resources for teaching challenging concepts dramatically affects the likelihood of teachers to have a high teaching activity. The results are summarized in Table 11.

Table 11. Bivariate logistic regression of the relationship between the use of resources for teaching challenging concepts on teachers likelihood to have a high teaching activity.

Variable	B	Wald χ^2	Sig.	Exp(B) (ODDS)	Probability
Secondary textbooks	0.441	2.399	0.121	1.555	0.61
Colleagues	0.253	0.800	0.371	1.288	0.56
Education and research journals	0.878	7.090	0.008	2.405	0.71
Online resources	0.767	6.285	0.012	2.153	0.68
Constant	−0.027	0.006	0.938	0.974	-

5.3. Differences in Teachers' Perceptions of STEM Teaching Based on Their Demographics

Next, we assessed the statistical differences between teachers' measures based on their demographic differences (teachers' demographic distribution is given in Table 1). This was done by employing the Mann–Whitney U test between two groups and the Kruskal–Wallis H test in cases with more than two groups.

5.3.1. Gender and Teaching Barrier

A Mann–Whitney U test was performed for SCTB scores based on gender groups. Results showed a statistically significant difference (U = 9704, $p = 0.047$) between the SCTB scores for male and female teachers. Female teachers (N = 136) had a higher mean rank of 160.15 than male teachers (N = 163), with a mean rank of 141.53. This illustrates that female teachers faced more barriers due to school-related issues than male teachers.

5.3.2. Age Group and Teaching Barrier

A Kruskal–Wallis H test was performed for SCTB scores based on the age group of teachers. The analysis revealed a statistically significant difference in SCTB scores across teachers of different age groups, $\chi^2(3) = 11.486$, $p = 0.009$, between the mean ranks of at least one pair of groups. For the six pairs of groups, Dunn's pairwise tests were used. Teachers in the 30 and below age group (mean rank = 186.10) faced significantly higher school-related barriers than those in the 51 or older age group (mean rank = 120.68) ($p = 0.006$, adjusted using the Bonferroni correction). There was no evidence that the other pairs were different. This indicates that the extent to which teachers face school-related teaching barriers statistically differs based on age. Hence, age is a factor that affects the teachers in creating a barrier to STEM teaching, and this barrier is due to school-related issues.

5.3.3. Grade Level of Teaching and Teaching Barrier

A Kruskal–Wallis H test was performed for SCTB scores based on the teachers' grade level of teaching. The analysis found a statistically significant difference in SCTB scores between the different grades that teachers taught in, $\chi^2(2) = 9.384$, $p = 0.009$, between the mean ranks of at least one pair of groups. Dunn's pairwise tests were used for the six pairs of groups. There was a marked difference between teachers who taught grade 12 and teachers who taught both grades 11 and 12 ($p < 0.01$, adjusted using the Bonferroni correction). There was no evidence that the other pairs were different. This reveals that the extent to which teachers face school-related teaching barriers statistically differs based on the grades they teach. Thus, grade level of teaching is a factor that affects the teachers in creating a barrier to STEM teaching, and this barrier is due to school-related issues.

5.3.4. Graduation University and Teacher's Pedagogy

A Kruskal–Wallis H test was performed for TP scores based on the university education of teachers. Teachers reported having completed their university or college studies inside Qatar, at an Arab university outside Qatar, an American or European university outside Qatar, or an Asian or African university outside Qatar. The analysis discovered a statistically significant difference in TP score between the different universities from which teachers obtained their degrees ($\chi^2(2) = 11.862$, $p = 0.008$) between the mean ranks of at least one pair of groups. Dunn's pairwise tests were used. There was a significant difference between the group of teachers who graduated from an American or European University outside Qatar and those who graduated from an Asian or African University outside Qatar ($p = 0.015$, adjusted using the Bonferroni correction). Moreover, there was substantial evidence ($p = 0.033$, adjusted using the Bonferroni correction) of a difference between the group of teachers who graduated from an Arab university outside Qatar and those who graduated from an Asian or African University outside Qatar. There was no evidence showing that the other pairs were different. This indicates that the extent to which teachers apply pedagogical approaches in their classrooms statistically differs based on the university from which they graduated. Therefore, teachers' academic background influences their STEM pedagogical approach to teaching students.

6. Discussion

This study highlights salient barriers facing high school teachers in Qatar when teaching STEM. In this study, our analysis utilized various factors that predict these barriers and the results revealed associations between teachers' demographic characteristics and environmental (contextual) variables, student-related barriers, school-related barriers, pedagogical approaches, and teachers' classroom activities.

6.1. Barriers to STEM Teaching

Social cognitive theory [49] and attribution theory [20,21] both provide a rationale for considering school context and other factors. As per the standardized beta weights, the context has a stronger relationship with teachers' perceptions than major background factors and personal opinions. This conclusion is corroborated by DeChenne and colleagues [50] in their study of 128 alumnus teaching assistants in STEM, which looked at the origins of teaching self-efficacy [50]. The study's findings showed that instructional self-efficacy is primarily influenced by the perception of the instructor's departmental and environmental aspects. In contrast to the current study's findings, the researchers discovered that environmental factors, such as the resources and allocated time, had a more significant impact than the peer-teaching relationship. Another study by [51] found a more profound link between instructors' self-efficacy and access to assets, as opposed to community support. Therefore, we assessed various environmental factors to understand the barriers teachers encountered in STEM teaching. This includes both school-related and student-related barriers.

The results derived from the present study disclosed three specific barriers to STEM teaching as reported by teachers: students' lack of the required skills, students' lack of the required knowledge, and students not having enough sleep. These results echo recent findings by [52–54]. These studies revealed that teachers noted that students often faced difficulty in solving STEM-related problems, did not perform well in academic areas, and were thus unable to apply their knowledge to self-directed STEM-related issues. While these problems may indicate that teachers felt their students lost interest in learning STEM, further empirical evidence is needed to explain how and why these challenges persist.

The decline in student interest was also reported to originate from a lack of parental and family involvement. These results corroborate findings of a study by [55], who concluded that parents' negative perceptions of STEM, particularly in communities bound by social or cultural norms, hamper teachers' STEM teaching. Indeed, several studies ascribe the decline in student STEM interest to a lack of parental and family involvement [56–61]. Prominent instances illustrating this decline include the absence of parental encouragement, lack of parental assistance with STEM subjects, and low parental aspirations or expectations [56].

The gains that parental involvement entails for students' STEM learning in particular are widely acknowledged in the literature [62–64]. Nevertheless, not all parents wanting to help their children can and know how to do so [57]. For example, parents' knowledge and understanding of the school's STEM curriculum may be limited. Different measures have effectively been used to bridge this gap between parents and children [65,66]. These possibilities for balanced STEM-related connections among children and households include school tasks, schoolwork responsibilities, after-school scientific associations, and trips to scientific centers. Community projects can also help build connections between children, parents, and educators. This provides added benefits to building constructive relationships with teachers, motivating them to be more competent in scientific training and teaching science more engagingly. Parent-teacher relationships can also be improved through such community-engaged STEM programs.

Grade level of teaching was found to yield substantial variances when analyzed against school-related teaching barriers. Our study's analyses indicated that the degree to which instructors experience school-related teaching barriers varies statistically depending on the grades they teach. Consequently, grade level of teaching is a factor that appears as a barrier to STEM teaching, which is caused by school-related concerns. This could be interpreted as implying that teachers who teach multiple grades are exposed to more teaching experience at school and are therefore more comfortable with the school-related activities.

The literature further indicates that teachers believe traditional school structures hinder effective implementation of STEM education [10]. School-related factors were measured as barriers to STEM teaching, as perceived by teachers, and assessed to determine significant differences between demographic factors. A Mann–Whitney U test for SCTB scores based on gender revealed a statistically significant difference between the SCTB scores for male and female teachers. Analysis estimates showed that female teachers faced more school-related barriers than their male counterparts. This finding has also been reported in previous work showing significant differences between female and male teachers' perception of STEM subjects [67–70].

Our study also examined whether school-related barriers facing teachers had any significant differences based on their age group. Results from a Kruskal–Wallis H test used to compare SCTB scores by teachers' age group demonstrated a statistically significant difference in school-related barriers teachers encountered based on their age groups. Consequently, teachers' age is a factor that can thwart STEM teaching. This could be due to younger teachers not being adapted to the school system or being perceived by the school in the same way as older teachers. Another possible reason could be due to young teachers being more critical of the school system as compared to older teachers. However, though previous literature has reported teachers' perception to be influenced by their experience and the time they have spent in the teaching profession [67,71–73], no reports have been made on the influence of school-related barriers based on the teacher's age.

6.2. Barriers to STEM Pedagogy

Previous studies indicate that differences in teachers' demographics can affect their implementation of pedagogical approaches in classrooms [74–76]. Our study revealed a statistically significant difference in TP scores across the universities teachers graduated from. Moreover, it was revealed that the university that conferred teachers' degrees has a substantial impact on their likelihood to use pedagogical techniques in teaching STEM. This could be due to American, European, and Arab Universities being more aware of innovative pedagogical approaches than Asian and African Universities due to educational research being more prevalent in the former. This provides implications for educationists in Qatar to emphasize employing qualified teachers from American, European, and Arab Universities. Further, emphasis on training and developing teachers to use pedagogical practices in teaching STEM could enrich high school teachers' efficacy in teaching STEM.

Also, regression analysis results indicated that teachers aged under 50 were more likely to employ pedagogical approaches in their STEM teaching. This is not to be confused with our previous finding on young teachers facing more school-related barriers. In one case, age is a predictor for employing pedagogical approaches. However, in the other case, age has significant impact on barriers to STEM teaching (this is general STEM teaching and not specific to using pedagogical approaches in STEM teaching). Though no previous literature has been reported on this, young teachers having a higher likelihood of using STEM pedagogies could be due to them having a higher passion and enthusiasm to use innovative pedagogies. On the other hand, older teachers are more adapted to traditional pedagogies and show less interests in taking up new pedagogies. These findings have implications for enhancing high school STEM teachers' ways of teaching.

Regression analysis showed that teachers who used online tools as a resource while teaching students were more likely to apply STEM pedagogies. This demonstrates that online resources were more adaptive for teachers employing STEM pedagogies. Evidence reveals that not using adequate online tools makes it difficult for teachers to integrate the technology component of STEM into their lessons [36]. In a study conducted by Yildirim and other researchers [77], teachers argued that the use of online tools in STEM classrooms piqued their students' curiosity and enhanced their inventiveness; it also encouraged enthusiasm towards learning, increased pupils' digital literacy, personalized the learning process, and simplified complex ideas.

Another regression model revealed that teachers who used educational and research journals to teach challenging concepts were more likely to employ STEM pedagogies. Using scholarly information to support teaching practices has become a standard expectation in many fields. In our study, only 34.56% of the teachers reported using educational and research journals to teach challenging concepts. While a wealth of research may be utilized to improve instructional practices, little can be found in the literature regarding how much educators search, acquire, read, employ, and disseminate research findings to help them teach [78]. A 2020 study carried out by Booher and other researchers [79] noted that teachers are interested in research and acknowledge its importance in informing their practice. However, the study also reported that teachers face difficulty identifying strong research materials and figuring out how to use that research to improve their teaching. Therefore, there is a need to change the culture and practice of research application in the classroom by increasing teachers' perspectives and practices. Further research in this area is needed in order for teachers to improve their efficacy and improve student learning using research evidence.

7. Limitations

The study's conclusions must be viewed in light of its limitations. One of the limitations of this study lies in its sole reliance on survey data of high school teachers' perceived barriers to teaching STEM in Qatar. The study's analyses, as presented above, disclosed associations between the barriers teachers reported and their demographic attributes, contextual (school-related) characteristics, and student-related factors. These results would be improved with additional qualitative data. For example, personal follow-up interviews with teachers who reported barriers related to the pedagogical approaches and classroom activities used would aid in getting an in-depth and informed understanding of these barriers. Another limitation of the present study is its focus on high school teachers' perceived barriers. Indeed, the study would benefit from looking at data from teachers in lower levels of schooling. For example, investigating data from teachers in preparatory school grades would enrich the study's findings by offering a comparative perspective.

Moreover, our findings are applicable to our sample population of Qatar-based, urban, mostly middle-class teachers. Different outcomes are expected for instructors from various demographics and ethnic backgrounds. To some extent, all of these factors may influence the interaction of the variables. To overcome this constraint, a substantially larger sample population is required. Moreover, due to the limited sample size (N = 199), there may be minor fluctuations in the significant differences based on various variables. However, we believe that the use of logistic analysis (together with the very significant results obtained) encourages confidence in the findings of this study.

8. Conclusions

High school teachers' perceptions of the barriers that impede teaching STEM subjects, including student- and school-related influences, constitute the core of our study's analyses. Our findings revealed that although teachers reported a limited number of barriers, a few remain of concern. Student-related barriers included high school students' lack of skills, knowledge, and sleep which are perceived by teachers to affect STEM instruction. Moreover, gender-based differences existed in regard to teachers facing school-related barriers, with female teachers facing more barriers compared to their male counterparts. Age is another factor that determines teachers' perceptions of the barriers hindering STEM instruction: teachers aged 30 or younger tend to face more school-related barriers. Equally interesting, teachers' perceptions of the decline in student interest in STEM subjects seems ascribed to the lack of parental and family involvement.

The pedagogical approaches teachers adopted in STEM teaching appear to be affected by age, university education, and student-related factors. Teachers who employed more activities in their teaching process were more likely to use STEM pedagogies. In particular, teachers who used online tools and research journals are more likely to engage students through STEM-related pedagogies. These findings provide the direction to inculcate STEM education in Qatari high schools. Further research is required to investigate these important issues.

STEM teachers are an essential resource for the successful implementing of STEM education in Qatar. While student development is necessary to facilitate a harmonic STEM environment for teachers, training teachers is also critical. Teachers need to be empowered through professional development programs that target STEM-related pedagogies, especially for teachers with non-Western university degrees and those belonging to older age groups. Gender disparities among teachers need to be addressed.

Some of the student-related barriers reported by teachers can be overcome by revisiting the pedagogical approaches used in teaching STEM to motivate students and pique their interest in STEM [80]. Teachers can also use more STEM resources that could enhance students' STEM interest and improve their skills and knowledge [81]. Teachers also need professional development resources to effectively implement STEM teaching [82]. This will help teachers to develop a positive interaction with STEM concepts and methodologies. To enhance teaching integrity, instructional approaches related to STEM should be explicitly taught and demonstrated to teachers, especially those who graduated from Asian or African universities.

Furthermore, the efficient utilization and incorporation of online tools into STEM lessons necessitate collaboration between content developers and STEM educators, preferably at an early stage in the design process. This would help in the educational planning by implementing content compatible with STEM teachers' knowledge and requirements. Moreover, global business enterprises and educators now demand 21st-century skills. Shifting demographics and student diversity also necessitate a re-evaluation of instructional pedagogies and the role of technology in schools, homes, and communities. For both learners and instructors, regardless of their varying learning styles, digital resources present an opportunity for facilitating rational thought, investigation-based learning, problem-solving, and collaboration.

This study utilized questionnaire data to identify the barriers viewed to impede STEM education in high schools in Qatar from the teachers' perspective. The present study's analyses could be complemented and enhanced further with rich, in-depth qualitative information to gain real insights into the dynamics and complexities surrounding existing STEM teaching practices and the challenges that hinder effective STEM education.

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Effect of the COVID-19 Pandemic on the Sense of Belonging in Higher Education for STEM Students in the United States and Mexico

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Abstract: The COVID-19 pandemic generated worldwide negative effects on college students' stress levels and motivation to learn. This research focuses on the lack of development of a sense of belonging in engineering students due to online classes during the pandemic and possible differences experiencing online classes between students from different contexts and cultures. Data were collected from 88 Mexican and 139 U.S. engineering students during the Spring 2021 semester using ten survey items asking students' perceptions of the effects of taking online courses during the COVID-19 pandemic on their sense of belonging in their major. Quantitative and qualitative analyses were conducted, aiming to determine the effects of taking online classes on students' sense of belonging in engineering. Findings stressed the poor sense of belonging that engineering students may have after taking online classes during the COVID-19 pandemic when they missed opportunities to develop meaningful relationships with their peers and professors due to the lack of good communication. Consequently, students had uncertainties about successful learning during the pandemic in both Mexico and the U.S. Thus, activities such as accessible office hours, study groups, and meetings with mentors and tutors should be promoted to help students recover from the lack of a sense of belonging in the engineering major generated during online classes due to the COVID-19 pandemic.

Keywords: post-pandemic; coronavirus; higher education; engineering students; remote classes; online classes; distance education; information technologies; students' perceptions; educational innovation

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1. Introduction

1.1. Background on the Effects of the COVID-19 Pandemic on Higher Education

Recent research has documented the effects of the COVID-19 pandemic on college students' mental health [1,2], stress levels, and motivation to learn [3]. These studies pinpoint the negative effects stemming from students' experiences in online courses during the pandemic. Prior work has also identified important links between college students' motivation to learn and their sense of belonging within their major and their institution [4]. Current theories about students' sense of belonging indicate that feelings of being connected, accepted, and validated at their universities and within their courses are crucial for their success and persistence in their majors [4–6]. Students' sense of belonging is also affected by institutional and cultural contexts, as well as access to infrastructures such as reliable internet connections or a comfortable study space, which can vary widely based on geographic location [3].

Different factors could influence students' sense of belonging in their academic community, such as their relationship with their peers [7], instructors, and teaching assistants [8]. These relationships can help students create bonds and support social integration into college [9]. Having good relationships with their peers may also help students feel accepted as a part of their major and develop a stronger sense of belonging within that community [10]. Sense of belonging at the course level has been shown to be a key factor for engineering students in developing their sense of belonging in their major [11], providing evidence of the important role that professors play in facilitating student learning and engagement [12].

The effects of the COVID-19 pandemic on education, particularly the effect of remote classes [13] and how students' emotions and learning experiences could be affected by hybrid courses [14], have also been studied. Likewise, cases are shown where laboratory courses went virtual [15,16] or where gamification was promoted to develop a more welcoming learning environment [17,18]. Another challenge during the online courses during the COVID-19 pandemic was testing, creating difficulties in completing qualitative and quantitative student performance assessments when they were taking supervised exams via digital platforms [19].

1.2. Sense of Belonging

The term belonging is usually used as a self-explanatory concept by social science researchers. The broad range of fields using the term, such as cultural theorists [20], sociologists [21], and education researchers [4], could generate misunderstandings in the current literature due to different interpretations of feelings of belonging. For example, belonging could be used as a synonym for national or ethnic identity [22,23] or an attachment to a particular place, group, or culture [24]. As a result of a lack of a clear, accepted definition of belonging, it is considered a multidimensional term, encompassing citizenship, nationhood, gender, ethnicity, identity, and emotional dimensions [21,25,26]. Additionally, a sense of belonging could be crucial for the social cohesion, loyalty, commitment, political order, and solidarity of people living in a community [27].

For this research, the definition of belonging is oriented more to the personal feelings of familiarity, comfort, security, and emotional attachment in any particular place or community [26]. This definition aims to separate a sense of belonging within a specific social context from the notion of national identity or citizenship that is more related to the geographical location of the individuals. We focus here on students' sense of belonging in their academic environment and how school-related experiences and activities could affect it.

Prior research has found a positive relationship between students' sense of belonging at the course level and their academic motivation [28], as well as between students' sense of belonging and their performance at the course level [7]. The literature suggests that characteristics of the learning environment, such as academic, pedagogical, and social interactions, could foster students' sense of belonging in their courses [29], and interactions between students and their professors could have a positive effect on students' sense of belonging in their college courses [30]. It is, therefore, important to consider how interactions are fostered and supported in academic contexts, as these variables characterize the learning environment that affects students' comfort and emotional security in their courses [31].

The literature suggests that a positive relationship between professors and students can generate a caring environment in which students feel like an essential part of their college community [9], giving them more confidence to communicate their ideas with their professors [32]. Connection with professors and peers may help students feel "at home" when they are on their campus, which ultimately increases their sense of belonging in their majors. Therefore, developing pedagogical strategies that prioritize a welcoming learning environment can facilitate students' management of both the academic and social aspects of their academic community [9]. Although the sense of belonging in a particular course is not enough to foster students' sense of belonging in their majors [4], a sense of belonging at the course level has been shown to be a key factor for students in developing their sense of belonging in their major [11], which ultimately affects students' persistence and efforts to complete their major [33].

Foundational work on the effects that a low sense of belonging may have on engineering students reveals that these students tend to switch out of science, engineering, technology, and mathematics (STEM) majors [34,35]. Research on the effects of the COVID-19 pandemic on college students has demonstrated decreased motivation [3] and accountability [2], which can ultimately have negative effects on their sense of belonging in their major. Additionally, feeling disconnected from their major and college community could make it more difficult to concentrate, which has been shown to adversely affect students' learning [2]. Hence, there is a need to understand the impact that the transition to online and hybrid learning during the COVID-19 pandemic could have on students' sense of belonging and learning, particularly for students from different countries and cultures.

1.3. Purpose

This research was conducted to address the gap in the literature about how online classes affected students' sense of belonging and learning during the COVID-19 pandemic. Most colleges offered online courses during the COVID-19 pandemic, and these courses were perceived in different ways by students. Developing a better understanding of how online courses affected students' sense of belonging in their major could be of paramount importance to improve the college learning environment once students get back to face-to-face classes. Understanding how students' sense of belonging was affected in learning environments in different countries and cultures could provide insight into the global effects of the transition to online classes due to the COVID-19 pandemic. Therefore, this research addressed the following research questions:

- RQ1: In what ways did a transition to online and hybrid courses during the COVID-19 pandemic affect undergraduate engineering students' sense of belonging in their major?
- RQ2: How did engineering students' sense of belonging affect their perceptions of learning during the online courses due to the COVID-19 pandemic?
- RQ3: In what ways do these effects differ for students in Mexico and the U.S. based on differences in demographics and culture?

2. Materials and Methods

2.1. Participants and Context

Participants in this study were selected from two larger studies focused on exploring the interactions between undergraduate engineering students' motivation, engineering identity, and sense of belonging. These participants were enrolled in engineering majors at two study sites: one private university in the north of Mexico, and one land grant institution in the southeastern U.S. All participants were taking online engineering-related courses during the COVID-19 pandemic, providing the opportunity for research teams to examine the potential effects of taking online courses on a students' sense of belonging.

The participants at both study sites were enrolled in online sophomore (third/fourth semester), junior (fifth/sixth semester), and senior (seventh semester or beyond) undergraduate engineering courses. U.S. participants were all sophomores (third/fourth semester). Participants at the Mexican university were biomedical engineering (BME) majors and were enrolled in courses such as biomedical engineering design, design of digital bioinstrumentation systems, and cardiovascular engineering. Participants at the U.S. university were from nine different engineering majors (Electrical and Computer, Materials Science, Chemical, Environmental, Industrial, Biomedical, Biosystems, Mechanical, and Civil) and were enrolled in undergraduate level courses required for their majors. For example, civil engineering majors were enrolled in geomatics, mechanics of materials, and senior capstone design.

2.2. Data Collection

Data for this study were collected using ten items from a larger survey about student motivation, engineering identity, and sense of belonging. The survey has been used to explore these factors for mid-year engineering students, with strong evidence of validity and reliability of data collected with the survey of this population [36]. The selected items (listed in Table 1) pertained to students' perceptions of the effects of taking online courses during the COVID-19 pandemic on their sense of belonging in their major. The voluntary survey was distributed online during the Spring semester of 2021. Out of the 302 students in the BME program at the Mexican university, a total of 88 students completed the survey (29% response rate), with 43 identifying as female (49%), 42 identifying as male (47%), and 3 participants who preferred not to answer this question. These numbers reflect the overall gender representation in engineering majors at the Mexican university. From the U.S. university, out of 803 sophomore students invited to complete the survey, 139 responded (17% response rate). Of these, 53 identified as female (38%), 84 identified as male (61%), and 2 preferred not to answer the question about their gender. These numbers reflect an overrepresentation of females at the U.S. university; based on institutional data reported for the Spring 2021 semester across all engineering majors surveyed, 24.8% of students identified as female and 75.2% of students identified as male. For the open-ended survey responses at the U.S. university, we selected the responses of sophomore Biomedical engineering (BME) majors (n = 21; 13 identified as female (62%), 7 as male (33%), and 1 participant who preferred not to answer this question). This subsample of only BME students from the U.S. university allowed for more direct alignment and comparison with the BME participants at the Mexican university.

Table 1. Survey questions related to COVID-19's effect on students' learning experiences.

Survey Question	Response Type
Q1. How has this transition affected your sense of belonging in engineering?	Open-Ended Response
Q2. In what ways are you connecting with each group?—Peers/colleagues, instructors, teaching assistants/mentors, and other engineering groups	Open-Ended Response
Q3. In what ways are you lacking in connection at this time?	Open-Ended Response
Q4. How has this transition affected your learning?	Open-Ended Response
Q5. To what extent has transitioned to online learning affected your sense of belonging in engineering?	Likert-Type Scale
Q6. To what extent are you connecting to your peers/colleagues?	Likert-Type Scale
Q7. To what extent are you connecting to your instructors?	Likert-Type Scale
Q8. To what extent are you connecting to your teaching assistants/mentors?	Likert-Type Scale
Q9. To what extent are you connecting to other engineering groups?	Likert-Type Scale
Q10. To what extent has transitioned to online classes affected your learning?	Likert-Type Scale

The ten COVID-19-related items included four open-ended questions and six Likert-type questions on a scale from zero (no effect/never) to six (major effect/a great deal). These questions (refer to Table 1) were developed based on prior findings of factors affecting students' sense of belonging in engineering (positive learning experiences, interactions with others outside the classroom, and personal connections) [8]. Over half of the questions were focused on students' connections with others because this factor was the most likely to be affected by online learning formats. Other questions were asked about how the transition to online classes affected students' sense of belonging and learning. The survey was presented to participants in English at both universities as the BME students at the Mexican university were required to speak English as a second language. There were slight wording changes between survey items for the two study sites to account for linguistic and cultural differences [37]. The word "colleagues" was used instead of "peers", "mentors" was used instead of "teaching assistants", and "professors" was used instead of "instructors" on the survey distributed at the Mexican university. All study protocols, for example, informed consent and de-identifying data, were conducted in accordance with the Institutional Review Board at the U.S. university and the principal research office (academic vice chancellor office and the dean's office of the school of engineering and sciences) guidelines at the Mexican university.

2.3. Data Analysis

2.3.1. Quantitative Analysis

A logistic binomial regression model [38] was used to determine which variables significantly affected participants' sense of belonging in their major during the online classes. Aiming to conduct this logistic binomial regression, the data were classified into two different groups according to the participants' level of sense of belonging in engineering depending on their response to the Q5 question ("To what extent has the transition to online learning affected your sense of belonging in engineering?"). Participants reporting a sense of belonging less than or equal to three were classified in the low group, and participants reporting a sense of belonging greater or equal to four were classified in the high group. These two groups (low and high sense of belonging) were used as a binomial dependent variable [39] for running the logistic binomial regression. Six independent variables were considered for the model: X1) connecting to peers/colleagues, X2) connecting to instructors, X3) connecting to teaching assistants/mentors, X4) connecting to other engineering groups, X5) online classes affecting learning, and X6) gender. These six independent variables were considered as possible influential factors in the participants' sense of belonging level according to the previously established theory [7,29,30]. Using these variables, regression models were created for each of the two study sites.

Additionally, odds ratios for all the independent variables of the regression model were calculated manually, using the estimated coefficient "B" as the "x" variable in the equation f(x) = e^x. Odds ratio values larger than one establish a positive relationship between the dependent variable (sense of belonging in engineering) and that particular independent variable, making it more likely that participants report a high sense of belonging if this odds ratio increases. Conversely, odds ratio values less than one establish that that particular independent variable has a negative effect on students' sense of belonging in engineering [40].

A Student's *t*-test [41] was conducted to analyze possible differences between the effect participants perceived on their learning within the low and high level of sense of belonging groups. Effect sizes for these *t*-test results were calculated by taking the difference between the mean of the effect of online classes on students' learning for each group (low and high level of sense of belonging) and dividing it by the standard deviation of the high sense of belonging group (the group with the highest number of participants, $n = 38$). To further analyze the possible correlation between a sense of belonging in engineering and the effects of the transition to online classes affecting learning during the pandemic, both, a linear binomial regression [38,39] and a Pearson correlation test [42] were used to determine if there was a correlation between these two variables. All inferential statistics and models were created using the statistics software R [43].

2.3.2. Qualitative Analysis

Responses to the four open-ended questions (questions Q1–Q4 in Table 1) were analyzed using open coding to enable codes to emerge as close as possible to the words and ideas of the participants [44]. This coding approach draws from constructivist grounded theory [45] to develop findings that accurately reflect the participants' experiences. All responses to these four questions were coded line by line, then the emerging codes for participants were compared side by side to find codes that could be combined into units of meaning [46] for each question. The code book for the final coding pass was developed by the two team members at the Mexican university and was then used by four researchers (the original two coders and two from the U.S. university) who conducted the qualitative coding of all responses. The researchers collaboratively resolved questions about the interpretation and application of codes. Sharing the codebook and verifying the meaning of each code provided a robust co-construction of the data interpretation between researchers, which established the communicative validity of the analysis [47].

The framework of belonging in academic contexts was used as a lens to guide the coding process and facilitate better analysis of the units of meaning. This framework helped the research team interpret the codes and guided the discussion of the qualitative results to thoroughly answer the research questions. This qualitative data analysis allowed the researchers to ensure procedural validity of the analysis [47], in that all units of meaning appropriately reflected participants' responses and feelings about their sense of belonging in their major and how the online classes affected their learning during the COVID-19 pandemic. Representative comments from the participants were selected to support and fully explain the findings. Most of the participants answered the open-ended questions in English (the second language for participants at the Mexican university), and these comments were quoted without modifications. Responses provided in Spanish were translated into English by the researchers at the Mexican university for the purposes of reporting the findings.

3. Results

3.1. Quantitative Analysis

Participants' responses to the six Likert-type questions are presented in Tables 2 and 3 to facilitate the comparison and analysis of the descriptive statistics.

The binomial regression models were generated with a binomial dependent variable of a low and high sense of belonging in engineering and six independent variables (X1: connecting with peers/colleagues; X2: connecting with instructors; X3: connecting with teaching assistants/mentors; X4: connecting with other engineering groups; X5: transition to online courses affecting learning; and X6: gender) for both study sites. The regression based on responses of participants at the Mexican university was presented as follows: "$\hat{Y} = -0.610 - 0.177X1 - 0.214X2 + 0.286X3 - 0.133X4 + 0.394X5 - 0.529X6$"; while the regression based on responses from participants at the U.S. university was: "$\hat{Y} = -0.593 - 0.051X1 + 0.140X2 + 0.037X3 - 0.229X4 + 0.285X5 - 0.257X6$".

Table 2. The number of responses for each level of the scale (0 no effect/never to 6 major effect/a great deal), and the means of all responses to the Likert-type questions for participants at the Mexican university.

0	1	2	3	4	5	6	Mean
Q5. To what extent has transitioning to online learning affected your sense of belonging in your major?							
5	17	5	12	13	24	12	3.48
Q6. To what extent are you connecting to with your colleagues *?							
2	5	4	19	12	24	22	4.20
Q7. To what extent are you connecting to your professors?							
4	12	16	17	18	17	4	3.13
Q8. To what extent are you connecting to your teaching mentors *?							
16	20	14	20	7	9	2	2.19
Q9. To what extent are you connecting to other engineering groups?							
20	18	16	9	10	7	8	2.27
Q10. To what extent has transitioning to online classes affected your learning?							
2	7	4	13	23	16	23	4.13

* = Note: The words "colleagues" and "mentors" were used on the survey distributed at the Mexican university instead of "peers" and "teaching assistants" (which were used on the survey distributed at the U.S. institution) for linguistic purposes.

Table 3. The number of responses for each level of the scale (0 no effect/never to 6 major effect/a great deal), and the means of all responses to the Likert-type questions for participants at the U.S. university.

0	1	2	3	4	5	6	Mean
Q5. To what extent has transitioning to online learning affected your sense of belonging in your major?							
13	18	9	30	20	25	21	3.36
Q6. To what extent are you connecting to your peers *?							
4	18	20	34	23	23	11	3.25
Q7. To what extent are you connecting to your professors?							
8	44	32	18	14	10	7	2.33
Q8. To what extent are you connecting to your teaching assistants *?							
13	35	25	19	12	11	6	2.32
Q9. To what extent are you connecting to other engineering groups?							
37	23	13	19	8	3	6	1.73
Q10. To what extent has transitioning to online classes affected your learning?							
2	9	13	19	28	29	35	4.14

* = Note: The words "colleagues" and "mentors" were used on the survey distributed at the Mexican university instead of "peers" and "teaching assistants" (which were used on the survey distributed at the U.S. institution) for linguistic purposes.

The graphs of the linear binomial regressions shown in Figure 1 suggest a positive correlation between the effects that online courses had on the participants' sense of belonging and their learning; and the results of the Pearson correlation test showed a highly significant positive correlation between these two factors as well, with p-values below 0.01 at both sites with correlation coefficients of 0.323 for the Mexican university participants and 0.386 for the U.S. university participants.

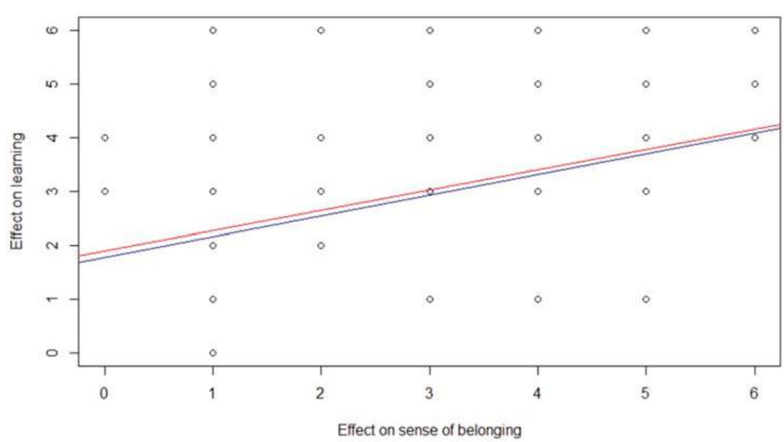

Figure 1. The linear binomial regression of the relationship of the effects that online courses had on participants' sense of belonging and their learning for the Mexican university participants (blue) and 0.386 for the U.S. university participants (red).

The results of the logistic binomial regression are presented in Tables 4 and 5 for participants at the Mexican and U.S. universities, respectively. These results show that, of all the independent variables in the model, only the students' perceptions of the effects of the transition to online classes on their learning were a significant predictor of participants' sense of belonging being low or high.

Table 4. The logistic binomial regression results showing predictors of a sense of belonging in engineering for participants at the Mexican university.

Independent Variables	B	SE	*p*-Value	Odds Ratio
Connection with colleagues	−0.177	0.192	NS	0.837
Connection with professors	−0.214	0.231	NS	0.807
Connection with mentors	0.286	0.215	NS	1.331
Connection with other BME groups	−0.133	0.161	NS	0.875
Online classes affecting learning	0.394	0.152	0.009 **	1.482
Gender	0.529	0.488	NS	1.697

B = estimated coefficient; SE = standard error; NS = not significant; ** = highly significant.

Table 5. The logistic binomial regression results showing predictors of a sense of belonging in engineering for participants at the U.S. university.

Independent Variables	B	SE	*p*-Value	Odds Ratio
Connection with colleagues	−0.051	0.152	NS	0.950
Connection with professors	0.140	0.167	NS	1.150
Connection with mentors	0.037	0.145	NS	1.038
Connection with other BME groups	−0.229	0.155	NS	0.795
Online courses affecting learning	0.285	0.150	NS	1.330
Gender	−0.258	0.226	NS	0.773

B = estimated coefficient; SE = standard error; NS = Not Significant.

The results of the *t*-test comparing the extent to which students' learning was affected during the transition to online courses (Q4, see Table 1) based on students' sense of belonging in engineering (low or high) are shown in Table 6.

Table 6. The comparison of students' mean of their perceptions of how much their learning was affected by the transition to online classes for the high and low sense of belonging groups.

Study Site	High Sense of Belonging in Engineering	Low Sense of Belonging in Engineering	*p*-Value	Effect Sizes
Mexico	3.641	4.53	0.0127	0.871
U.S.	3.7	4.615	0.0008	0.818

The *t*-test results and effect sizes (see Table 6), which indicate the extent to which a significant difference is likely to indicate a true difference between means [48], show that students' perceptions that their learning was affected by the transition to online classes were significantly different between students with a high and low sense of belonging.

3.2. Qualitative Analysis

The coding of responses to the four open-ended questions, presented in Tables 7–9, show the nature of the challenges students faced due to the transition to online classes during the pandemic. These tables also include the frequency with which each code appeared in students' responses at the two study sites. Note that the sum of the percentages in each table is larger than 100% because some of the participant responses were co-coded with more than one code.

Table 7. Codes that emerged from responses to Q1, "How has this transition affected your sense of belonging in engineering?" for participants at the two study sites.

Codes	Mexican University (*n* = 88)	U.S. University * (*n* = 18)
1-Difficulty with peer relationships	43%	86%
2-Lack of practice time	30%	0%
3-No effect due to coping mechanisms	17%	15%
4-Questioning sense of belonging in engineering	25%	0%
5-Difficulty with teacher-student relationship	19%	0%
6-Leveling learning opportunities	24%	0%

* Not all U.S. participants responded to all open-ended survey questions; therefore, there is a difference in the number of participants for each question in Tables 7–9.

Table 8. Codes that emerged from responses to Q3, "In what ways are you lacking in connection at this time?" for participants at the two study sites.

Codes	Mexican University (*n* = 88)	U.S. University * (*n* = 19)
1-Difficulty with personal interactions with peers and professors	66%	68%
2-Difficulty with the development of new academic and friendly connections	39%	21%
3-Decreasing motivation to speak and express opinions	40%	5%
4-Facilitating academic performance	20%	5%

* Not all U.S. participants responded to all open-ended survey questions; therefore, there is a difference in the number of participants for each question in Tables 7–9.

Table 9. Codes that emerged from responses to Q4, "How has this transition affected your learning?" for participants at the two study sites.

Codes	Mexican University (*n* = 88)	U.S. University * (*n* = 21)
1-Promoting self-learning activities	7%	24%
2-Distractions affecting focus on classes	26%	38%
3-Feeling discouraged and tired due to online classes	26%	32%
4-Missing practice opportunities	27%	0%
5-Lacking peer discussions and significant learning opportunities	18%	14%

* Not all U.S. participants responded to all open-ended survey questions; therefore, there is a difference in the number of participants for each question in Tables 7–9.

The results presented in Table 7 show that students experienced difficulties developing new peer relationships while taking online classes during the pandemic. Students noted the difference between how they are used to interacting with peers and online interactions, for example in this quote from a participant at the Mexican university: "This transition has affected due to the lack of interaction with my peers, which is not the same as online interaction". Students also noted the challenge of developing relationships: "Since I had no biomedical courses before COVID-19, I haven't really met most of my engineering colleagues" (a participant from the Mexican university). Students from the U.S. shared similar responses, such as: "I cannot physically see the struggles and successes that my fellow BMEs are going through. It is more difficult to lean on one another when we are doing remote learning". Participants at the Mexican university reported that missing time in laboratories to put into practice what they learned limited the extent to which they feel part of the BME community, as shown in these quotes from participants: “The physical separation from everything that I was hoping to do, especially laboratory practices, have definitely had a toll on that feeling” and “I don’t like online classes because this career is very practical”. In contrast, students from the U.S. university did not report such effects, with responses like, “The BME department has done an excellent job reaching out and making me feel connected”. Another result from Table 7 is that participants from the Mexican university mentioned that the online courses leveled some learning opportunities, giving a certain type of students the confidence to participate in class and seek help if they struggled to understand any topic. These comments about leveling the learning opportunities were not mentioned by the U.S. university participants, suggesting that Mexican students were the only ones that perceived that the online environment helped them to overcome feelings of anxiety to express their ideas in front of all their peers with comments such as: “Ironically I feel I have spoken to more classmates since I add them in WhatsApp, and since I am shy, online is easier”.

Participant responses to Q2 (“In what ways are you connecting with each group?”) showed a clear difference between how participants connect with their peers, professors, and other BME groups. Connection with their peers and BME groups was often through the use of social media platforms (Facebook, Twitter, etc.) and texting applications such as WhatsApp. They reported using email and meetings in video conference platforms (such as Zoom) to connect with their professors and mentors.

When asked about their challenges in connecting with different groups, most students at both study sites reported difficulties developing meaningful personal interactions with their peers and professors (refer to Table 8). Example quotes from participants at the Mexican university include, “There is a lack of trust or comfort between our classmates because we really don’t know each other”, and “Almost no time is dedicated to communicating, also it feels awkward most of the time”. Similar responses came from participants at the U.S. university: “The fact that we can’t come together as a community to physically help one another through things like study groups, review sessions, and just learning together”. Developing new academic and professional connections was also challenging despite having enough technology to communicate with other BME groups and professors. For example: “I don’t generally feel much of an incentive to enter into other BME groups despite me knowing that I’d benefit from doing so” or “I think there needs to be more dialogue between professors and students about how the pandemic is affecting our personal/academic lives”. Note that fewer participants at the U.S. university identified a decrease in motivation to express their opinions than those at the Mexican university.

One of the biggest issues identified by participants at both study sites as affecting their learning was the distractions that they experienced at home. This issue was reflected in comments such as, “I think that since you are at home there are many things that can interrupt you, even when you have a personal space and a settled time”, (Mexican university participant) and “It is a lot harder to focus, and it is stressful to make sure your Wi-Fi and technology are always working” (U.S. university participant). Similar to participants’ thoughts about how their sense of belonging was affected by the transition to online classes, participants at the Mexican university felt that they were lacking practice to better understand what they were doing in their engineering course with comments such as: “I’m not learning any technical topics relating to the application of engineering” or “I believe that having to take practical classes online has definitely affected the amount of knowledge I got”. Students also mentioned that they were feeling discouraged or tired due to their online classes, with responses such as: “I have learned almost nothing and struggle to have any motivation to learn new topics” (U.S. university participant).

4. Discussion

4.1. Insights on Student Experiences in the Context of the University in Mexico

In response to RQ1 (In what ways did a transition to online and hybrid courses during the COVID-19 pandemic affect undergraduate engineering students' sense of belonging in their major?), quantitative results showed that most students felt that the transition to online classes affected their sense of belonging in their major, with a mean of 3.5 out of 6. This widespread affectation coincides with the study done by Skliarova et al. [49], where college-level students stated that they preferred face-to-face classes instead of remote classes due to the difficulty of the transition due to COVID-19. As shown in Table 2, the most common response to the question about the extent to which transitioning to online classes affected their sense of belonging in BME was 5 out of 6, with 24 students reporting that their sense of belonging in engineering was significantly affected by the transition to online courses during the pandemic (refer to Table 2). These results support other findings that transitioning to online classes negatively affected students' feelings about their major and the way they perceive their academic community [8]. This may be related to the significant correlation between the effects that online courses had on participants' sense of belonging and their learning due to the COVID-19 pandemic as shown in Figure 1. This correlation supports other studies showing that students who feel less connected with their academic environment and community are more likely to struggle to learn new topics about their major, affecting their sense of belonging and ability development [7]. Engineering educators should be aware that some of their post-pandemic students may be struggling to keep track of their course material due to their poor development of a sense of belonging and a lack of identification with their academic community [29,30]. This could ultimately negatively affect their learning abilities and interest in making an extra effort to perform better in their college courses [33].

These findings are supported by the logistic binomial regression results as shown in Table 4. The only significant predictor for a high negative effect on participants' sense of belonging in engineering was the variable "online classes affecting learning". This correlation was highly significant, and the odds ratio showed that an incremental increase in the perception that online courses affected students' learning made them 1.48 times more likely to feel a lower sense of belonging in their major. The qualitative analysis of the question "how has this transition affected your sense of belonging in engineering?" provided more insight into why engineering students felt that online courses affected their connection with their academic community. The most common response to this question, as shown in Table 7, was that online classes created challenges in forming and maintaining peer relationships. This finding suggests that friendly and cooperative relationships with other students are an essential part of developing a sense of belonging in engineering and missing these connections can be an important factor in a lack of connection with a student's major [9,10,50]. These findings may be especially related to this cohort of students, many of whom have never met their peers in person at the time of this study. Another notable factor in the lack of a sense of belonging in engineering was the lack of practice time in laboratories and theory demonstration in class, with 30% of the engineering students reporting these feelings (refer to Table 7). These findings make it clear that students consider laboratory practice and hands-on activities to be important parts of their engineering training. Lacking this practice makes students believe they are missing basic knowledge about their major and feel like they do not belong to the engineering community. This issue could be partly due to the fact that this generation of students belongs to an educational system that prioritizes teaching based on acquiring competencies, as is reported according to the research trends in education innovation in the world [51].

The analysis of the responses to questions about how well they were connecting with others (Q6–Q9 in Table 1) showed that participants' connection with their peers was the least affected during online classes compared to connections with other groups. Findings of the qualitative analysis of the question "In what ways are you connecting with each group?—Peers, Instructors, TAs, Other engineering groups" suggest that engineering students found a way to keep in touch with their peers, primarily via WhatsApp groups. However, the qualitative analysis of responses about what participants were lacking in connection, as shown in Table 8, reveals that this connection between peers was not necessarily effective, with 66% of participants reporting difficulties in developing personal relationships with their peers and professors. Moreover, most students felt that they were in communication with strangers, making learning and discussions of different ideas less likely to happen. Although challenges in communication due to technology were not an issue among participants, the goal of connecting with their peers was only to complete a specific task or assignment. Relationship development and learning can be affected by this lack of meaningful connection [10,32]. Concerning the aforementioned effect, using information and communications technology (ICT) to form links between people has been shown to have a positive effect on promoting and engaging a remote network of participation for teaching and learning through the citizen science approach [52].

Similarly, students' interactions with possible role models were affected due to the transition to online classes, with relatively low mean scores for connection with professors, mentors, and other engineering groups as shown in Table 2. According to the responses to the question "In what ways are you connecting with each group?—Peers, Instructors, Mentors, Other engineering groups", students mentioned email and social media as an easy way to communicate with their professors, mentors, and other engineering groups. The issue was that this way of communication created a disconnection between them and these important groups of their academic community, generating doubts about their sense of belonging in the engineering community [12,30]. The qualitative analysis of the question "In what ways are you lacking in connection at this time?" showed that a majority of engineering students experienced difficulties in effectively connecting with their friends and professors, as shown in Table 8, with many participants mentioning that these difficulties negatively affected their motivation to speak and express their opinions in class.

For engineering educators to maximize student learning and their relationships with their students, they need to address the lack of connection students perceive in online classes [13]. This issue could be addressed by designing activities that promote more confidence and open new ways of connecting between students and professors, mentors, and other professional engineering groups, aiming to compensate for possible experiences of ineffective connection during the COVID-19 pandemic [3]. These could include the use of online discussion boards, small breakout groups in online meetings, or having students create brief presentations of the course content asynchronously (i.e., outside of class time).

In response to the RQ2 (How did engineering students' sense of belonging affect their perceptions of learning during the online courses due to the COVID-19 pandemic?), students perceived that their learning was affected during the transition to online classes during the pandemic, as shown in Table 2 and Figure 1. These results highlight the importance of developing strategies to help engineering students improve their prior knowledge post-pandemic. These new strategies would need to help students to develop a stronger sense of community and better relationships with their peers, professors, and mentors as well. This way, both engineering students' sense of belonging and learning could be improved in parallel [5,6], as the findings of this research suggest a strong correlation between these two factors.

The analysis of participants' responses to the question on how the transition to online classes affected their learning (refer to Table 9) revealed the detrimental effect of distractions students experience in their homes, with 26% of participants reporting such challenges affecting their ability to stay focused on their academic activities. These findings suggest professors should be prepared for students having difficulties focusing for long periods of time during online classes. This could be exacerbated by reports that students usually multitask during online courses [14]. Another important issue that students perceived as negatively affecting their learning was the lack of practice time in labs and hands-on activities. Students feeling less prepared due to the lack of opportunities to put into practice what they have learned in their online classes could have long-lasting effects [15,16].

4.2. Insights on Student Experiences in the Context of the University in the Southeastern U.S.

Further analysis of RQ1 (In what ways did a transition to online and hybrid courses during the COVID-19 pandemic affect undergraduate engineering students' sense of belonging in their major?) helped determine that the majority of participants at the university in the U.S. stated that the transition to online learning has had a relatively high impact on their sense of belonging in engineering. In a similar study, students reported a consistently negative impact of the transition to online and hybrid learning on their sense of belonging in engineering [8]. The correlation shown in Figure 1 highlights the implications of this negative impact; for an incremental increase in the student-identified effect on their learning, the impact on their sense of belonging in engineering is amplified based on an odds ratio greater than one.

Although students provided neutral responses to the Likert-type question about the extent to which they connected with peers, many participants' open-ended responses indicated that connection was lacking for them during the pandemic. There is an observed interrelatedness between students' diminished connection with peers, for any amount of diminished connection with peers, and a small decrease in the sense of belongingness. Although statistical significance was not observed in the U.S. data for this relationship, it is still noteworthy as it tells us that the amount in which students interact with colleagues may have bearing on their sense of belonging, but not to an amplified degree.

Interrelatedness between students' lack of connection with professors and their sense of belonging showed that for an observed drop in connection with professors, there was an amplified observable deterioration in the sense of belonging. This demonstrates that there are opportunities for increased connection between instructors, teaching assistants, and students so capitalizing on this opportunity would likely yield an overall higher sense of belonging in engineering.

The relatively low response to the question about connecting with other engineering groups is an indication that students are not branching out and forming new relationships with others outside the structure of their courses. Perhaps a contributor to this low response value was the ambiguity of the term "other groups".

Freeman et al.'s study of the sense of belonging in first-year college students supports the idea that a sense of belonging relates to student learning [4]. Some students reported relying on technology, such as social media platforms, to connect with other students and groups. Upper-level students reported feeling more connected to engineering groups than FYE students. This difference may be because they have had time to build connections and join clubs, study groups, professional organizations, etc. The online transition having less effect on upper-level students' learning may be because there are more project-based courses in senior courses, such as capstone, compared to FYE and sophomore courses, which tend to be more lecture-based.

4.3. Mexican and U.S. Students

In response to the RQ3 (In what ways do these effects differ for students in Mexico and the U.S. based on differences in demographics and culture?), participants at both study sites perceived their sense of belonging in engineering as being affected by the transition to online learning in a similar way, which suggests that the negative effects experienced by engineering students during the COVID-19 pandemic transcend geographic locations. This is important because economically advantaged countries, such as the U.S., might be considered as being better prepared to offer online courses than developing countries, such as Mexico, due to their advanced infrastructure and telecommunication technology [3]. Our study shows that any technological advantages, whether real or perceived, did not help U.S. students feel more connected with their academic community than their Mexican counterparts. Students from both countries experienced issues adapting to online classes during the pandemic and most of them struggled to develop a sense of belonging in their major. Insight into how participants connected with their peers and professors during online classes (Tables 2 and 3) supports the idea that the U.S. infrastructure may have provided an advantage, as Mexican participants reported more issues connecting with their peers than the U.S. participants. It is interesting to note that these connection issues did not generate a difference between the participants' sense of belonging in engineering at the two study sites.

Our quantitative analyses showed that learning and a sense of belonging are significantly correlated in both the Mexican and U.S. contexts. This correlation needs to be further investigated to determine possible causality aiming to understand the role of online classes in this correlation and to examine if the correlation exists for other populations in different contexts. Regardless of whether courses are delivered online, knowing more about students' sense of belonging could help engineering educators develop strategies to make students feel welcome and comfortable in their academic community, which ultimately could help them to improve their learning experiences [7,27,28]. This may be particularly relevant in the Mexican context since participants' perceptions that online courses affected their learning was the only significant predictor of a lack of sense of belonging in engineering.

The finding that participants classified as having a low sense of belonging in their major reported a significantly higher negative effect on their learning than those classified as having a high level of sense of belonging was similar for participants in both study sites. This provides further support for the idea that promoting a more welcoming environment in classes and better ways of connecting with other students and professors could help develop a stronger sense of belonging [26], which ultimately could improve students' learning experiences and interest in engineering majors [29].

The biggest issue participants identified with the online classes was the lack of face-to-face communication, which affected students' relationships with their peers and was reflected in a low sense of belonging in engineering. The majority of participants in both study sites reported that online classes affected their sense of belonging and that they experienced difficulties developing meaningful relationships with their peers. These findings pinpoint the importance that having a positive relationship with their peers has on engineering students' sense of belonging [30]. Since U.S. students' relationships with their peers were affected in a significant way, U.S. professors and educators need to pay special attention to this issue and try to promote more face-to-face activities that could help their students to feel like they are in a community where they can talk about their life and academic experiences and learn from each other [25]. Lacking meaningful connection affected the way that engineering students interacted with their academic community, and even if the students had the opportunity to establish a telecommunication window with their professors and peers, the main goal of communicating ideas, doubts, or personal feelings was not achieved as it was in face-to-face communication [8].

One of the most important goals of all academic activities is students' learning, and according to these research findings, engineering students' learning was negatively affected by the transition to online courses due to the COVID-19 pandemic. The U.S. students' response to Q10 was the highest mean of all the six Likert-type questions, and it was the second highest for the Mexican students. Figure 2 shows how students' sense of belonging in engineering was affected due to the remote classes during the COVID-19 pandemic. A series of problems related to communication limitations and telecommunications and information technologies infrastructure deficiencies deteriorated students' learning experiences; consequently, this issue affected the sense of belonging in the students toward engineering majors.

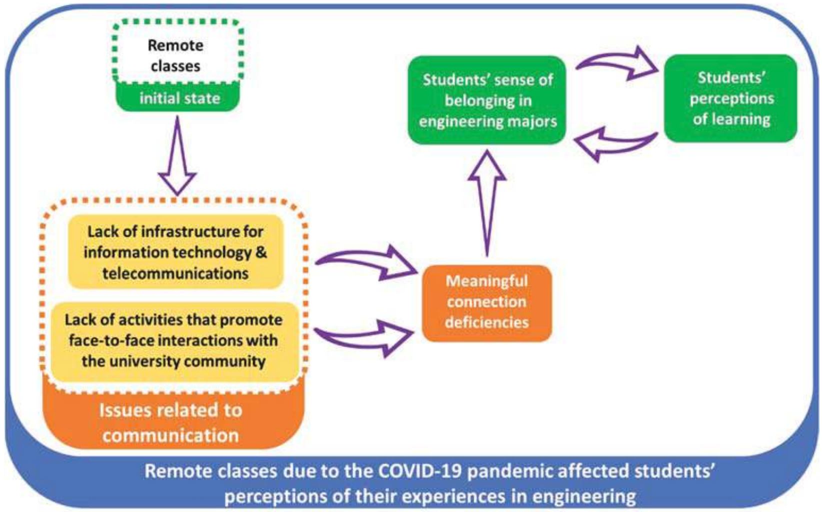

Figure 2. Online courses' effect on engineering students' sense of belonging and learning.

Further analysis of the qualitative responses helped us to better understand the reasons why engineering students felt that online courses affected their learning, and what kind of factors were similar or different between students in Mexico and the U.S. Both Mexican and U.S. participants reported that having to spend many hours in front of a screen was tiring, and that made them feel discouraged to get involved in class activities, making learning new topics a challenging task [9]. Similarly, students were easily distracted by their home environment and lack a special place to concentrate on their classes. This issue affected their ability to focus on their class material and ultimately hindered students' learning. It is important to note that the U.S. participants reported struggling with this issue more than the Mexican participants, and further research needs to be conducted to analyze the reasons for this lack of focus when the environment is not what it used to be in regular classes for the U.S. students. Knowing more about the reasons why students are easily distracted when they are alone in their homes, instead of in their classroom where they could be distracted by any of their peers, could be of paramount importance if universities want to establish online courses in the future.

The online classes had a different effect on Mexican and U.S. participants' learning and academic behavior, creating a greater interest in self-regulated learning activities for the U.S. participants and motivating them to search for knowledge by their own means. This positive effect of online courses needs to be promoted by U.S. professors, even when they return to face-to-face classes [13]. On the other hand, Mexican participants were less motivated to look for self-regulated learning opportunities, and Mexican professors need to develop teaching strategies where students have to take more responsibility for their learning in case their connection with their peers and professors is jeopardized again. Another difference between the Mexican and U.S. participants was that the Mexican participants reported that missing practice opportunities in their engineering courses was the main reason for their difficulties learning during the online classes, while none of the U.S. participants mentioned this lack of practice opportunities as an issue affecting their learning experiences. This finding suggests that U.S. universities may be well prepared to conduct online practices and labs, making students feel like they are getting that practice experience, while this could be a limitation for Mexican universities [3]. As practice is important to engineering students, Mexican universities need to work harder to improve online practice opportunities and labs if they are interested in online courses in the future.

4.4. Limitations and Future Works

This research compared two populations from different countries and cultures, creating a challenge in selecting the right students to compare their experiences during online classes due to the COVID-19 pandemic. This issue generated a mismatch between the two study populations in terms of student levels, with U.S. participants taking courses in their sophomore year, while Mexican participants were taking courses in their sophomore, junior, and senior years. Students' experiences and sense of belonging development could be different between students in their second year and students in upper-level courses, and more information about these possible differences needs to be analyzed in future research. An additional limitation in terms of context is that the data collected for this study were from students at single institutions for each country, which could generate possible differences from students in other contexts and majors. A limitation of the data collection is that, although the validity and reliability of data collected through close-ended survey questions were established in previous studies [36], students' interpretations of open-ended survey questions related to COVID were not verified; these questions were developed based on the emerging literature, not on how students themselves described their experiences. This could be addressed in future studies by interviewing students about how they interpreted open-ended survey questions.

4.5. Future Work

Future research about students' sense of belonging during online classes should include an analysis of telecommunications technology availability and how these variables could ameliorate the lack of meaningful communication and connection development. In addition, it would be interesting to incorporate other populations in different universities and majors with the aim of creating a deeper understanding of students' sense of belonging development during online classes. Likewise, it is pertinent to consider conducting more studies from a longitudinal perspective in order to observe the long-term effects on engineering professionals that graduated after experiencing online classes during the COVID-19 pandemic.

5. Conclusions

Engineering educators need to be aware of the importance of generating a positive learning environment in their classes and academic activities with the aim of developing their students' sense of belonging in engineering. Helping students to identify with and feel connected to their peers, professors, mentors, and other engineering groups could help them feel motivated to be involved in more engineering-related activities that could help them perform better in their classes and successfully complete their assignments. The findings of this research stressed the poor sense of belonging that engineering students may have after taking online classes during the COVID-19 pandemic when they missed opportunities to develop meaningful relationships with their peers and professors due to the lack of good connection with these key pieces of the engineering academic community. These findings were very similar in the Mexican and U.S. universities, showing that telecommunication infrastructure is not enough to recreate a learning environment where students can feel connected and develop a sense of belonging with their academic community. Additionally, regarding the lack of connecting opportunities with the academic community, Mexican participants reported a poor sense of belonging development because they felt that they lost important opportunities to practice what they learned after missing lab practices and hands-on activities. This issue was not reported by U.S. participants, suggesting that good telecommunications infrastructure and well-equipped labs could be excellent tools if engineering programs want to go fully online in the future.

Most of these issues affecting engineering students during classes delivered online disappeared when students returned to campus, but the lack of the development of students' sense of belonging and possible misunderstandings generated by the two years of online courses should be addressed by engineering educators. Activities such as more accessible office hours, study groups, and meetings with mentors and tutors should be highly promoted to help students recover from any academic and motivational struggles that may have been generated during the online classes due to the COVID-19 pandemic. Failing to develop a well-connected environment that aims to foster engineering students' sense of belonging could have a negative effect on their learning and performance since this study found a significant correlation between students' sense of belonging and their learning.

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