Chapter

Applications of Silk in Biomedical and Healthcare Textiles

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Abstract

Global trends are shifting towards environmental friendly materials and manufacturing methods. Therefore, natural fiber applications are gaining traction globally. Silk, a natural protein fiber is one of the textile fibers that have recently received more attention due to the new frontiers brought about by technological advancement that has expanded the use of silk fiber beyond the conventional textile industry. The simple and versatile nature of silk fibroin process-ability has made silk appealing in wide range of applications. Silk is biocompatible, biodegradable, easy to functionalize and has excellent mechanical properties, in addition to optical transparency. This review chapter explores the use of silk in biomedical applications and healthcare textiles. Future trends in silk applications are also highlighted.

Keywords: Silk, Silk fibroin, Bio-applications, Functional textiles

1. Introduction

Silk is a natural fibrous protein biopolymer, spun by arthropods like spiders, mites, fleas and silkworms [1]. The structure, composition and properties of silk differ depending on their specific function and source [2]. Silkworms are one of the silk spinning insects that has been researched in detail and finds wide applications in textiles [3]. Silk production, also known as sericulture, has a long history that is usually closely associated with China. Silk was discovered in 2640 B.C. by Hsi-Ling-Chi, who also found out that silk fiber loosened and unwound in hot water; and twisted to make thread that was used to weave a very strong cloth. Hsi-Ling-Chi later developed a means of raising silkworms and a method of reeling the fibers to make garments [4, 5]. As silk became a very precious commodity, sericulture spread within china and to other countries. Demand for silk products created a trade route that is famously known as Silk Road [6].

Silk filaments from silkworms are classified into two types; mulberry and non-mulberry (also called wild or vanya silk). Mulberry silk are generally produced by *Bombyx mori* which are insects belonging to the Bombycidae family. *Bombyx mori* feeds on mulberry plant leaves. Mulberry silk is further divided into bivoltine and multivoltine, depending on the number of silk cocoon crops harvested annually. Bivoltine is harvested twice a year while multivoltine is harvested throughout the year [7]. Non-mulberry silk on the other hand, is silk from Saturniidae family. Non-mulberry silk includes tasar silk, muga silk and eri silk. Tasar silk is secreted by *Antheraea* silkworms. They have hard and compact cocoons. Tasar silk can either be tropical tasar

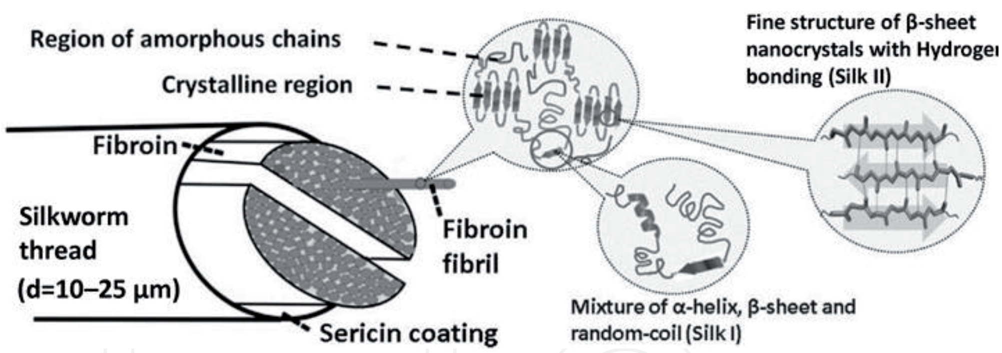

Figure 1.
Schematic presentation of the silk fibroin (SF) structure; d represents the diameter of a single silkworm thread [13]. Reproduced with permission.

or temperature tasar. Muga silk is produced by *Anteraea assamensis* silkworm; it has a unique natural golden color, with significant luster and durability. Eri silk is produced by *Philosamia synthia ricini (*also called *Samia cynthia)* silkworms, which usually feed on castor or papa plant leaves. Eri silk being in the wild silk category, has however been completely domesticated just like mulberry silkworms. Eri silk cocoons draw shorter silk fibers when compared to other silks which draw continuous filaments [8, 9].

Silk cocoons comprise over 95% proteins and about 5% impurities (mineral salts, waxes, ash). Raw silk consists of two proteins; sericin (gum) and fibroin (fibers). Sericin and fibroin are composed of amino acid chains. The types and composition of these amino acids are different for sericin and fibroin. Non-mulberry silk has lower sericin with higher levels of impurities compared to mulberry silk [10]. After degumming, sericin and other impurities are removed from the raw silk fibers. Therefore, degummed silk is composed of mainly fibroin protein [11, 12].

Several authors have reviewed, described and demonstrated the structure of silk fiber varieties, especially *Bombyx mori* in relation to several performance properties. These include: conformations of silk, heavy chains with possible chain folding and micelle assembly in water, primary structure, 12 repetitive and 11 amorphous regions, amino acid sequences of i, ii, and iii, hierarchal structure among others (**Figure 1**) [13].

Silk fibers are usually used for conventional textile applications after the removal of sericin and other impurities. Recently however, due to excellent mechanical and optical properties, as well as its biocompatibility, biodegradability and implant ability, silk has found increased applications in functional textiles [1, 14, 15]. This has been made possible by the simple and versatile nature of the silk fibroin process ability into various forms such as sponges, gels, strands, blocks, foam, films, and more recently, nanofibers [16–21]. Applications of silk in biomedical materials, drug delivery and in optics and sensing are therefore discussed in this chapter. The chapter underscores the forms and properties of silk making them suitable in these applications.

2. Common manufacturing processes for silk-based functional products

More recently, silk fibroin (SF) films with fineness ranging from hundreds nanometers to tens micrometres are obtained from regenerated solutions through liquid processing including: spin coating, inject printing, doctor blade, soft lithography, contact printing or nano- imprinting, among others; that support industrial scale production. Doping, blending and functionalization of SF has also been a route to achieve substrates for advanced technological use in organic electronic sensors based on field effect transistors, and with optically active dyes, particularly for biomedical applications [22–25]. Nano and micro-patterning, through spin coating and lasing, was used to obtain stilbene-doped silk film of significant mechanical performance and optical performance [24].

Innovative attempts during breeding and feeding of silk worms, through incorporation of dopants in the diet, have yielded modified SF substrates of functional value; e.g. silk threads with electrical conductivity through incorporation of silver nanoparticles in mulberry diet, fluorescence introduced in silk fiber through colorant compounds in mulberry feed, among others [26–29]. These approaches save on extra processes and time that would be required as after treatments, and enhance the durability of such functions. Optimization of silk-worm breeding is often required for control and reproducibility of functional substrates. For example, among others, the silkworm survival rates, temperature conditions and duration of the larval cycle are monitored.

Based on different varieties of *B. mori*, in 2019, a silk fibroin based technology was developed in order to optimize and support industrial bio-manufacturing [30]. The evaluation and standardization of extraction, purification, and characterization methods were reported; yielding biocompatible SF substrates with high purity and outstanding chemo-physical performance. The result was a validated bio-diagnostic microfluidic and photonic device (a lab-on-a-chip) (**Figure 2**).

Several conventional textile spinning and construction methods are used for production of functional silk yarns, fabrics; including a variety of finishing technologies through which active functional ingredients may also be introduced. Therefore, such might be applied during fiber spinning (e.g. for sutures) and after fabric construction through a variety of wet and dry finishing processes [31]. Innovative approaches include micropatterning, 3D printing and more nanotechnology based systems (**Figure 3**).

Electrospinning is a common method used in the production of nanofibers and microfibers from SF solutions. The ensuing fibers possess a high specific surface, favoring the use of such scaffolds in tissue regeneration [34, 35]. The mechanism of electrospinning (**Figure 4**) is based on a high electric voltage applied to the fiber polymer solution. The polymer solution is ejected when the electric force overcomes the surface tension of the polymer solution, forming a polymer jet. Electrospinning can be of needle or needleless. The needle electrospinning utilizes a high-voltage

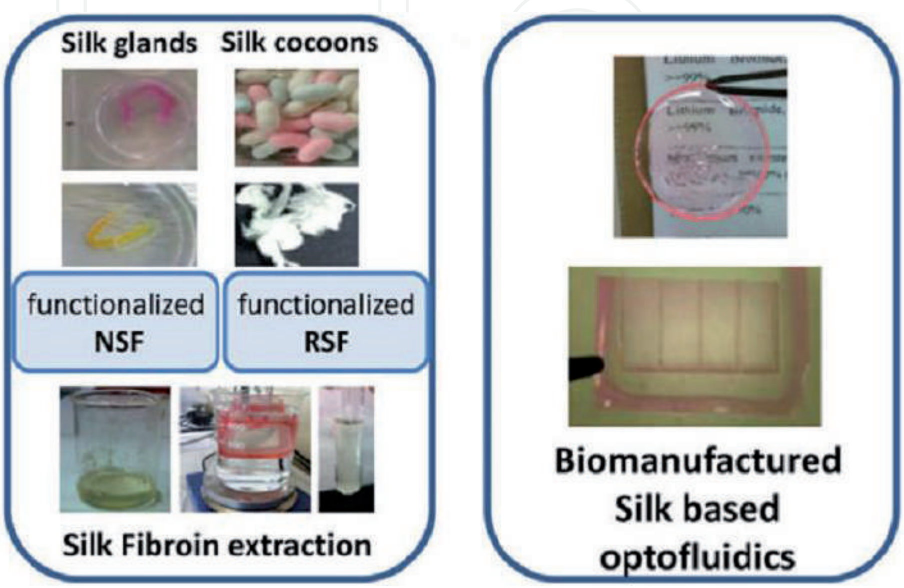

Figure 2.
Schematic picture of the biomanufacturing approach to obtain SF based technological substrates [30]. Reproduced with permission.

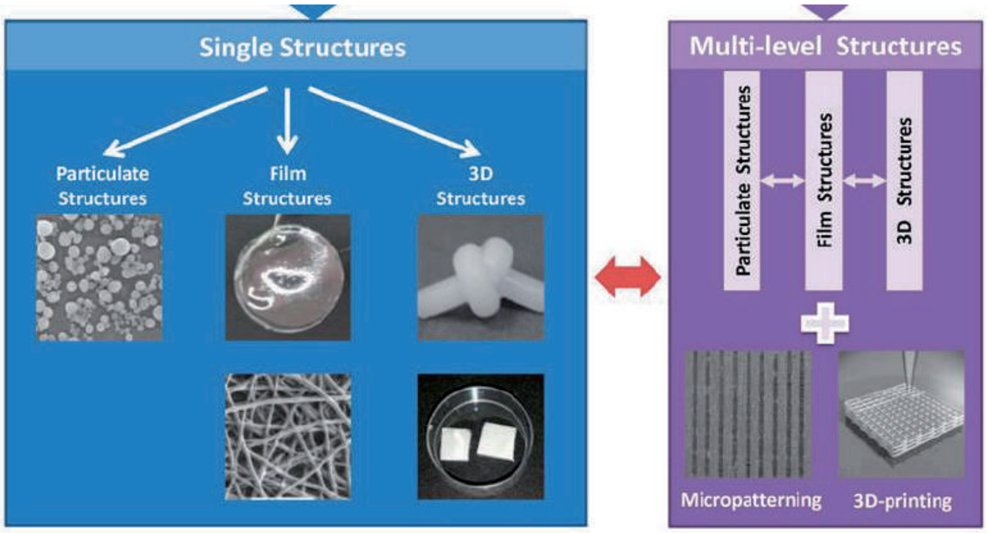

Figure 3.
Structural design of SF-based biomaterials from single structures to multi-level structure [32, 33]. Reproduced with permission.

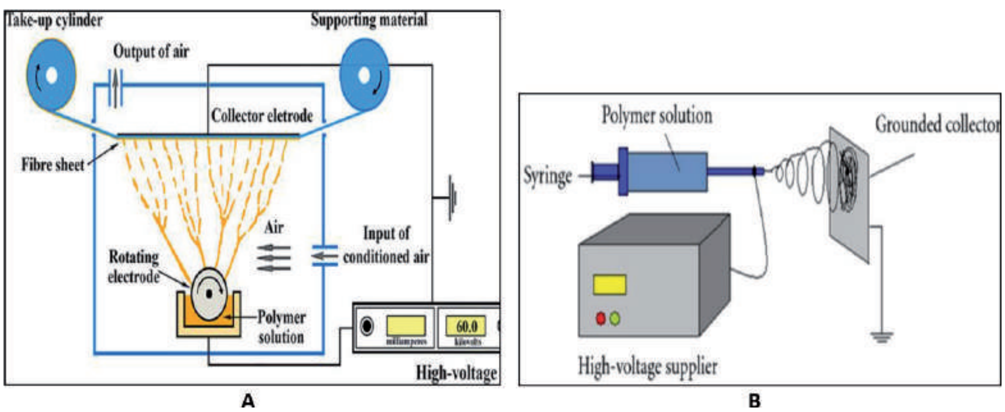

Figure 4.
Schematic images of needle-less (A) and Needle (B) electrospinning processes [40]. Reproduced with permission.

power supply, and a syringe needle connected to a power supply and pointed towards a collector. Needle electrospinning options pose a demerit of very low productivity, thus, unsuitable for practical commercial value. Needleless electrospinning setups have been innovated recently. In these systems, polymer jets form simultaneously from the surface of polymer solution by self-assembly [36–41].

3. Silk in biomedical textiles

Biomedical textiles are composed of fibrous units produced from natural or synthetic materials. These textiles are used in either external or internal environment of living organisms [42]. Biomedical textiles are further used, medically, to improve the medical condition of a patient [43, 44]. Some biomedical textiles include implantable, non-implantable and extracorporeal devices as well as hygiene and health care products [45]. Non-implantable materials/devices include wound dressings materials like bandages and gauzes. While, implantable materials/devices include artificial arteries, heart valves, sutures, and vascular grafts among others. Extracorporeal devices mainly include artificial body organs. Hygiene and health care products include sanitary towels, tissue paper, wipes, hospital gowns and uniforms, hospital bed covers, surgical covers, masks and caps. Other biomedical textiles include polymer sensors and wearable medical implants [46, 47].

Textile materials used in biomedical applications must be non-allergic, non-carcinogenic, non-toxic, biodegradable and biocompatible. Additionally, biomedical textile materials must be able to be stable to handling and use. For example, during sterilization and use, they should not change their physical or chemical properties (e.g. through oxidation or chemical reaction). Other important properties for these textiles include: high tensile strength, elasticity, high burst stream, low permeability and durability [42, 48, 49]. Different synthetic (e.g. polyester, nylon, acrylics, and polyethylene) and natural (e.g. silk and cotton) fibers are used in production of biomedical textiles. Silk fibers possess good toughness and ductility in terms of elongation at break, tensile modulus and tensile strength; suitable for biomedical applications[1, 50]. Additionally, regenerated silk solutions are gaining popularity in producing various biomaterials in form of gels, films, membranes and sponges [51].

3.1 Silk in wound dressing

Studies have shown that silk fabricated through non-weaving and electrospinning can be used in wound dressings, and as drug carriers [1, 46, 52, 53]. Xia *et al*. [54] reported that silk fibers functionalized with silver nanoparticles presented special antibacterial properties in a wound dressing material. A two-layered wound dressing developed from a wax-coated silk woven fabric, a sericin sponge and a bioactive layer of glutaraldehyde cross-linked silk fibroin gelatin was reported to reduce the size of the wound, collagen and epithelialization [55–57]. He *et al*. [58] asserts that fibroin hydrogel from *Bombyx mori* cocoons has good healing properties due to its biocompatibility nature, low biodegradability and immunogenic properties. On the other hand, Chouhan *et al*. [59] found that nanofibrous mats of silk, functionalized with Poly Vinyl Alcohol, (as a blend) mat supported diabetic wound healing. The mats were able to promote tissue re-modeling and also regulated extracellular matrix; thus the wound healing.

3.2 Silk garments for dermatology treatment

Atopic Dermatitis is a worldwide health concern, with a higher prevalence in developing countries, and occurring in among many age groups. Symptoms for Atopic Dermatitis include redness and itchiness of the skin. These symptoms can be severe leading to a chronically repeating flare characterized by serious eczema (distribution of skin lesions) [60]. Treatment and management of this condition requires skin stabilization, flare prevention, as well as the use of medication that can cure the symptoms [61]. Silk garments have been used as a textile-based therapy for Atopic Dermatitis owing to their hygienic properties including antibacterial properties. Additionally, silk filament fibers are strong and round in shape, and therefore fine and smooth. Wearers experience comfort to the skin as this structure prevents and scratching from friction and irritation to the skin [62]. Moreover, the fine and smooth fibers have no or very little abrasive effect on atopic skin. This enhances the recovery of the irritated skin unlike with rough fibers that irritate the skin. Due to a significant moisture regain, silk fibers are also able to maintain body humidity therefore reducing the sweat circulation and moisture loss that can make xerosis worse [63]. A study by Hung *et al*. [60] further the ability of silk garments to significantly decrease the severity level of dermatitis symptoms. The study emphasized the merits with the smoothness of silk which is friendly to the irritated skin. The fiber enhances collagen synthesis and also reduces inflammation which cures eczematous lesion [63, 64]. Moreover, hygienic properties of silk act as a skin barrier, protecting the skin from bacteria, viruses and other contamination that reduces the inflammation [60, 65]. Of importance is the sensory experience of patients with silk garments as highlighted by these studies; they contribute to the physical and emotional comfort of dermatitis patients which possibly aids the healing process. Therefore, silk garments can be used as a non-pharmacological therapy to impede the severity of Atopic Dermatitis and other related dermatology conditions.

3.3 Silk in hygiene and health care products

The good mechanical properties of silk, its softness and antibacterial properties partly account silk's application in producing hygiene and health care products. Some applications of silk in hygiene and health care include: materials used in hospital wards and operating theatre as well as materials used in care and safety of hospital staff and patients. Silk materials used in operating theatre are in form of patient drapes, and surgical gear (as gowns, caps, masks and cover cloths) [46]. Silk, functionalized with titanium dioxide nanoparticles was used to produce a photocatalytic silk mask paper. The mask was found to exhibit special protective functions— degrading volatile organic compounds achieved by combining the unique properties of silk fibers and nano-TiO_2 [66–69].

3.4 Silk-based tissue engineering

Tissue engineering applies principles of biological sciences and engineering to develop biological substitutes to replace, enhance and maintain damaged or defective tissues such as cartilage, bone, skin and even organs [70, 71]. The choice of the biomaterial and the methods used determines whether the resulting bio-substitute will be functional. Silk has good mechanical properties, has a slow degradation rate and a low inflammatory response which makes it fit for use in tissue engineering. However, Sericin can elicit immune response and must therefore be completely removed before being used [72]. The type of silk that is commonly used in tissue engineering is *Bombyx mori* silk. Other types of silk that are gaining popularity include silk fibers from; *P. ricini*, *A. assama*, A. *pernyi* and *A. mylitta* [71, 73]. Silk-based tissue engineering includes: Scaffolds in form of skin grafts/artificial skin, bone grafts, artificial pancreas, cardiac tissue, artificial liver, artificial Intervertebral Disc Intervertebral disc, among others [74].

3.4.1 Skin grafts/artificial skin

Skin, the largest body organ protects the body against infections from pathogens and microorganisms [75]. Due to certain illness, the skin may get damaged and may require some replacement in form of grafts. A good graft is supposed to cover and protect the intended place without causing any negative immune response. This promotes fast healing that reduces chances of scarring on the body [46].

In the recent past, different biomaterials like silk fibroin, cellulose alginate, collagen, polycaprolactone (PCL), polylactic acid (PLA), silicone, dextranelastin and polyethylene glycol(PEG) have been explored as possible cellular scaffolds for skin grafts and wound healing [73, 76, 77]. Among these biomaterials, silk has been used to mimic human skin as well as in wound healing. This is because silk has notable properties like low immune response, biodegradability, biocompatibility and is cost-effective [1].

Additionally, studies have proved that silk supports human keratinocytes and fibroblasts which are important in engineering artificial skin [46, 73, 78]. Studies by Chauhan et al. [59, 79] have reported successful use of electrospun silk fibroin from *A. assama* and *P. ricini* silk species in wound dressing. The studies also reported that a blend of electrospun silk fibron with polyvinyl alcohol promotes faster healing of wounds due to granulation during tissue formation. Other studies have demonstrated the use of electrospun silk fibroin from *A. assama* keratinocytes being successfully used in engineering artificial skin.

The therapeutic performance of SERI Surgical Scaffold has been studied; including open label clinical trials and case reports. A few studies have cited side effects such as poor scaffold integration (**Figure 5**), that have required surgical removal of the scaffold [80].

Comparing woven fabric, non-woven fabric and a film foam from silk fibroin in relation to cell culture responses by human oral keratinocytes, studies reported that water vapor-treated non-woven silk fibroin had better cell adhesion and dispersion of human fibroblasts and keratinocytes [46, 81]. This suggests that silk based biomaterials for tissue engineering requires a careful selection of fabrication techniques and material to blend with. Electrospinning is one of the preferred techniques for making non-woven nano-scale fiber mats for engineering artificial skin [51]. More results from electrospinning silk for tissue engineering include: electrospun silk fibroin scaffolds, 3D nonwoven scaffolds made from crosslinking silk fibroin with formic acid, and water vapor-treated silk fibroin nanofiber matrices among others. [46, 81, 82]. Reported blends that have been used successfully with silk for producing artificial skin include alginate, chitin, intermolecular cross-linked recombinant human-like collagen and biomimetic nanostructured collagen [46, 83–85].

3.4.2 Bone grafts

Today, various biomaterials are available for developing scaffold-based bone tissue. One of such material is silk fibroin which has good biological and physic-chemical properties— making it suitable for developing osteoinductive functional

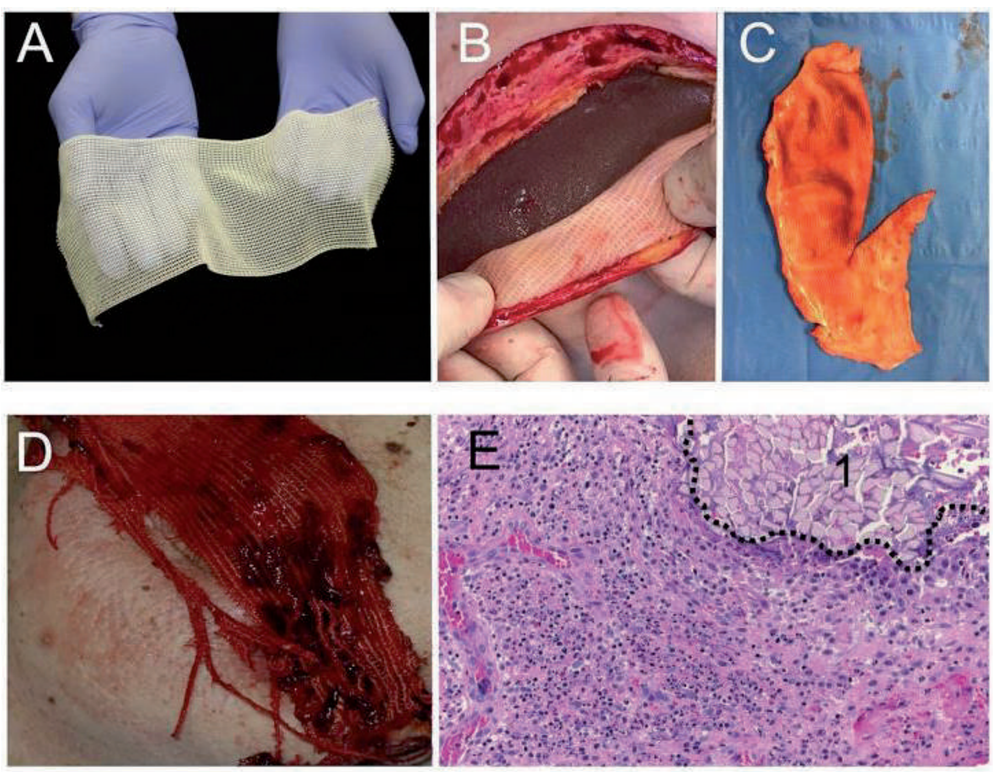

Figure 5.
Examples of SERI Surgical Scaffold implant loss in humans. A) Silk fibroin surgical mesh prior to implantation. B) Intraoperative view showing a free lying scaffold in the breast pocket. C) Retrieved scaffold surrounded with seroma. D) Interaoperative view of surgically removed scaffold with interpenetrated granulation tissue/scar plate (at >5 months), and E) histology of retrieved sample showing granulation tissue with neutrophiles and giant cells at the material (1) interface (dotted line). Reproduced with permission [80]. Copyright 2018, Elsevier.

bone grafts that resemble collagen [86, 87]. Silk fibroin from *A. mylitta* is reported to make porous scaffolds that mimic borne tissue [88]. Meinel et al. [89] induced osteogenic differentiation of human mesenchymal stromal cells in *B. Mori* silk fibroin to develop a bone graft. Other studies have explored blending *B. Mori* silk fibroin with hydroxyapatite to repair segmental bone defects [90, 91]. Findings by Reardon et al. [92] suggest that electrospun *B. mori* and *A. assama* silk fbroin blended with 70S bioactive glass repairs osteochondral tissue defects. Moreover, a study by Moses et al. [93] reports use of copper-doped bioactive glass silk composite matrices to repair large volume bone defects.

Fixation devices, including bone plates and bone screws have been manufactured from *B. mori* fibroin by casting in hexafluoroisopropanol, and formed into desired shaped (**Figure 6**) [94]. Silk screws tested in rats were well tolerated, showed early resorption and new bone formed around the threads of the screw. Such devices are easily malleable with hydration, allowing shaping for unique anatomical locations during surgery.

3.4.3 Artificial ligament and tendon

Tissue engineering for ligament and tendons requires biomaterials that are biodegradable, have good mechanical properties, good structural integrity,

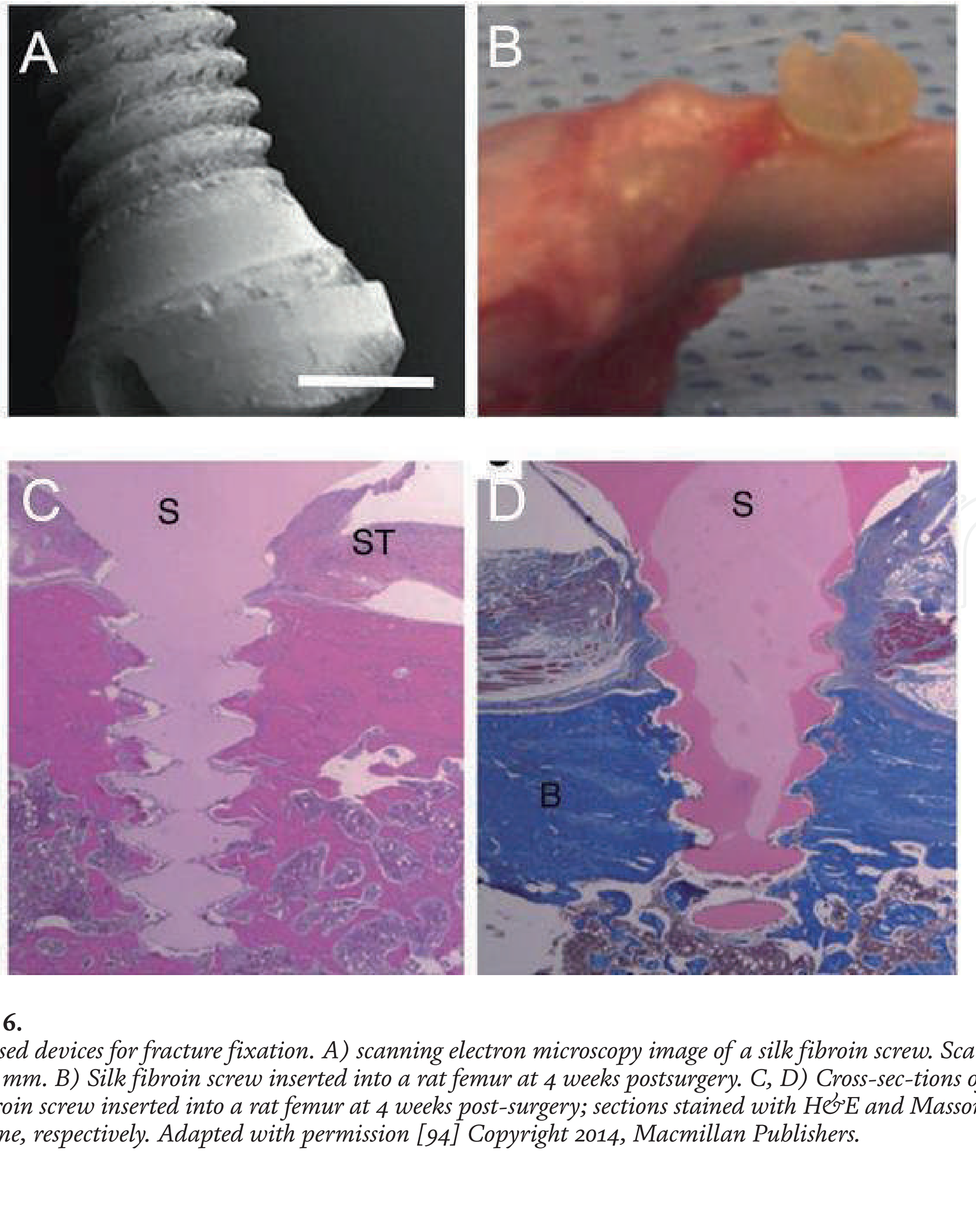

Figure 6.
Silk-based devices for fracture fixation. A) scanning electron microscopy image of a silk fibroin screw. Scale bar is 1 mm. B) Silk fibroin screw inserted into a rat femur at 4 weeks postsurgery. C, D) Cross-sec-tions of the silk fibroin screw inserted into a rat femur at 4 weeks post-surgery; sections stained with H&E and Masson's trichrome, respectively. Adapted with permission [94] Copyright 2014, Macmillan Publishers.

biocompatible and promote regeneration of new ligament and tendon tissues [46]. Silk is thus a suitable fiber that meets these requirements for performance and function [1, 93]. Weaving and braiding are reported as the most preferred techniques for making silk based ligament and tendon [95–97]. Other studies have reported crosslinking silk fibers with collagen matrix, coating poly(lacticco-glycolic acid) fibers with silk, blending silk fibers with fibroblast growth factor and transforming growth factor-β (TGF-β) in developing artificial ligament and tendon [46, 98–100].

3.4.4 Cardiac tissue

The most difficult part in cardiac tissue engineering is to perfectly mimic the original extracellular matrix. Patra et al. [101] and Stoppel et al. [102] reported to have successfully used scaffolds made *B. mori* and *A. mylitta* silk fibroins to treat myocardial infarction. Moreover, Mehrotra et al. [103] developed a 3-D cardiac construct made from stacking cell-laden silk films; the constructs proved to be good for cardiac tissue regeneration [73].

3.4.5 Liver modules

Different bio-artificial liver and cell therapies to treat liver diseases are available today. Cirillo et al. [104] developed a film from a blend of silk fibroin and collagen. A study by She et al. [105] examined a film made from silk fibroin, chitosan and heparin scaffolds that showed hepatocyte regeneration. Another study [106] reports scaffolds made from a blend of polylactic acid (PLA) and silk fibroin had a higher differentiation and proliferation as compared to scaffolds made from pure PLA alone. Likewise, a study by Janani et al. [107] reports that a functional liver can be fabricated from a blend of mulberry (*B. mori*) and non-mulberry (*A. assama*) silk fibroin.

3.4.6 Artificial pancreas

Different types of microspheres, hydrogels and nanoparticles have been developed to ensure a continuous release of insulin in diabetic patients [108]. In the recent past, islets have been encapsulated with biomaterials before they are transplanted to prevent immune response and to have a continuous insulin release [109]. A study by Davis et al. [110] reports encapsulating islets in silk hydrogel which improved the in vivo functions of the islets after transplanting. In another study, a bio-artificial pancreas was developed using silk alginate to encapsulate insulin secreting cells [73].

3.4.7 Artificial intervertebral disc

A perfect biomaterial for making artificial intervertebral disc must have high tensile strength, be biocompatible and be able to simulate the natural extracellular matrix [111]. A study by Park et al. [112] reports a biphasic hybrid scaffold that was developed from a blend of silk fibroin and hyaluronic acid to simulate the components of an intervertebral disc (nucleus pulposus (NP)) and an annulus fibrosus (AF)). In a related study, Du et al. [113] fabricated a 3-D biphasic silk fibroin scaffold to mimic the AF phase and phase separation technique for the NP phase. Moreover, Bhunia et al. [114] developed a bio-artificial AF construct with directional freezing technique involving concentric rings of lamellar silk scaffolds. The study further reports the proliferation of primary porcine AF cells using a mulberry and a non-mulberry silk combination which helped in cellular maturation, alignment and extracellular matrix deposition.

3.5 Silk in sutures

Sutures are an important material in surgical operations for primary wound closure. For this reason, various materials have been used in making sutures. These materials can be classified as either organic or synthetic according to their origin, or absorbable and non-absorbable according to their durability in the body [115]. Important properties for a good suture include: high tensile strength, elasticity, wound safety, knot safety and tissue reactivity [116, 117].

Silk, a natural non-absorbable suture material has been in use as a suture for several decades. However, other degradable synthetic sutures have dominated the market in the recent past. Nonetheless, silk suture is still preferred in cardiovascular, ocular and neural surgery because of its superior properties like good knot strength, ease of processing, minimum propensity to tear through tissue and biocompatibility [117].

Various modifications have been done on silk to improve its weak characteristics such as adding poly vinyl alcohol into silk fibroin to improve the tensile strength, elongation at break and the knot strength [118]. Bloch & Messores [119], reported coating silk filaments with fibroin and bounding them together to reduce the capillarity of silk sutures. Viju & Thilagavathi [120] coated silk-braided sutures with chitosan to improve the antimicrobial activity, tenacity and knot strength. Sudh et al. [121] developed a drug loaded antimicrobial silk suture for use in wound closure and wound healing meant to prevent surgical site infections. Choudhury et al. [122] developed a low-temperature O_2 plasma-treated (*Antheraea assama*) silk fibroin (AASF) yarn impregnated with amoxicillin trihydrate. This was aimed at producing a controlled antibiotic-releasing suture (AASF/O_2/AMOX) to prevent site bacterial infection and fasten wound healing. This shows the potential of silk in developing suture with special properties.

Type of Drug Delivery System/material	Associated active ingredient	Key results
Silk sponges	Erythromycin	Sustained drug release and prolonged antimicrobial activity against Staphilococcus Aureus
Silk films	Horseradish peroxidase (HRP)	Enhanced stability
	Glucose oxidase (GOx)	Increased enzymatic activity
	FITC-dextran	Controlled drug release
	Epirubicin	Controlled drug release
Silk lyogels	Hydrocortisone IgG	Enhanced efficacy Enhanced stability and sustained release
Insertable Silk discs	IgG and HIV inhibitor 5P12-RANTES	Enhanced stability and modified release profile
Silk nanoparticles	Curcumin	Modified release profile and enhanced cellular uptake
Silk microspheres	Horseradish peroxidase (HRP)	Modified the release profile
Silk coated PCL microspheres	Vancomycin	Modified the release profile
Silk coated liposomes	Ibuprofen	Enhanced adhesion to human corneal epithelial cells, tunable drug release
	Emodin	Selective targeting of keloid cells

Table 1.
Silk-based drug delivery systems [100].

3.6 Silk in drug delivery

Drug delivery through polymeric systems has gained popularity over the years [51]. These systems serve as reservoirs to active ingredient in drugs and improve the drug's physicochemical properties [123]. Polymeric drug delivery systems are also good in specific targeting, intracellular transport and some are biocompatible which help in improving efficiency of the treatment and the life quality of the patients [123, 124]. A good drug delivery system should be able to stabilize the active ingredient in drugs, be able to modulate the drug's release mechanism, be biocompatible and biodegradable, as well as minimize any side effects of tissue specific targeting of highly toxic drugs [125–127].

Silk fibroin is used in drug delivery systems owing to its properties such as good mechanical properties, mild aqueous processing conditions, biocompatibility, biodegradability and its ability to enhance the stability of active ingredient in drugs; as proteins and small molecules [46, 128]. That notwithstanding, silk fibroin solutions can be processed using various techniques to produce different forms of delivery systems like scaffolds, films, hydrogels, nanoparticles, microspheres, and microcapsules among others [129]. Additionally, silk fibroin has carboxyl and amino groups which allow bio-functionalization with different biomolecules for targeted drug delivery [130]. Silk based drug delivery systems include hydrogels, micro particles, lyophilized sponges, films, nano-fibers and nano-particles.

Formulation	Gene	Cell line
Recombinant silk–elastin-like polymer hydrogels (SELPs)	Ad[1]–CMV[2]–LacZ[3]	Head and neck cancer in mice
	pDNA[4] (pRL[5]-CMV-luc[6])	NA
	Ad–Luc–HSVtk[7]	Head and neck cancer in mice
3D porous scaffold	Adenovirus Ad-BMP7[8]	Human BMSCs
Bioengineered silk films	pDNA (GFP[9])	Human HEK cells
Spermine modified SF	pDNA and VEGF165–Ang-1[10]	In vivo-rat
SF-Coated PEI/DNA Complexes	pDNA (GFP)	HEK 293 and HCT 116 cells
SF layer-by-layer assembled microcapsules	pDNA-Cy5[11]	NIH/3 T3 fibroblasts
Bioengineered silk–polylysine–ppTG1 nanoparticles	pDNA	Human HEK and MDA-MB-435 cells
Magnetic-SF/polyethyleneimine core-shell nanoparticles	c-Myc[12] antisense ODNs[13y]	MDA-MB-231 cells

[1]*Adenovirus.*
[2]*Cytomegalovirus promoter gene.*
[3]*Beta galactosidase reporter gene.*
[4]*Plasmid DNA.*
[5]*Renilla luciferase.*
[6]*Luciferase reporter gene.*
[7]*Herpes simplex virus thymidine kinase gene.*
[8]*Bone morphogenic protein.*
[9]*Green fluorescent protein.*
[10]*Vascular endothelial growth factor and angiopoietin-1.*
[11]*Fluorescent probe.*
[12]*MYC Proto-Oncogene.*
[13]*Oligodeoxynucleotides [100].*

Table 2.
Silk –based gene delivery systems [100].

Different researches have reported successful use of silk fibroin in delivery systems for different drugs and genes [131–133]. **Tables 1** and **2** below presents some silk based drug and genes delivery systems.

4. Silk in protective clothing

Protective clothing are defined as textile structure designed to protect the human body from external threats such as fire, bullets, heat, cold, mechanical, biological, radiological, thermal and chemical hazards. Protective clothing are in different forms e.g. masks, gloves, vests, coats, aprons, hats, hoods or totally encapsulating chemical protective suits [134]. Some general characteristics of good protective clothing include: reliable barrier protection, durability, good fit, flexible, light weight, ease of care, maintenance and repair, ease of disposal and recycling.

Because of the interesting characteristics of silk, various research studies have examined its use in developing protective textiles. Some of these characteristics include hydrophobicity, antimicrobial and antiviral properties [135]. Recently, Parlin et al. [135] examined the potential of silk fabrics as a protective barrier for personal protective equipment and as a functional material for face coverings during the COVID-19 pandemic. Results of this study showed that the use of the commercially available 100% silk material can be used in producing protective coverings that can prolong the lifespan of N95 respirators. The study also found 100% silk fabrics suitable for developing face coverings for the general public to prevent COVID-19 [135]. Additionally, the study suggests that because silk has unique properties such as antimicrobial, antiviral, breathability, and slight hydrophobicity; prevention of penetration of droplets and antibacterial activity can imply potential use in developing respirator inserts [136, 137]. Moreover, other studies had showed that silk could be used as an antimicrobial barrier mask, with better filtration when multiple layers are used [135]. Besides, silk neither irritates the skin nor increases local humidity around the covered face, and prevents accidental stimulation of face touching; making it good for prolonged wear [138].

Another study by Zulan et al. [139] reports use of silk/graphene composite to make flame retardant protective clothing that can be used by fire fighters. Loh et al. [140] reports woven silk fabrics can be used for ballistic protection for aerospace, sports, military, marine and automotives. Mongkholrattanasit et al. [141] studied the ultraviolet (UV) protection properties of silk fabric dyed with eucalyptus leaf extract. Pad-dry and pad-batch techniques together with a metal mordant ($AlK(SO_4)_2$, $CuSO_4$, and $FeSO_4$) were used to apply a natural dye extracted from eucalyptus leaves on silk fabric. Results of his study showed that the UV protection factor of the silk fabric increased with an increase in the dye concentration and a darker shade gave the best UV-protective silk fabrics. Moreover, a study by Zhou et al. [142] also reports silk fabrics treated with red radish extracts provides good UV protection and that such fabrics can be used in making umbrellas, shade structures, awnings, and baby carrier covers among others.

5. Silk in optics and sensing

Synthetic biomaterials have been widely used in optics and sensing applications. For ophthalmic applications, which include lens replacement, retina reconstruction, vitreous replacement and ocular surface reconstruction, various materials such as poly-methylmethacrylate (PMMA), silicone, acrylics, poly-tetrafluoroethylene among others have been extensively used due to the biological inert nature of these materials [143, 144]. With technological advances, regenerative medicine strategies have shifted to relying on the ability of the biomaterial scaffolds in supporting human cell adhesion, growth and maintenance of the right cells that encourage tissue replacement as well as integration with adjacent tissues [145]. Since most synthetic biomaterials lacked the aforementioned abilities, emerging technologies attempted the modification of synthetic biomaterial surfaces [146]. However, a major limitation of surface modified synthetic materials was that such materials are not transparent, especially for applications in tissue grafts which need to be optically clear and they are not biodegradable [143]. Materials derived from nature have therefore become popular because they support cell attachment and proliferation. These materials include cross-linked collagen-chitosan hydrogels [147], keratin [148], cross-linked collagen gels [149], silk fibroin [150] etc.

Apart from ophthalmic applications, there has been an increased desire for real-time diagnostics, sensing and deep tissue light delivery, which has led to development of photonic medical devices from materials which are implantable and biocompatible. These devices can therefore be used within the body for therapeutics and long term health monitoring, where they are integrated into the living tissue in the human body [151]. Non-biodegradable inorganic materials such as silicon, gold and compound semiconductors have been traditionally used in photonic devices. However, their biocompatibility have been found to be dependent on the device size, the presence of coatings and mechanical properties [152]. Hydrogel materials from poly-vinylalcohol (PVA) and poly-ethylglycol (PEG), which are biocompatible have also been used in tissue engineering applications because of their ability to retain water and mimic the human body extracellular matrix [153]. However, they have not found extensive application in sensing because of their poor adhesion to substrates and poor mechanical properties [154]. Selection of the right material for implantable photonic devices requires consideration of biocompatibility properties as well as the structural stability, mechanical flexibility and optical clarity [151]; requirements that silk fibroin meet. Silk fibroin is thus gaining traction in optical interfaces and sensor applications in implantable biomedical fields owing to its good mechanical and optical transparency, coupled with its biodegradability and biocompatibility [14]. Silk in film form has a free standing structure with thickness ranging from 20 to 100 μm. The films are very transparent across the visible region of the spectrum and are mechanically robust with smooth surfaces. The films can also be patterned during fabrication to form traverse features that are tens of nanometers, making them attractive in optical device applications [155].

Substratum for corneal limbal epithelial cells has been developed from silk fibroin membranes, by casting dialyzed solutions of silk fibroin protein. The transparent silk membrane was found to support growth of human limbal epithelial (HLE) cell growth, which did not change even when the silk membranes were cast in the presence of fetal bovine serum (FBS) [156]. Such properties are favourable in the development of tissue engineered membranes for restoration of damaged ocular surfaces. Porous silk films have also been fabricated and shown to have potential in use as a carrier of cultivated epithelial sheets during regeneration of corneal epithelium [157].

Diffractive optical elements were fabricated by molding silk fibroin solution on poly-dimethylsiloxane (PDMS) moulds with ruled and holographic diffraction grating, producing nano-patterned silk optical elements of thickness ranging from 30 to 50 μm and a refractive index of n = 1.55. These nano-patterned silk gratings had a diffraction efficiency of 34%, at a wavelength of 633 nm in the first order, which compares to that of transmissive glass gratings. This led to successful formation of silk micro-lens arrays and silk lenses, which couple light into biological substrates [158]. Such silk gratings can also be functionalized, to maintain the biologically active optical elements. Therefore this could allow the use of these silk devices in delivering light to biological matrices and concentrate photons with doped substrates for biological function probes. In another study, silk diffraction gratings with desired patterns were fabricated through photo-induced polymerization of silk conjugates and a photo-initiator, producing good diffraction intensity [159].

Silk micro-prism arrays (MPAs) were prepared by micro-molding technique, resulting into a silk reflector film of 100 μm in thickness. The MPAs provided contrast and optical signal enhancement by retro-reflecting scattered photons through layers of tissue when used in vivo on BALB/c mice. The silk MPAs had no adverse biological effects, degraded slowly and were integrated into the native tissue. Functionalization of silk MPA with doxorubicin (a chemotherapeutic drug), was further reported to allow controlled delivery, storage and imaging of therapeutics, besides improving noninvasive tissue imaging [160].

Optical waveguides, which have the ability to transport and manipulate light in a controlled manner [161], have also been fabricated from silk. Silk fibroin ink, used in direct ink writing technique, has enabled creation of silk optical waveguides. These have been found to easily guide light of wavelength 633 nm. These waveguides were reported to exhibit comparable optical loss measurements to those of thin silk films, an indication that they can be applied in fabrication of functionalized, biocompatible and biodegradable biophotonic elements [155].

Silk fibroin hydrogels have also found use in surface plasmon resonances (SPR) sensors, fabricated by utilizing the principle of metal–insulator–metal (MIM) absorber. Inclusion of a thin insulator layer of 20 nm silk fibroin hydrogel between two 200 nm gold films enables the MIM structure produced to become highly sensitive to changes in thickness and refractive index of the insulating layer. Thus, the hydrogel properties of the silk spacer, which can accommodate water molecules by up to 60% in volume, increases sensitivity to analytes. Sensitivity is dependent on the refractive index and swelling ratio of the silk hydrogel. The silk polymer chains can also act as fluidic channels that facilitate flow of analytes in water, through a nano-sized layer, making silk plasmonic structures suitable for glucose sensor applications [162].

A wearable strain sensor was fabricated by carbonizing pristine silk georgette through high temperature treatment, followed by encapsulation in poly-dimethylsiloxane (PDMS), an elastic polymer. This has shown promising potential for applications in monitoring a wide range of motion based human activities [163]. Silk based wearable sensors utilizes the principle of transformation of silk fibroin through thermal treatment, into an electrically-conductive graphite nano-carbon [164]. Transparent and flexible silk nanofiber-derived carbon membranes have also been fabricated for multifunctional electronic skin with human physiological signal monitoring capabilities [165, 166]. Silk based self-powered pressure sensor films for use in wearable devices have also been fabricated through synthesis of silk and poly-vinylidene fluoride-co-trifluoroethylene [167]. In order to provide a strong interface between a biological surface and a sensor for epidermal electronics, calcium modified silk fibroin has been fabricated and shown to have strong adhesive properties with good stretchability, conductivity and reusability. Therefore calcium modified silk fibroin shows the potential to be applied as an adhesive for epidermal biomedical sensors [168].

Another promising application of silk is in the coating of otherwise non biocompatible optical fibers for bio-sensing inside the human body. Silica exposed core fiber are reported to have been coated with a thin layer of silk and thereafter, doped with fluorophore 5,6-carboxynapthofluorescein (CNF). The doped-silk layer was found to produce fluorescent signals that are coupled into the core of Silica exposed core fiber, allows for remote measurement of pH along the fiber length, when used in mice [169].

6. Conclusion

Silk fiber from different varieties has largely been used beyond the traditional textile scope. The widest and earlier use has been noted in biomedical use, especially as sutures, and protective wear due to the enviable properties highlighted for each function. The traditional classification of silk was tagged to luxury. Beyond this, research has been expounded on the functionality of silk. The various forms, including regeneration into nanofibers, nanofilms and nanomembranes provide surfaces for novel functionalization when processed with specific agents. Collagen has been reported the most as a functional material added to silk for, especially biomedical applications. Optics and sensing, present a unique and promising future for functional silk— especially in e-textiles and bio-sensing. However, it is also important to underscore that at different stages of regeneration, the silk structure seems to get altered; especially the loss of considerable strength resulting from altered crystallinity and re-orientation of β-sheets of silk fibroin. Owing to the low proportion of silk production on the market compared to cotton, and synthetic fibers, it is important to explore the annual global demand of silk in regard to future needs for silk in functional textiles. It is also important to explore statistics, on silk processed through novel methods like electrospinning, with respect to commercial viability. For instance, it is often required to strictly control biomaterial properties during processing, owing to the complexity of biomaterial molecules. Of important focus is the standardization of process/manufacturing parameters and equipment in the attempt to commercialize silk functional products. However, with increasing demand for more environmentally sustainable materials and products, more bio-based sectors and economies will emerge; hence, an increased uptake of natural biomaterials such as silk, in higher technology application needs.

Conflict of interest

The authors have no conflicts of interest to declare.

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References

[1] Altman G, Diaz F, Jakuba C, Calabro T, Horan R, Chen J, et al. Silk-based biomaterials. Biomaterials. 2003;24(3):401-16.

[2] Craig C, Hsu M, Kaplan D, Pierce NE. A comparison of the composition of silk proteins produced by spiders and insects. International Journal of Biological Macromolecules. 1999;24(2-3):109-18.

[3] Babu M. Silk–production and future trends. Handbook of Natural Fibres: Elsevier; 2020. p. 121-45.

[4] Singh T. Sericulture. 2007.

[5] Capinera JL. Sericulture. Encyclopedia of Entomology: Springer; 2008. p. 3345-8.

[6] Merlange G. Silk in the orient. Journal of the Royal Central Asian Society. 1939;26(1):65-76.

[7] Lee Y-W. Silk Reeling and Testing Manual: Food and Agriculture Organization; 1999.

[8] Padaki NV, Das B, Basu A. 1 - Advances in understanding the properties of silk. In: Basu A, editor. Advances in Silk Science and Technology: Woodhead Publishing; 2015. p. 3-16.

[9] Hanumappa H. Sericulture for Rural development: Himalaya Publishing House; 1986.

[10] Padaki N, Das B, Basu A. Advances in understanding the properties of silk. Advances in silk science and technology: Elsevier; 2015. p. 3-16.

[11] Gupta V, Rajkhowa R, Kothari V. Physical characteristics and structure of Indian silk fibres. Indian Journal of Fibre and Textile research. 2000;25(1):14-9.

[12] Hearle JW, Morton WE. Physical properties of textile fibres: Elsevier; 2008.

[13] Volkov V, Ferreira A, Cavaco-Paulo A. On the Routines of Wild-Type Silk Fibroin Processing Toward Silk-Inspired Materials: A Review. Macromolecular Materials and Engineering. 2015;300(12):1199-216.

[14] Omenetto F, Kaplan D. A new route for silk. Nature Photonics. 2008;2(11):641-3.

[15] Yucel T, Lovett M, Kaplan D. Silk-based biomaterials for sustained drug delivery. Journal of Controlled Release. 2014;190:381-97.

[16] Jiang C, Wang X, Gunawidjaja R, Lin YH, Gupta M, Kaplan D, et al. Mechanical properties of robust ultrathin silk fibroin films. Advanced functional materials. 2007;17(13):2229-37.

[17] Wang X, Kim HJ, Xu P, Matsumoto A, Kaplan D. Biomaterial coatings by stepwise deposition of silk fibroin. Langmuir. 2005;21(24): 11335-41.

[18] Wang X, Kluge J, Leisk G, Kaplan D. Sonication-induced gelation of silk fibroin for cell encapsulation. Biomaterials. 2008;29(8):1054-64.

[19] Jin H-J, Fridrikh S, Rutledge G, Kaplan D. Electrospinning *Bombyx mori* silk with poly (ethylene oxide). Biomacromolecules. 2002;3(6):1233-9.

[20] Kim U-J, Park J, Li C, Jin H-J, Valluzzi R, Kaplan D. Structure and properties of silk hydrogels. Biomacromolecules. 2004;5(3):786-92.

[21] Jin HJ, Park J, Karageorgiou V, Kim UJ, Valluzzi R, Cebe P, et al. Water-stable silk films with reduced

β-sheet content. Advanced Functional Materials. 2005;15(8):1241-7.

[22] Bettinger C, Bao Z. Biomaterials-based organic electronic devices. Polymer international. 2010;59(5):563-7.

[23] Capelli R, Amsden J, Generali G, Toffanin S, Benfenati V, Muccini M, et al. Integration of silk protein in organic and light-emitting transistors. Organic electronics. 2011;12(7):1146-51.

[24] Toffanin S, Kim S, Cavallini S, Natali M, Benfenati V, Amsden J, et al. Low-threshold blue lasing from silk fibroin thin films. Applied Physics Letters. 2012;101(9):091110.

[25] Kim D-H, Kim Y-S, Amsden J, Panilaitis B, Kaplan D, Omenetto F, et al. Silicon electronics on silk as a path to bioresorbable, implantable devices. Applied physics letters. 2009;95(13):133701.

[26] Nambajjwe C, Musinguzi WB, Rwahwire S, Kasedde A, Namuga C, Nibikora I. Improving electricity from silk cocoons through feeding silkworms with silver nanoparticles. Materials Today: Proceedings. 2020;28:1221-6.

[27] Tansil N, Li Y, Teng CP, Zhang S, Win KY, Chen X, et al. Intrinsically colored and luminescent silk. Advanced Materials. 2011;23(12):1463-6.

[28] Tansil N, Koh LD, Han MY. Functional silk: colored and luminescent. Advanced Materials. 2012;24(11):1388-97.

[29] Sagnella A, Chieco C, Virgilio ND, Toffanin S, Posati T, Pistone A, et al. Bio-doping of regenerated silk fibroin solution and films: a green route for biomanufacturing. RSC Advances. 2014;4(64):33687-94.

[30] Benfenati V, Toffanin S, Chieco C, Sagnella A, Virgilio ND, Posati T, et al. Silk fibroin based technology for industrial biomanufacturing. Factories of the Future: Springer, Cham; 2019. p. 409-30.

[31] Koh L-D, Cheng Y, Teng C-P, Khin Y-W, Loh X-J, Tee S-Y, et al. Structures, mechanical properties and applications of silk fibroin materials. Progress in Polymer Science. 2015;46:86-110.

[32] Luo K, Yang Y, Shao Z. Physically crosslinked biocompatible silk-fibroin-based hydrogels with high mechanical performance. Advanced Functional Materials. 2016;26(6):872-80.

[33] Ghosh S, Parker S, Wang X, Kaplan D, Lewis J. Direct-write assembly of microperiodic silk fibroin scaffolds for tissue engineering applications. Advanced Functional Materials. 2008;18(13):1883-9.

[34] Brian LD. Processing of *Bombyx mori* silk for biomedical applications. In: Kundu SC, editor. Silk Biomaterials for Tissue Engineering and Regenerative Medicine: Elsevier; 2014. p. 78-99.

[35] Kamalha E, Zheng YS, Zeng YC, Mwasiagi JI. Effect of solvent concentration on morphology of electrospun *bombyx mori* silk. 2014.

[36] Niu H, Wang X, Lin T. Needleless electrospinning: developments and performances. Nanofibers-production, properties and functional applications. 2011:17-36.

[37] Lukáš D, Sarkar A, Martinová L, Vodsed'álková K, Lubasová D, Chaloupek J, et al. Physical principles of electrospinning (Electrospinning as a nano-scale technology of the twenty-first century). Textile progress. 2009;41(2):59-140.

[38] Niu H, Lin T, Wang X. Needleless electrospinning. I. A comparison of cylinder and disk nozzles. Journal of applied polymer science. 2009;114(6):3524-30.

[39] Yarin A, Zussman E. Upward needleless electrospinning of multiple nanofibers. Polymer. 2004;45(9):2977-80.

[40] Sasithorn N, Martinová L, Horáková J, Mongkholrattanasit R. Fabrication of silk fibroin nanofibres by needleless electrospinning. In: Haider S, Haider A, editors. Electrospinning-Material, Techniques, and Biomedical Applications; Intech: London, UK. Croatia: InTech; 2016. p. 95-113.

[41] Wei L, Sun R, Liu C, Xiong J, Qin X. Mass production of nanofibers from needleless electrospinning by a novel annular spinneret. Materials & Design. 2019;179:107885.

[42] Holland C, Numata K, Rnjak-Kovacina J, Seib P. The biomedical use of silk: past, present, future. Advanced healthcare materials. 2019;8(1):1800465.

[43] Qin Y. 2–An overview of medical textile products. Medical Textile Materials Jiaxing: Woodhead Publishing. 2016:13-22.

[44] Kennedy JF, Bunko K, Santhini E, Vadodaria K, Rajasekar S. The use of 'smart'textiles for wound care. Advanced Textiles for Wound Care: Elsevier; 2019. p. 289-311.

[45] Daniele M, Boyd D, Adams A, Ligler F. Microfluidic strategies for design and assembly of microfibers and nanofibers with tissue engineering and regenerative medicine applications. Advanced healthcare materials. 2015;4(1):11-28.

[46] Li G, Li Y, Chen G, He J, Han Y, Wang X, et al. Silk-based biomaterials in biomedical textiles and fiber-based implants. Advanced healthcare materials. 2015;4(8):1134-51.

[47] Rajendran S, Anand SC. Woven textiles for medical applications. Woven Textiles: Elsevier; 2020. p. 441-70.

[48] Chen X, Guan Y, Wang L, Sanbhal NA, Zhao F, Zou Q, et al. Antimicrobial textiles for sutures, implants, and scaffolds. Antimicrobial Textiles: Elsevier; 2016. p. 263-85.

[49] Syed M, Khan M, Sefat F, Khurshid Z, Zafar M, Khan A. Bioactive glass and glass fiber composite: biomedical/dental applications. Biomedical, Therapeutic and Clinical Applications of Bioactive Glasses: Elsevier; 2019. p. 467-95.

[50] Kluge J, Li A, Kahn B, Michaud D, Omenetto F, Kaplan D. Silk-based blood stabilization for diagnostics. Proceedings of the National Academy of Sciences. 2016;113(21):5892-7.

[51] Kamalha E, Zheng YS, Zeng YC, Mutua F, editors. FTIR and WAXD study of regenerated silk fibroin. Advanced Materials Research; 2013: Trans Tech Publ.

[52] Wharram S, Zhang X, Kaplan D, McCarthy S. Electrospun silk material systems for wound healing. Macromolecular Bioscience. 2010;10(3):246-57.

[53] Farokhi M, Mottaghitalab F, Fatahi Y, Khademhosseini A, Kaplan D. Overview of silk fibroin use in wound dressings. Trends in biotechnology. 2018;36(9):907-22.

[54] Xia Y, Gao G, Li Y. Preparation and properties of nanometer titanium dioxide/silk fibroin blend membrane. Journal of Biomedical Materials Research Part B: Applied Biomaterials: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials. 2009;90(2):653-8.

[55] Wang M, Yu J, Kaplan D, Rutledge G. Production of submicron diameter silk fibers under benign

processing conditions by two-fluid electrospinning. Macromolecules. 2006;39(3):1102-7.

[56] Kamalathevan P, Ooi P, Loo Y. Silk-based biomaterials in cutaneous wound healing: a systematic review. Advances in skin & wound care. 2018;31(12):565-73.

[57] Chouhan D, Mandal B. Silk biomaterials in wound healing and skin regeneration therapeutics: From bench to bedside. Acta Biomaterialia. 2020;103:24-51.

[58] He S, Shi D, Han Z, Dong Z, Xie Y, Zhang F, et al. Heparinized silk fibroin hydrogels loading FGF1 promote the wound healing in rats with full-thickness skin excision. Biomedical engineering online. 2019;18(1):1-12.

[59] Chouhan D, Janani G, Chakraborty B, Nandi S, Mandal B. Functionalized PVA–silk blended nanofibrous mats promote diabetic wound healing via regulation of extracellular matrix and tissue remodelling. Journal of tissue engineering and regenerative medicine. 2018;12(3):e1559-e70.

[60] Hung M-H, Sartika D, Chang S-J, Chen S-J, Wang C-C, Hung Y-J, et al. Influence of silk clothing therapy in patients with atopic dermatitis. Dermatology Reports. 2019;11(2).

[61] Thomas K, Bradshaw L, Sach T, Batchelor J, Lawton S, Harrison E, et al. Silk garments plus standard care compared with standard care for treating eczema in children: A randomised, controlled, observer-blind, pragmatic trial (CLOTHES Trial). PLoS medicine. 2017;14(4):e1002280.

[62] Criton S, Gangadharan G. Nonpharmacological management of atopic dermatitis. Indian Journal of Paediatric Dermatology. 2017;18(3):166.

[63] Hermanns J-F, Goffin V, Arrese J, Rodriguez C, Piérard G. Beneficial effects of softened fabrics on atopic skin. Dermatology. 2001;202(2):167-70.

[64] Agner T. Staphylococcal-mediated worsening of atopic dermatitis: many players involved. The British journal of dermatology. 2010;163(6):1147.

[65] Macias E, Pereira F, Rietkerk W, Safai B. Superantigens in dermatology. Journal of the American Academy of Dermatology. 2011;64(3):455-72.

[66] Sha L-Z, Zhao H-F, Xiao G-N. Photocatalytic degradation of formaldehyde by silk mask paper loading nanometer titanium dioxide. Fibers and Polymers. 2013;14(6):976-81.

[67] Sha L, Zhao H. Preparation and properties of Nano-TiO 2 photo-catalytic silk respirator paper. Fibers and Polymers. 2012;13(9):1159-64.

[68] Lawrence B, Pan Z, Liu A, Kaplan D, Mark Rosenblatt. Human corneal limbal epithelial cell response to varying silk film geometric topography in vitro. Acta biomaterialia. 2012;8(10):3732-43.

[69] Lawrence B, Wharram S, Kluge J, Leisk G, Omenetto F, Rosenblatt M, et al. Effect of hydration on silk film material properties. Macromolecular bioscience. 2010;10(4):393-403.

[70] Levenberg S, Khademhosseini A, Langer R. Embryonic stem cells in tissue engineering. Essentials of Stem Cell Biology: Elsevier; 2009. p. 571-81.

[71] Caddeo S, Boffito M, Sartori S. Tissue engineering approaches in the design of healthy and pathological in vitro tissue models. Frontiers in bioengineering and biotechnology. 2017;5:40.

[72] Song G. Improving comfort in clothing: Elsevier; 2011.

[73] Bandyopadhyay A, Chowdhury SK, Dey S, Moses JC, Mandal B. Silk: a promising biomaterial opening new vistas towards affordable healthcare solutions. Journal of the Indian Institute of Science. 2019:1-43.

[74] Behrens MR, Ruder WC. Biopolymers in Regenerative Medicine: Overview, Current Advances, and Future Trends. Biopolymers for Biomedical and Biotechnological Applications. 2021:357-80.

[75] Groeber F, Holeiter M, Hampel M, Hinderer S, Schenke-Layland K. Skin tissue engineering—in vivo and in vitro applications. Advanced drug delivery reviews. 2011;63(4-5):352-66.

[76] Vasconcelos A, Cavaco-Paulo A. Wound dressings for a proteolytic-rich environment. Applied microbiology and biotechnology. 2011;90(2):445-60.

[77] Abrigo M, McArthur S, Kingshott P. Electrospun nanofibers as dressings for chronic wound care: advances, challenges, and future prospects. Macromolecular bioscience. 2014;14(6):772-92.

[78] Zhang X, Reagan M, Kaplan D. Electrospun silk biomaterial scaffolds for regenerative medicine. Advanced drug delivery reviews. 2009;61(12):988-1006.

[79] Chouhan D, Chakraborty B, Nandi S, Mandal B. Role of non-mulberry silk fibroin in deposition and regulation of extracellular matrix towards accelerated wound healing. Acta biomaterialia. 2017;48:157-74.

[80] Arjen van Turnhout, Franke C, Vriens-Nieuwenhuis E, Sluis Wvd. The use of SERI™ Surgical Scaffolds in direct-to-implant reconstruction after skin-sparing mastectomy: A retrospective study on surgical outcomes and a systematic review of current literature. Journal of Plastic, Reconstructive & Aesthetic Surgery. 2018;71(5):644-50.

[81] Min B-M, Lee G, Kim SH, Nam YS, Lee TS, Park WH. Electrospinning of silk fibroin nanofibers and its effect on the adhesion and spreading of normal human keratinocytes and fibroblasts in vitro. Biomaterials. 2004;25(7-8):1289-97.

[82] Min BM, Jeong L, Lee KY, Park WH. Regenerated silk fibroin nanofibers: Water vapor-induced structural changes and their effects on the behavior of normal human cells. Macromolecular Bioscience. 2006;6(4):285-92.

[83] Yoo CR, Yeo I-S, Park KE, Park JH, Lee SJ, Park WH, et al. Effect of chitin/silk fibroin nanofibrous bicomponent structures on interaction with human epidermal keratinocytes. International journal of biological macromolecules. 2008;42(4):324-34.

[84] Roh D-H, Kang S-Y, Kim J-Y, Kwon Y-B, Kweon HY, Lee K-G, et al. Wound healing effect of silk fibroin/alginate-blended sponge in full thickness skin defect of rat. Journal of Materials Science: Materials in Medicine. 2006;17(6):547-52.

[85] Wang G, Hu X, Lin W, Dong C, Wu H. Electrospun PLGA–silk fibroin–collagen nanofibrous scaffolds for nerve tissue engineering. In Vitro Cellular & Developmental Biology-Animal. 2011;47(3):234-40.

[86] Wittmer C, Claudepierre T, Reber M, Wiedemann P, Garlick J, Kaplan D, et al. Multifunctionalized electrospun silk fibers promote axon regeneration in the central nervous system. Advanced functional materials. 2011;21(22):4232-42.

[87] Salgado A, Coutinho O, Reis R. Bone tissue engineering: state of the art and future trends. Macromolecular bioscience. 2004;4(8):743-65.

[88] Mandal B, Kundu S. Osteogenic and adipogenic differentiation of rat bone marrow cells on non-mulberry and mulberry silk gland fibroin 3D scaffolds. Biomaterials. 2009;30(28):5019-30.

[89] Meinel L, Hofmann S, Betz O, Fajardo R, Merkle H, Langer R, et al. Osteogenesis by human mesenchymal stem cells cultured on silk biomaterials: comparison of adenovirus mediated gene transfer and protein delivery of BMP-2. Biomaterials. 2006;27(28):4993-5002.

[90] Leukers B, Gülkan H, Irsen S, Milz S, Tille C, Schieker M, et al. Hydroxyapatite scaffolds for bone tissue engineering made by 3D printing. Journal of Materials Science: Materials in Medicine. 2005;16(12):1121-4.

[91] Liu H, Fan H, Toh S, Goh J. A comparison of rabbit mesenchymal stem cells and anterior cruciate ligament fibroblasts responses on combined silk scaffolds. Biomaterials. 2008;29(10):1443-53.

[92] Reardon PJ, Konwarh R, Knowles J, Mandal B. Mimicking hierarchical complexity of the osteochondral interface using electrospun silk-bioactive glass composites. ACS applied materials & interfaces. 2017;9(9): 8000-13.

[93] Wang Y, Kim H-J, Vunjak-Novakovic G, Kaplan D. Stem cell-based tissue engineering with silk biomaterials. Biomaterials. 2006;27(36):6064-82.

[94] Perrone G, Leisk G, Lo T, Moreau JE, Haas DS, Papenburg BJ, et al. The use of silk-based devices for fracture fixation. Nature communications. 2014;5(1):1-9.

[95] Altman G, Horan R, Lu H, Moreau J, Martin I, Richmond J, et al. Silk matrix for tissue engineered anterior cruciate ligaments. Biomaterials. 2002;23(20):4131-41.

[96] Hairfield-Stein M, England C, Paek H, Gilbraith K, Dennis R, Boland E, et al. Development of self-assembled, tissue-engineered ligament from bone marrow stromal cells. Tissue engineering. 2007;13(4):703-10.

[97] Liu L, Liu J, Wang M, Min S, Cai Y, Zhu L, et al. Preparation and characterization of nano-hydroxyapatite/silk fibroin porous scaffolds. Journal of Biomaterials Science, Polymer Edition. 2008;19(3):325-38.

[98] Chen J, Altman G, Karageorgiou V, Horan R, Collette A, Volloch V, et al. Human bone marrow stromal cell and ligament fibroblast responses on RGD-modified silk fibers. Journal of Biomedical Materials Research Part A: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials. 2003;67(2):559-70.

[99] Moreau J, Chen J, Horan R, Kaplan D, Altman G. Sequential growth factor application in bone marrow stromal cell ligament engineering. Tissue engineering. 2005;11(11-12):1887-97.

[100] Panas-Perez E, Gatt C, Dunn M. Development of a silk and collagen fiber scaffold for anterior cruciate ligament reconstruction. Journal of Materials Science: Materials in Medicine. 2013;24(1):257-65.

[101] Stoppel W, Hu D, Domian I, Kaplan D, III LB. Anisotropic silk biomaterials containing cardiac extracellular matrix for cardiac tissue engineering. Biomedical materials. 2015;10(3):034105.

[102] Patra C, Talukdar S, Novoyatleva T, Velagala S, Mühlfeld C, Kundu B, et al. Silk protein fibroin from Antheraea mylitta for cardiac tissue engineering. Biomaterials. 2012;33(9):2673-80.

[103] Mehrotra S, Nandi SK, Mandal B. Stacked silk-cell monolayers as a biomimetic three dimensional construct for cardiac tissue reconstruction. Journal of Materials Chemistry B. 2017;5(31):6325-38.

[104] Cirillo B, Morra M, Catapano G. Adhesion and function of rat liver cells adherent to silk fibroin/collagen blend films. The International journal of artificial organs. 2004;27(1):60-8.

[105] She Z, Liu W, Feng Q. Silk fibroin/chitosan/heparin scaffold: preparation, antithrombogenicity and culture with hepatocytes. Polymer International. 2010;59(1):55-61.

[106] She Z, Jin C, Huang Z, Zhang B, Feng Q, Xu Y. Silk fibroin/chitosan scaffold: preparation, characterization, and culture with HepG2 cell. Journal of Materials Science: Materials in Medicine. 2008;19(12):3545-53.

[107] Janani G, Nandi S, Mandal B. Functional hepatocyte clusters on bioactive blend silk matrices towards generating bioartificial liver constructs. Acta biomaterialia. 2018;67:167-82.

[108] Qiu Y, Park K. Environment-sensitive hydrogels for drug delivery. Advanced drug delivery reviews. 2001;53(3):321-39.

[109] Vaithilingam V, Tuch B. Islet transplantation and encapsulation: an update on recent developments. The review of diabetic studies: RDS. 2011;8(1):51.

[110] Davis N, Beenken-Rothkopf L, Mirsoian A, Kojic N, Kaplan D, Barron A, et al. Enhanced function of pancreatic islets co-encapsulated with ECM proteins and mesenchymal stromal cells in a silk hydrogel. Biomaterials. 2012;33(28):6691-7.

[111] Stergar J, Gradisnik L, Velnar T, Maver U. Intervertebral disc tissue engineering: A brief review. Bosnian journal of basic medical sciences. 2019;19(2):130.

[112] Park S-H, Gil ES, Cho H, Mandal B, Tien L, Min B-H, et al. Intervertebral disk tissue engineering using biphasic silk composite scaffolds. Tissue Engineering Part A. 2012;18(5-6):447-58.

[113] Du L, Zhu M, Yang Q, Zhang J, Ma X, Kong D, et al. A novel integrated biphasic silk fibroin scaffold for intervertebral disc tissue engineering. Materials Letters. 2014;117:237-40.

[114] Bhunia B, Kaplan D, Mandal B. Silk-based multilayered angle-ply annulus fibrosus construct to recapitulate form and function of the intervertebral disc. Proceedings of the National Academy of Sciences. 2018;115(3):477-82.

[115] Silverstein L, Kurtzman G, Shatz P. Suturing for optimal soft-tissue management. Journal of Oral Implantology. 2009;35(2):82-90.

[116] Lilly G, Armstrong J, Salem J, Cutcher J. Reaction of oral tissues to suture materials: Part II. Oral Surgery, Oral Medicine, Oral Pathology. 1968;26(4):592-9.

[117] Chu C. Types and properties of surgical sutures. Biotextiles as medical implants: Elsevier; 2013. p. 231-73.

[118] Lee KH, Baek DH, Ki CS, Park YH. Preparation and characterization of wet spun silk fibroin/poly (vinyl alcohol) blend filaments. International journal of biological macromolecules. 2007;41(2):168-72.

[119] Bloch A, Messores A, inventors; Ethicon Inc., assignee. Silk suture. United States of America1969.

[120] Viju S, Thilagavathi G. Effect of chitosan coating on the characteristics

of silk-braided sutures. Journal of Industrial Textiles. 2013;42(3):256-68.

[121] Sudha D, Dhurai B, Ponthangam T. Development of herbal drug loaded antimicrobial silk suture. Indian Journal of Fibre & Textile Research (IJFTR). 2017;42(3):286-90.

[122] Choudhury AJ, Gogoi D, Chutia J, Kandimalla R, Kalita S, Kotoky J, et al. Controlled antibiotic-releasing Antheraea assama silk fibroin suture for infection prevention and fast wound healing. Surgery. 2016;159(2):539-47.

[123] Tomeh MA, Hadianamrei R, Zhao X. Silk fibroin as a functional biomaterial for drug and gene delivery. Pharmaceutics. 2019;11(10):494.

[124] Luo Z, Li J, Qu J, Sheng W, Yang J, Li M. Cationized *Bombyx mori* silk fibroin as a delivery carrier of the VEGF165–Ang-1 coexpression plasmid for dermal tissue regeneration. Journal of Materials Chemistry B. 2019;7(1):80-94.

[125] Torchilin V. Multifunctional, stimuli-sensitive nanoparticulate systems for drug delivery. Nature reviews Drug discovery. 2014;13(11):813-27.

[126] Yin Z, Kuang D, Wang S, Zheng Z, Yadavalli V, Lu S. Swellable silk fibroin microneedles for transdermal drug delivery. International journal of biological macromolecules. 2018;106:48-56.

[127] Rezaei F, Damoogh S, Reis R, Kundu S, Mottaghitalab F, Farokhi M. Dual drug delivery system based on pH-sensitive silk fibroin/alginate nanoparticles entrapped in PNIPAM hydrogel for treating severe infected burn wound. Biofabrication. 2020;13(1):015005.

[128] Choi M, Choi D, Hong J. Multilayered controlled drug release silk fibroin nanofilm by manipulating secondary structure. Biomacromolecules. 2018;19(7):3096-103.

[129] Seib P. Reverse-engineered silk hydrogels for cell and drug delivery. Therapeutic delivery. 2018;9(6):469-87.

[130] Vepari C, Kaplan D. Silk as a biomaterial. Progress in polymer science. 2007;32(8-9):991-1007.

[131] Moses JC, Nandi SK, Mandal B. Multifunctional cell instructive silk-bioactive glass composite reinforced scaffolds toward osteoinductive, proangiogenic, and resorbable bone grafts. Advanced healthcare materials. 2018;7(10):1701418.

[132] Lv Q, Hu K, Feng Q, Cui F, Cao C. Preparation and characterization of PLA/fibroin composite and culture of HepG2 (human hepatocellular liver carcinoma cell line) cells. Composites Science and Technology. 2007;67(14):3023-30.

[133] Li A, Kluge J, Guziewicz N, Omenetto F, Kaplan D. Silk-based stabilization of biomacromolecules. Journal of Controlled Release. 2015;219:416-30.

[134] Gorji M, Bagherzadeh R, Fashandi H. Electrospun nanofibers in protective clothing. Electrospun nanofibers: Elsevier; 2017. p. 571-98.

[135] Parlin A, Stratton S, Culley T, Guerra P. A laboratory-based study examining the properties of silk fabric to evaluate its potential as a protective barrier for personal protective equipment and as a functional material for face coverings during the COVID-19 pandemic. PloS one. 2020;15(9):e0239531.

[136] Dong Z, Song Q, Zhang Y, Chen S, Zhang X, Zhao P, et al. Structure,

evolution, and expression of antimicrobial silk proteins, seroins in Lepidoptera. Insect biochemistry and molecular biology. 2016;75:24-31.

[137] Borkow G, Zhou S, Page T, Gabbay J. A novel anti-influenza copper oxide containing respiratory face mask. PLoS One. 2010;5(6): e11295.

[138] Parlin A, Stratton S, Culley T, Guerra PA. Silk fabric as a protective barrier for personal protective equipment and as a functional material for face coverings during the COVID-19 pandemic. medRxiv. 2020.

[139] Zulan L, Zhi L, Lan C, Sihao C, Dayang W, Fangyin D. Reduced graphene oxide coated silk fabrics with conductive property for wearable electronic textiles application. Advanced Electronic Materials. 2019;5(4):1800648.

[140] Loh K, Tan W, Oh R, editors. Developing Woven Enhanced Silk Fabric for Ballistic Protection. Solid State Phenomena; 2012: Trans Tech Publ.

[141] Mongkholrattanasit R, Kryštůfek J, Wiener J, Viková M. UV protection properties of silk fabric dyed with eucalyptus leaf extract. The Journal of The Textile Institute. 2011;102(3):272-9.

[142] Zhou Y, Yang Z-Y, Tang R-C. Facile and green preparation of bioactive and UV protective silk materials using the extract from red radish (*Raphanus sativus* L.) through adsorption technique. Arabian Journal of Chemistry. 2020;13(1):3276-85.

[143] Lace R, Murray-Dunning C, Williams R. Biomaterials for ocular reconstruction. Journal of Materials Science. 2015;50(4):1523-34.

[144] Williams R, Wong D. Ophthalmic biomaterials. Biomedical Materials: Springer; 2009. p. 327-47.

[145] Mason S, Rosalind Stewart, Kearns V, Williams R, Sheridan C. Ocular epithelial transplantation: current uses and future potential. Regenerative medicine. 2011;6(6):767-82.

[146] Nguyen P, Yiu S. Ocular surface reconstruction: recent innovations, surgical candidate selection and postoperative management. Expert Review of Ophthalmology. 2008;3(5):567-84.

[147] Rafat M, Li F, Fagerholm P, Lagali N, Watsky M, Munger R, et al. PEG-stabilized carbodiimide crosslinked collagen–chitosan hydrogels for corneal tissue engineering. Biomaterials. 2008;29(29):3960-72.

[148] Reichl S, Borrelli M, Geerling G. Keratin films for ocular surface reconstruction. Biomaterials. 2011;32(13):3375-86.

[149] Dravida S, Gaddipati S, Griffith M, Merrett K, Madhira SL, Sangwan V, et al. A biomimetic scaffold for culturing limbal stem cells: a promising alternative for clinical transplantation. Journal of tissue engineering and regenerative medicine. 2008;2(5):263-71.

[150] Harkin D, George K, Madden P, Ivan Schwab, Hutmacher D, Chirila T. Silk fibroin in ocular tissue reconstruction. Biomaterials. 2011;32(10):2445-58.

[151] Humar M, Kwok S, Choi M, Yetisen A, Cho S, Yun S-H. Toward biomaterial-based implantable photonic devices. Nanophotonics. 2017;6(2):414-34.

[152] Bar-Ilan O, Albrecht R, Fako V, Furgeson D. Toxicity assessments of multisized gold and silver nanoparticles in zebrafish embryos. Small. 2009;5(16):1897-910.

[153] Hoffman A. Hydrogels for biomedical applications. Advanced drug delivery reviews. 2012;64:18-23.

[154] Morais J, Papadimitrakopoulos F, Burgess D. Biomaterials/tissue interactions: possible solutions to overcome foreign body response. The AAPS journal. 2010;12(2):188-96.

[155] Parker S, Peter D, Jason A, Jason B, Jennifer L, David K, et al. Biocompatible silk printed optical waveguides. Advanced Materials. 2009;21(23):2411-5.

[156] Chirila T, Barnard Z, Harkin D, Schwab I, Hirst *L. Bombyx* mori silk fibroin membranes as potential substrata for epithelial constructs used in the management of ocular surface disorders. Tissue Engineering Part A. 2008;14(7):1203-11.

[157] Higa K, Takeshima N, Moro F, Kawakita T, Kawashima M, Demura M, et al. Porous silk fibroin film as a transparent carrier for cultivated corneal epithelial sheets. Journal of Biomaterials Science, Polymer Edition. 2011;22(17):2261-76.

[158] Lawrence BD, Cronin-Golomb M, Georgakoudi I, Kaplan DL, Omenetto FG. Bioactive silk protein biomaterial systems for optical devices. Biomacromolecules. 2008;9(4):1214-20.

[159] Pal R, Kurland N, Wang C, Kundu S, Yadavalli V. Biopatterning of silk proteins for soft micro-optics. ACS Applied Materials & Interfaces. 2015;7(16):8809-16.

[160] Tao H, Jana K, Sean S, Eleanor P, Angelo S, Bruce P, et al. Implantable, multifunctional, bioresorbable optics. Proceedings of the National Academy of Sciences. 2012;109(48):19584-9.

[161] Hofmann S, Henri H, Annette K, Ralph M, Gordana V-N, David K, et al. Control of in vitro tissue-engineered bone-like structures using human mesenchymal stem cells and porous silk scaffolds. Biomaterials. 2007;28(6):1152-62.

[162] Lee M, Jeon H, Kim S. A highly tunable and fully biocompatible silk nanoplasmonic optical sensor. Nano letters. 2015;15(5):3358-63.

[163] Wang C, Xia K, Jian M, Wang H, Zhang M, Zhang Y. Carbonized silk georgette as an ultrasensitive wearable strain sensor for full-range human activity monitoring. Journal of Materials Chemistry C. 2017;5(30):7604-11.

[164] Cho SY, Yun YS, Lee S, Jang D, Park K-Y, Kim JK, et al. Carbonization of a stable β-sheet-rich silk protein into a pseudographitic pyroprotein. Nature communications. 2015; 6(1):1-7.

[165] Wang C, Xia K, Zhang M, Jian M, Zhang Y. An all-silk-derived dual-mode E-skin for simultaneous temperature–pressure detection. ACS applied materials & interfaces. 2017;9(45):39484-92.

[166] Wang Q, Jian M, Wang C, Zhang Y. Carbonized silk nanofiber membrane for transparent and sensitive electronic skin. Advanced Functional Materials. 2017;27(9):1605657.

[167] Jung M, Lee K-J, Kang J-W, Jeon S, editors. Silk-Based Self Powered Pressure Sensor for Applications in Wearable Device. 2020 International Conference on Electronics, Information, and Communication (ICEIC); 2020: IEEE.

[168] Seo JW, Kim H, Kim K, Choi S, Lee H. Calcium-Modified Silk as a Biocompatible and Strong Adhesive for Epidermal Electronics. Advanced Functional Materials. 2018;28(36):1800802.

[169] Khalid A, Peng L, Arman A, Warren-Smith S, Schartner E, Sylvia G, et al. Silk: A bio-derived coating for optical fiber sensing applications. Sensors and Actuators B: Chemical. 2020;311:127864.

Chapter

Application Technologies for Functional Finishing of Textile Materials

Zeynep Omerogullari Basyigit

Abstract

Nowadays, the primary energy resources and existing water reserves in the world are gradually decreasing. Because of global warming and high consumption of energy and water, researches have focused on new technologies and methods which aim of optimum use of resources while applying functionalites to the material. When the energy and water consumption of industries is examined, it could be obviously determined that the textile industry is seen to be at a substantial level. For this reason, in this chapter broad information of application systems including conventional and low-liquor application techniques with updated versions which show notable improvements in textile industry lately, have been detailed in a way of properties, parameters and running mechanisms on textile materials.

Keywords: low-liquor application, energy, water, finishing, application, textile

1. Introduction

Today, consumption of fossil fuels is dramatically increasing along with improvements of life such as industrialization processes with the increase of the world population. It has long been recognized that this excessive fossil fuel consumption not only leads to an increase in the rate of diminishing fossil fuel reserves, but it also has a significant adverse impact on the environment, resulting in increased health risks and the threat of global climate change [1]. The potentially most important environmental problem relating to energy and water resources is global climate change (global warming or the greenhouse effect). The increasing concentration of greenhouse gases such as carbon dioxide, methane, chlorofluorocarbons, halons, nitrous oxide, ozone, and peroxyacetylnitrate in the atmosphere is acting to trap heat radiated from Earth's surface and is raising the surface temperature of Earth [2]. This climate change has an increasingly negative impact on water resources; causing a serious decrease in available water reserves in the world [3]. In order to solve this problem, researchers have been focused on new methods for optimum use of resources with new technologies which save energy and reduce water consumption.

When the energy consumption in textile enterprises are compared to other branches of industry, it can be seen that the textile industry is seen to be at a substantial level. It could also be note that finishing departments are the most energy consuming ones among the other parts of textile manufactories. 45–75% of the energy consumed in finishing departments is listed as wet processes, 15–40% for drying and fixing processes, 8–18% for other processes and ventilation. Electricity consumption is not much in finishing departments; however, heat energy and water consumption is at very high level [4, 5]. For this reason, energy and water-saving technologies play an important role in the machines and application methods used in finishing processes.

Although textile finishing processes can be applied in different material forms (fiber, tops, yarn, fabric etc.), the most common is fabric finishing. General expectations for all these finishing are having homogenous effect, non-damaged fibers, non-broken fabric, repeatable and economical process, low environmental impact and reduced energy and water consumption. Different application techniques are used in the studies related to give desired properties to textile materials. Most of these application techniques are wet processes. These wet processes include exhaustion, impregnation, vacuum application, maximum application techniques as well as spraying, coating, transfer and foam application methods which are among the low-liquor application techniques [6]. In addition to these methods, microencapsulation, plasma application, sol–gel technology and lamination techniques, which have become increasingly important in recent years, are also included in finishing applications.

Nowadays, the methods and techniques used in the textile industry are desired to be environmentally-friendly and to save water and energy besides the other requirements such as functionality, durability, repeatability and being cost-effective. With the increase of diversification of today's industrial requirements, one functionality on the fabric may be insufficient to meet these requirements, therefore, although it varies according to area of utilization, being multifunctionality becomes more of an issue. In some cases, the fact that the fabric has more than one functionality on the whole surface entirely, regardless of front or back sides of the material, causes an increase in cost unnecessarily and also prevents showing sufficient efficiency in the area of use. For instance; for a sportswear outfit, the interior structure of the fabric is desired to be hydrophilic to absorb the sweat and water occurred during movement of the body, while the outer structure of the material is expected to water–oil-soil repellent. If the water repellency functionality is applied to the entire fabric, water repellant chemicals will act functional on the outer side of the fabric while it will serve as blocking barriers by preventing the absorption of sweat and water in the interior side of the material. This will not only bring on difficulties in use but also cause increased unnecessary cost during the finishing process of the material.

Since the conventional padding application methods, which are still in use widely today, do not allow the transfer of different chemicals to different sides, both sides of the fabric are treated with the same chemical substance and due to unnecessary material transfer, both the expected requirements cannot be fully met and cause an increase in costs. For this reason, it has emerged that some functionality needs to be applied to a single surface of the fabric.

Providing multifunctionality in a single-bath could have disadvantages in many respects that all the requested functionalities are mixed with each other in a single recipe and in the same bath. The first of these disadvantages is that all basic and auxiliary chemicals used in the same bath, belonging to different functionalities, may not be compatible with each other. Since the chemical structures of materials belonging to different functionalities are different, their mechanism of action is also different, and therefore problems may be encountered in providing a homogeneous mixture. The second of these disadvantages is that since all the chemicals are mixed with each other, the functionalities will be given in a mixed order regardless of the back or front face of the fabric, unfavorable functionality may be occurred on the undesired side or the requested efficiency is not achieved as expected or no functionality is obtained at a sufficient level. Therefore, due to all these problems and requirements, achieving multifunctionality by transferring more than one functionality to the same and/or different sides of the fabric in an effective and permanent way in accordance with the field of use has become a necessity both in industrial and academic terms.

There is a way of combining fabric layers with different functionalities by lamination methods or so, for obtaining multifunctionality, but because of each separate layer has own functionality, the endproduct takes up more space in terms of volume and increases the cost of the material. For this reason, multifunctionality in single-layer fabrics should be carried out by considering the requirements of providing mobility to the user, being useful and flexible, and saving in material costs.

Due to all the above-mentioned requirements in textile industries; advantages and disadvantages of existing conventional methods besides new generation finishing processes which focuses on reducing water and energy consumption mostly, are defined in this chapter.

2. Wet finishing processes

Most of the textile finishing application techniques are wet processes. These wet processes can be listed as follows: exhausting process, impregnation, coating, transfer, spraying and foam application. It should be noted there is an optimum level of liquor application which is just high enough to ensure adequate distribution of the chemicals within the fabric. This critical add-on value (CAV) depends on fiber type, fabric construction and fabric pretreatment [6–11]. The wet processes have been in use for a long time however; they have been updated in many ways nowadays; such as using new technologies in impregnation machines with lower wet pick-up ratios, providing homogenous application in new version of chemical foam application, removing the blockage occurred in nozzles of spraying machines. Minimum application methods, which focuses on reducing water and energy consumption, have an increased importance recently in finishing processes with a wide range of functionalities provided such as water–oil-soil repellency, flame retardancy, antibacterial efficiency and so many other functionalities due to their significant advantages over conventional methods. The application technologies including conventional ones and updated low-add-on finishing applications have been detailed in this review.

2.1 Exhausting process

The essence of the application with the exhaustion method is that the product to be treated is in wet-process for a long time at the long liquor ratio. The liquor ratio in the studies according to the exhaustion method is in the range of 1:2–1:100. This method is also called full bath method or discontinue method. The fabric to be treated is placed in a bath and allowed to absorb the finishing agent from the bath until a chemical-balance is reached between the finishing agent on the fiber and the one in the bath. In order to provide sufficient and economical results in this method, it is essential that the finishing material used has an affinity towards the textile material. In other words, the finishing material dissolved or homogeneously dispersed in the bath should have a high desire to be withdrawn from the bath by the fibers.

Dyeing process can be carried out with textile fibers, yarns, fabrics or garments. However, there are reasons for dyeing different fiber forms. Fiber dyeing is used as a styling technique; natural fibers or staple synthetics are dyed in bundles or baskets. Dope or solution dyeing is the process where color is mixed into the polymer solution prior to fiber extrusion. Certain synthetics fibers such as polyethylene can only be colored using this technique. Yarn dyeing which is also a styling technique, is used to produce stripes, plaids, and some complex designs with 100% fiber content products. Beam dyeing is a technique where multiple yarns are wound side by side onto a single perforated beam. This can be a few hundred or even a few thousand yarns wound onto a single beam. Fabric or piece dyeing is the most cost efficient and highest productivity technique. Fabric dyeing machines include jet machines, dye becks, fabric beam, and jig dyeing machines. All of these machines as well as most of the yarn dyeing machines are batch or exhaust machines [12]. Some of the machines used in exhaustion method are shown in **Figures 1** and **2** [10, 15].

Advantages:

- Processing time, temperature and composition of the liquor (pH of the liquor, amount of electrolyte, auxiliary substances) can be adjusted as desired. Thus, the application speed (proper application of the dyestuff from the beginning) and the application amount (color fixation in dyeing) can be adjusted.
- The process can be easily intervened and additional toning can be made. Therefore, it is easier to attach the result than the impregnation method.
- It provides ease of operation as washing, bleaching, dyeing and finishing processes are carried out in the same machine.

Disadvantages:

- The most important disadvantage is that the liquor ratio is long, so the consumption of water, finishing chemicals and energy (required for both heating and moving the liquor) is so high.

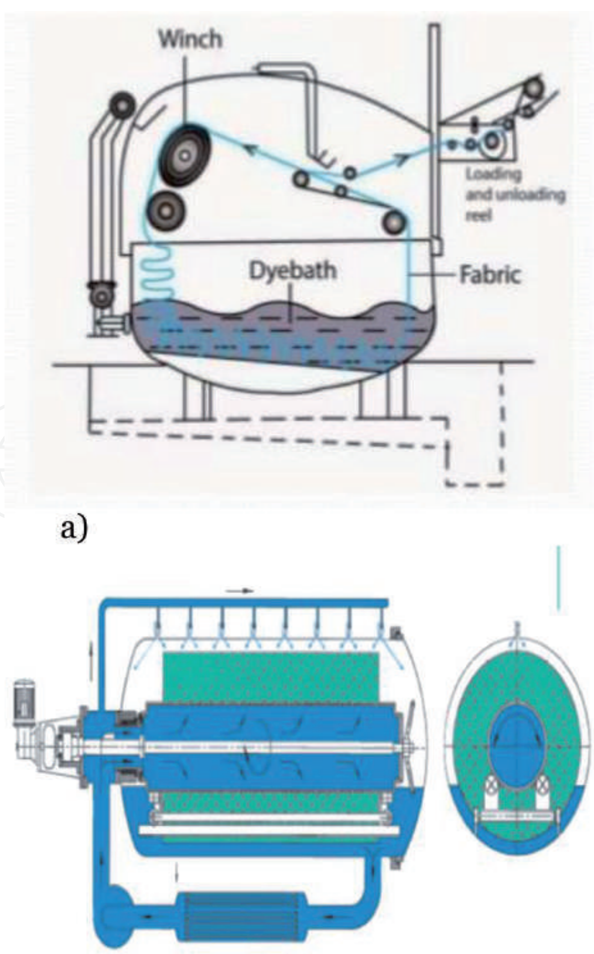
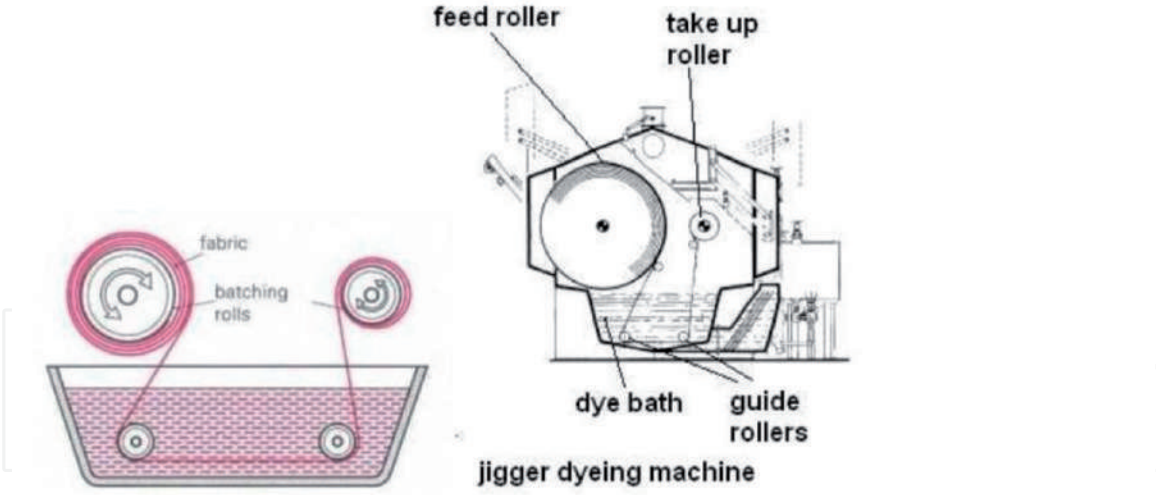
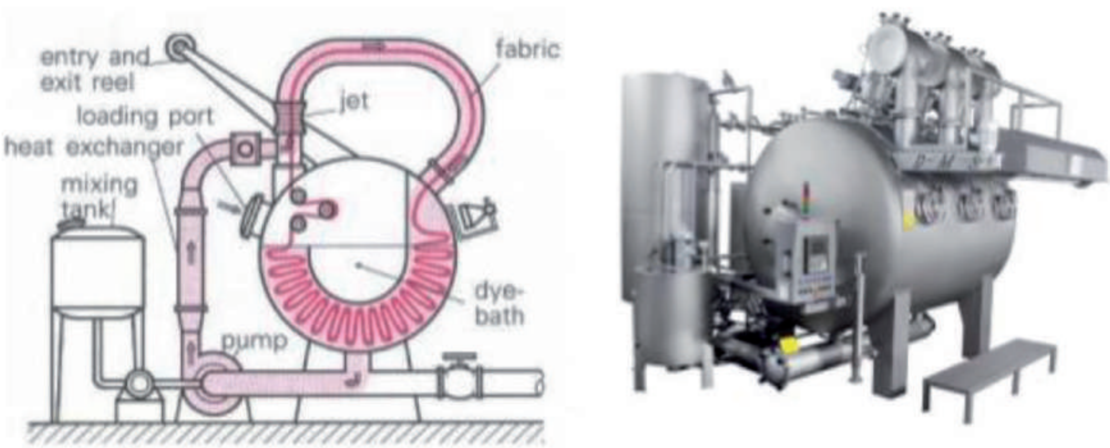


Figure 1.
Exhausting process machines in textile finishing (a) winch dyeing (b) beam dyeing [13, 14].



c)



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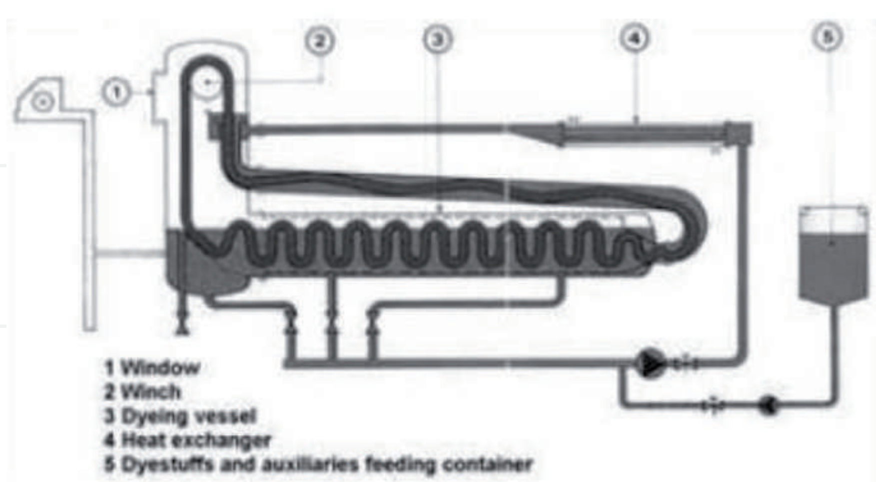

e)

Figure 2.
Exhausting process machines in textile finishing (c) jigger dyeing (d) jet dyeing (e) over-flow dyeing machines [13, 14].

- These are the discontinue methods that have long processing time (usually longer than 30 minutes).
- It requires a hand work and long time for operating the machine before application [5, 6, 8–10, 15].

2.2 Impregnation method

The application process, which is done by passing the textile product through the liquor in a bath within a short time (t < 30 seconds) and squeezing, is called impregnation (padding) method. After the fabric has been padded through the liquor and prior to being squeezed through the rollers of the padder, the liquor is distributed as follows: within the fibers; in the capillary regions-between the fibers; in the spaces between the yams; on the fabric surface [11, 15]. Two characteristics stand out in this method: short liquor ratio and short processing time. In impregnation method, it is important to not to use finishing chemicals that have affinities to the textile materials, or it should be at a very low level. As this is a continuous method, the concentration of the liquor absorbed by the product at the beginning should be same in the bath and at the end of the process. However, if finishing materials with high substantivity are used, the process results in with a tailing effect (when dyeing is done by padding method, gradual color change occurs along the fabric length because of the decrease in the concentration within time) [6, 9, 15]. Since most of the materials used in textile pretreatment do not show much substantivity towards fibers, unlike those used in dyeing, the most used application technique in these processes is impregnation. The types of impregnation machines work due to padding mechanism are shown in **Figure 3**. This method has also some disadvantages varied according to the types of the system, such as high concentration of finishing chemicals and long-time processing in pad-batch, tailing effect in pad-roll dyeing which is also labor intensive process, high energy consumption in pad-steam and necessity of an extra machine in pad-jig method which results in over costing investment. It should be also noted that high wet-pick-up ratios associated with the padding system are disadvantageous, not only because of the high thermal-drying and water consumption costs, but also because, during the evaporation of the liquor in thermal drying, the molecules of the applied substances tend to migrate from the inside to the outside of the fabric, leaving behind an uneven chemical distribution which leads to a decreased fabric durability of the functionality [5, 7, 15].

This method is divided into two as dry to wet impregnation and wet to wet impregnation. Since it is easier for a dry textile product to be absorbed in a bath containing finishing material (because the capillarity of the fibers is high due to its absorption ability), the dry-to-wet impregnation method works in shorter periods than wet-to-wet impregnation method. However; if a second wet finishing process is to be carried out after a wet finishing process, when the drying step is considered to be a very expensive intermediate process, the advantage of removing this part and saving energy indirectly will be achieved. Moreover, the risk of migration of the finishing chemicals which occur in drying process before the dyestuff/finishing agents are fixed on the fibers, could be prevented by removing this interim drying process in wet to wet impregnation [5, 15].

2.3 Transfer method

In this minimum (low wet-pick-up) application method made in special foulard, the fabric itself is not dipped into the bath. The liquor containing the finishing agent is taken by a rolling roller and transferred to the back surface of the fabric. That's why we could see this type of finishing systems under the name of "Lick/Kiss Roll Applicators" [19]. Transferring is an application method that can be applied with high viscosity finishing liquors. Excess liquor on the transfer roller or fabric is scraped off with the help of doctor blades. The **Figure 4** shows 4 different transfer systems, which differ in terms of the number of rollers, the location of the paddle

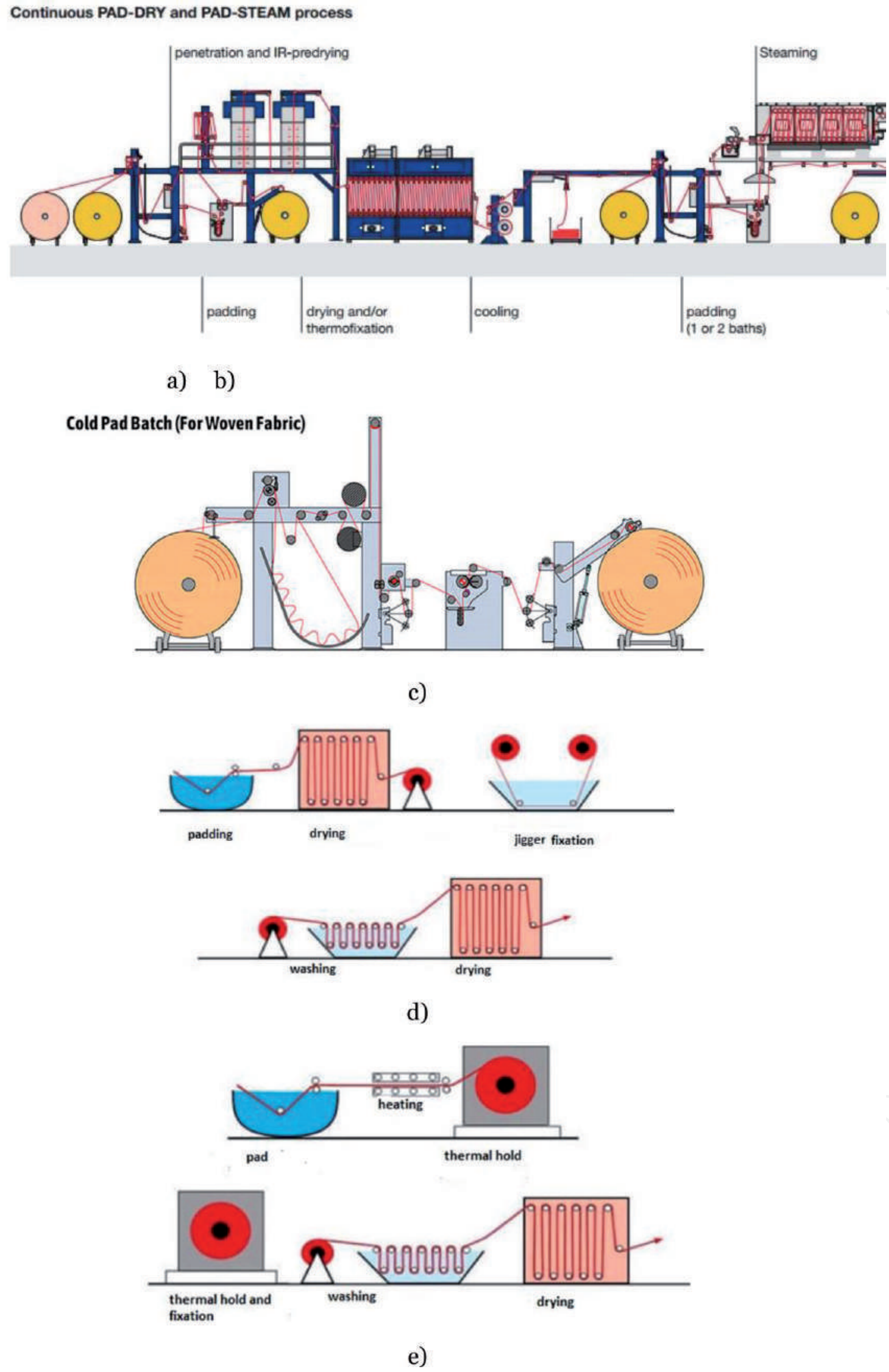

Figure 3.
Impregnation machines (a) pad-dry-cure (b) pad-steam (c) pad-batch (d) pad-jig (e) pad-roll [16–18].

and measurement techniques [6, 7, 9, 11, 15, 19]. The schematic representation of Triatex MA machine which uses on-line monitoring to control the wet pick-up values, has been shown in **Figure 4d**. The kiss roll rotational speed is automatically adjusted (with the help of β-rays measured by detectors) [15] relative to the fabric speed to maintain the desired wet pickup.

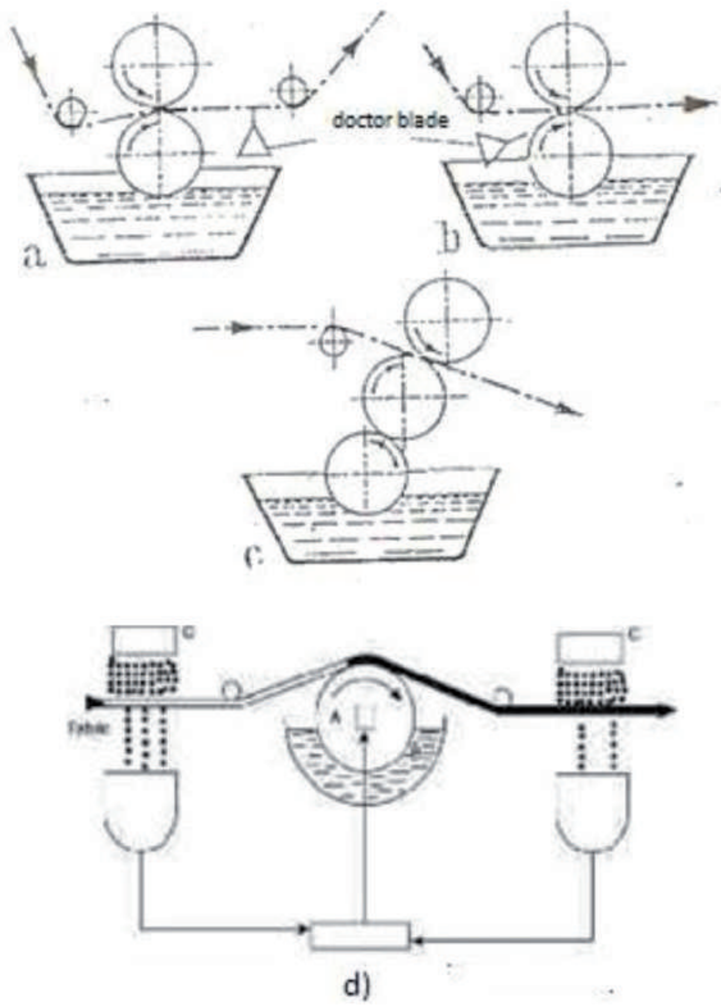

Figure 4.
Different types of transfer (with lick/kiss roll applicators) finishing methods (a) and (b) two-roller with doctor blade type (c) three-roller transfer type (d) Triatex MA [15, 19].

The amount of finishing agent transferred to the textile product is determined by following parameters; the structure of the transfer roller, condition of doctor blade and other rollers, viscosity of the liquid, the passing speed of the fabric and the rotation speed of the transfer roller. There are two big benefits of working with less liquor; firstly, energy savings as less water will need to be removed during subsequent drying and secondly, reduction of the risk of migration of dyestuffs or finishing substances that have not yet been fixed during drying. However; this method has also some disadvantages.

- The main problem in the operations of this method is the inconsistency of the formation of a smooth liquor on the transfer roller. This homogenous formation is not only dependent on the structure of the roller surface, but it's also closely related to the composition of the liquor.

- The second problem is the disability to ensure that the same amount of liquor continuously applied to the textile material [11, 15, 19].

2.4 Spraying method

Spraying method in finishing process has been known and applied on textiles for a long time however; it has not been improved much for many years because of some difficulties in conventional (nozzle) spraying machines mentioned below:

- It is difficult to apply the same amount of liquor all over the fabric continuously,

- Nozzles are frequently clogged, especially when working with viscous chemicals.

- A part of liquor sprayed in very fine particles is placed on other parts of the machine instead of the fabric, causes excessive pollution and unnecessary chemical loss.

Especially after the oil crisis in 1974, the spraying method has become updated with the increase in the importance of the application processes which has low wet-pick-up values. To overcome the difficulties in conventional spraying methods, indirect spray applications have been demonstrated by the Farmer Norton and Weko applicators. In these systems, the spray is generated by pumping the finishing solution by a proportioning pump from a well onto the center of a rapidly rotating set of spinning discs (Farmer Norton) or rotors (Weko) [7, 15, 19, 20]. In addition to have the main advantages of being in the minimum application system, spraying technology has some other advantages such as; being suitable for wet-to-wet applications, no tailing effect even if the chemicals have the affinity, ability to be applied on one or two sides of the fabric upon request [15, 20]. Weko Fluid application system has been shown in **Figure 5**.

2.5 Coating method

Finishing liquors with high viscosity can be applied directly to one side of the fabric. As a result of such application, a large amount of finishing material can be transferred to the surface of the material and this process is also called "coating", since the finishing agent mostly covers the surface of the material. The coating method is frequently used especially for producing artificial leather and waterproof finishing process. Multi-layered functional materials can be produced

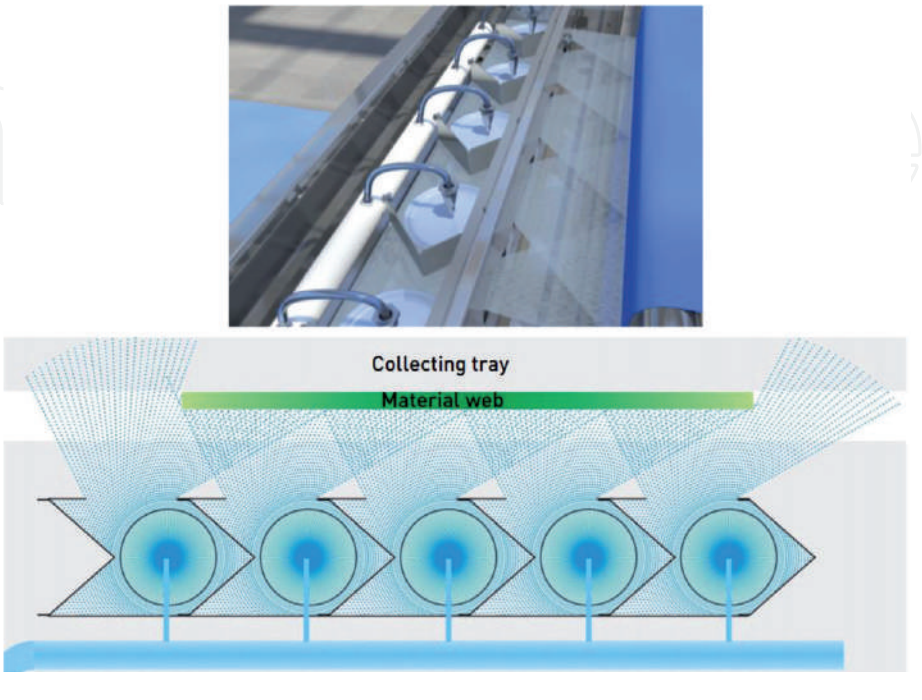

Figure 5.
WEKO-fluid application system [20].

with different coating methods including direct (directly coating on to the fabric) and indirect (using for exp. silicone paper during coating) system [15, 21–23]. In **Figure 6** illustrations of direct and indirect coating systems have been shown [23]. The basic mechanism of a direct coating method is spreading polymer on the textile material, in the form of thick liquid (viscous) or paste using a special knife called doctor blade [21]. The smoothness and the thickness of the applied layer are adjusted with the help of doctor blades.

In "blade on air" coating system, the fabric passing under the blade does not lean anywhere. Therefore, it is not possible to make thick and very smooth coatings with this type of coating. It is preferred for light coatings of loose woven fabrics. However; the coating material that passes to the other side of the fabric due to the loose texture, it contaminates the rubber band or roller under the blade and causes uneven coating. In "blade over the roller" system, the fabric that passes under the doctor blade is based on a rotating rubber or steel cylinder. The thickness of the layer applied in the coatings can be adjusted precisely. But on the other hand, since the cylinder cannot stretch; dust or fly can be trapped under the blade, causing soiling and forming drag lines [21].

There are some other coating processes used in the film and paper industries which require expensive equipment and which must be carried out on a large scale

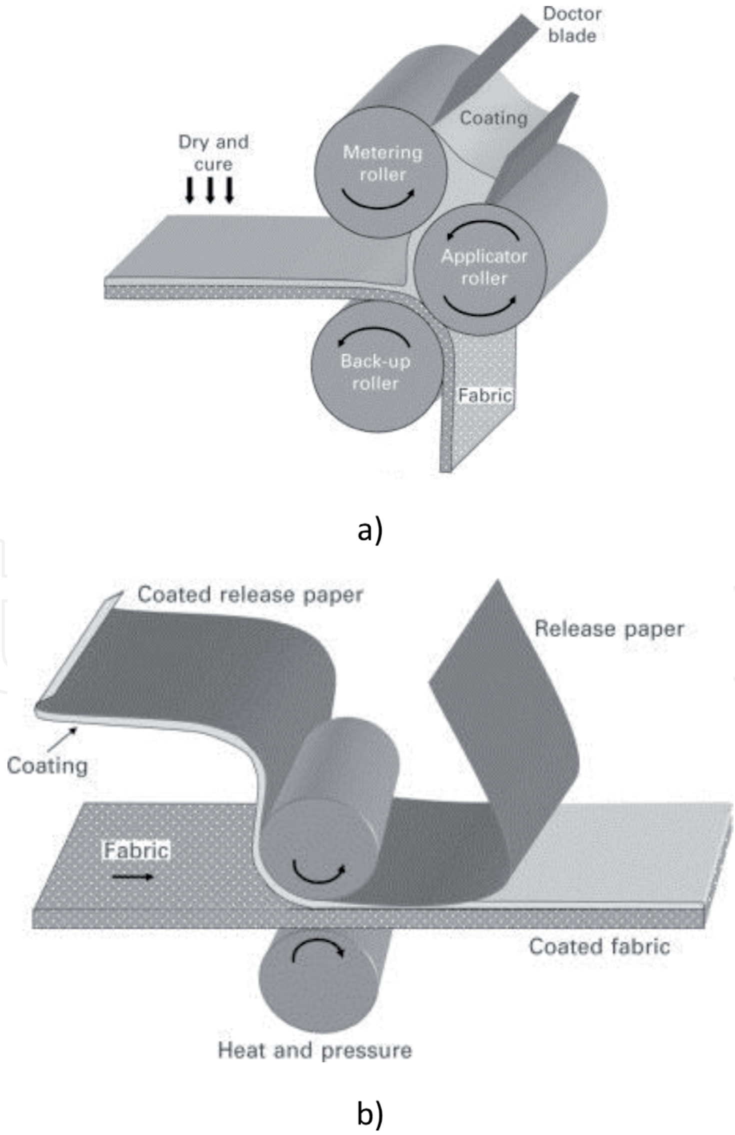

Figure 6.
(a) Direct coating system (three-roll coatings: Nip feed coating) (b) indirect coating system (transfer coating) [23].

to be commercially viable. Among these are powder coating, vacuum deposition, electrostatic deposition and sputtering techniques. It is possible, for example, to produce highly reflective surfaces by these methods, but a smooth continuous surface is required and fabrics may not be suitable [21, 22].

2.6 Foam application method

The most important and interesting development in the application of finishing agents to textile products in the mid-1970s is undoubtedly the application methods with foam. Machines that enable working with foams instead of aqueous solutions have been put on the market because of increased energy costs in the textile industries. However, the application studies with foam, which developed very rapidly in the beginning, have entered a pause and had no significant improvement until 2010 [24].

Foam is a microheterogeneous colloidal mixture, short or long-lasting a metastable system in which the surface area is increased nearly 1000 times by inflating a liquid with a suitable gas (air), and therefore contains less liquid. Foam is obtained by dispersing the air in water as fine particles with the help of surfactants. If a surfactant is dissolved in aqueous solution and air bubbles are present in this solution, then a surfactant film covers the air bubbles. Air bubbles move towards the upper surface of the liquid which covered with a tenside film. Thereby, a second tenside film is formed around the upward air bubbles (**Figure 7**) In this way, the air bubble in which the liquid is located between the two tenside films surrounding, called a "foam cell" [7, 15, 24, 25].

There are many types of foam application such as; open foam method (Horizontal pad foam, Knife-roll-over foam, Autofoam systems), offset open foam methods (Küsters Janus contact roller system and Monforts vacuum drum system), closed foam methods (FFT Foam Finishing Technology-Gaston County Dyeing Machine, CFS Chemical Foam System-Gaston System, Stork rotary screen foam applicator and Stork CFT Coating and Finishing Technology) have been shown in **Figures 8–10** [24, 29, 30]. As seen in the figures, there have been much improvement in the profiles of foam applicators in time in order to prevent the problems such as non-uniform and uneven applications during processes. The case in point can be the improvement of CFS parabolic profile which has been developed to solve "dead foam" issue occurred in FFT. With the help of parabolic chamber, equal distance paths are covered from the point of foam inlet to the fabric surface so that the problem of wet and unfoamed parts occurred partly in FFT foamed fabrics have been solved [24, 29].

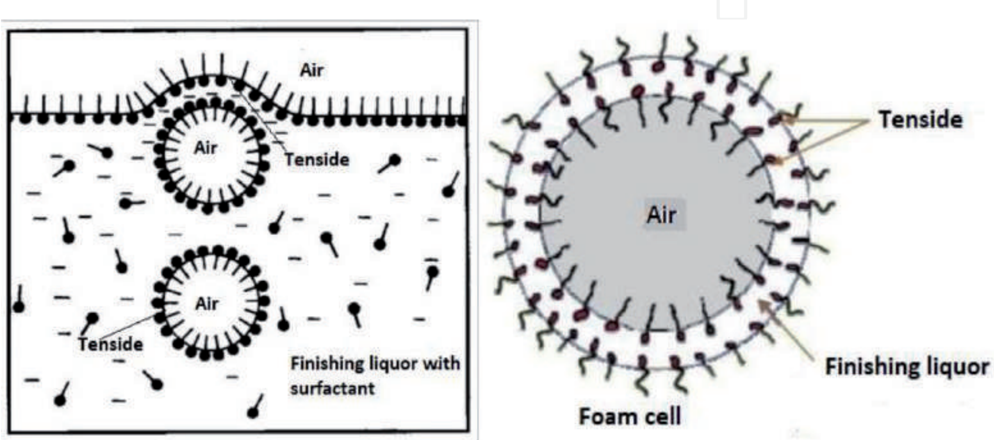

Figure 7.
Formation of a foam cell.

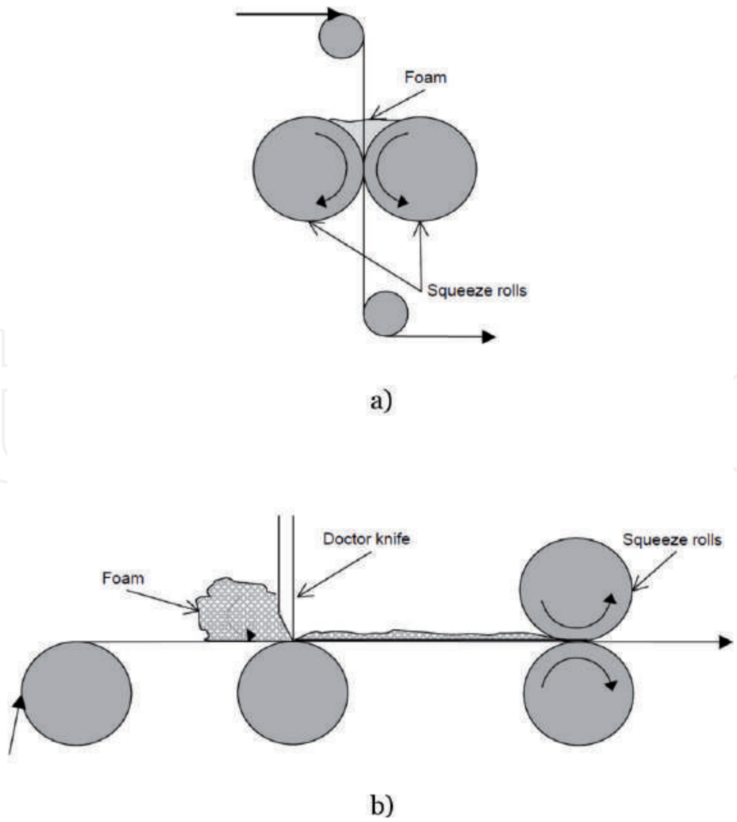

Figure 8.
Types of foam application (a) horizontal pad foam (b) knife-roll-over foam [24, 26–28].

For an effective foam application process, the followings should be taken into consideration:

- The foam should not be collapsed during the time between it is taken from the foam generator and transferred to the fabric.

- On the other hand, when the foam reaches out the textile product, it should collapse into the fabric as quickly as possible. Foam stability constitutes an important place in foam applications. Very stable foams play role in decreasing the penetration efficiency into the fabric whereas unstable foams cause uneven applications because of collapsing before the application. Therefore, foam cell should be in semi-stable form.

- The foam and the tenside used in the application must have good compatibility with other chemical substances in the bath.

- The foam to be used in a finishing process should always has the same form and the same concentration.

- Another important point in foam application is that the foams should not have much water. If the foam that does not contain much water, it is transferred directly onto the fabric surface moving perpendicularly without spreading around the fabric surface. On the other hand, when the conventional finishing liquors first penetrated to the fabric, they spread parallel to the fabric surface by capillarity effect. For this reason, in conventional finishing applications such as in padding methods non-functional caked chemical residuals remained at the fibers intersections cause uneven application and nonhomogeneous penetration [15, 27].

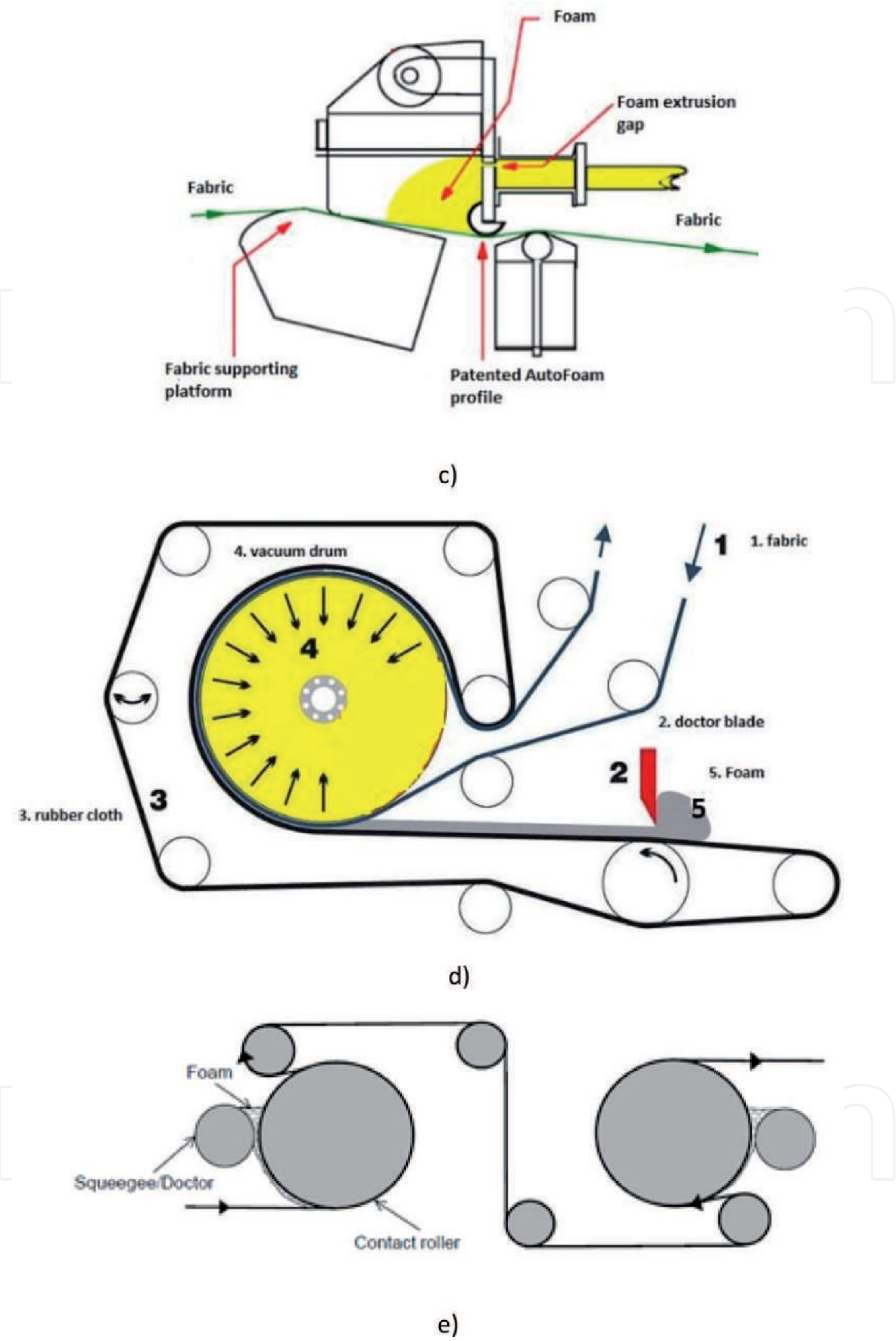

Figure 9.
Types of foam application (c) autofoam systems (d) Monforts vacuum drum system (e) Küsters Janus contact roller system [24, 26–28].

2.6.1 Advantages of foam application

Foam finishing is a versatile application system which could be very effective for bleaching, dyeing and varied finishing processes. It can be also used to apply different applications to the face and back side of the fabric in a single pass with

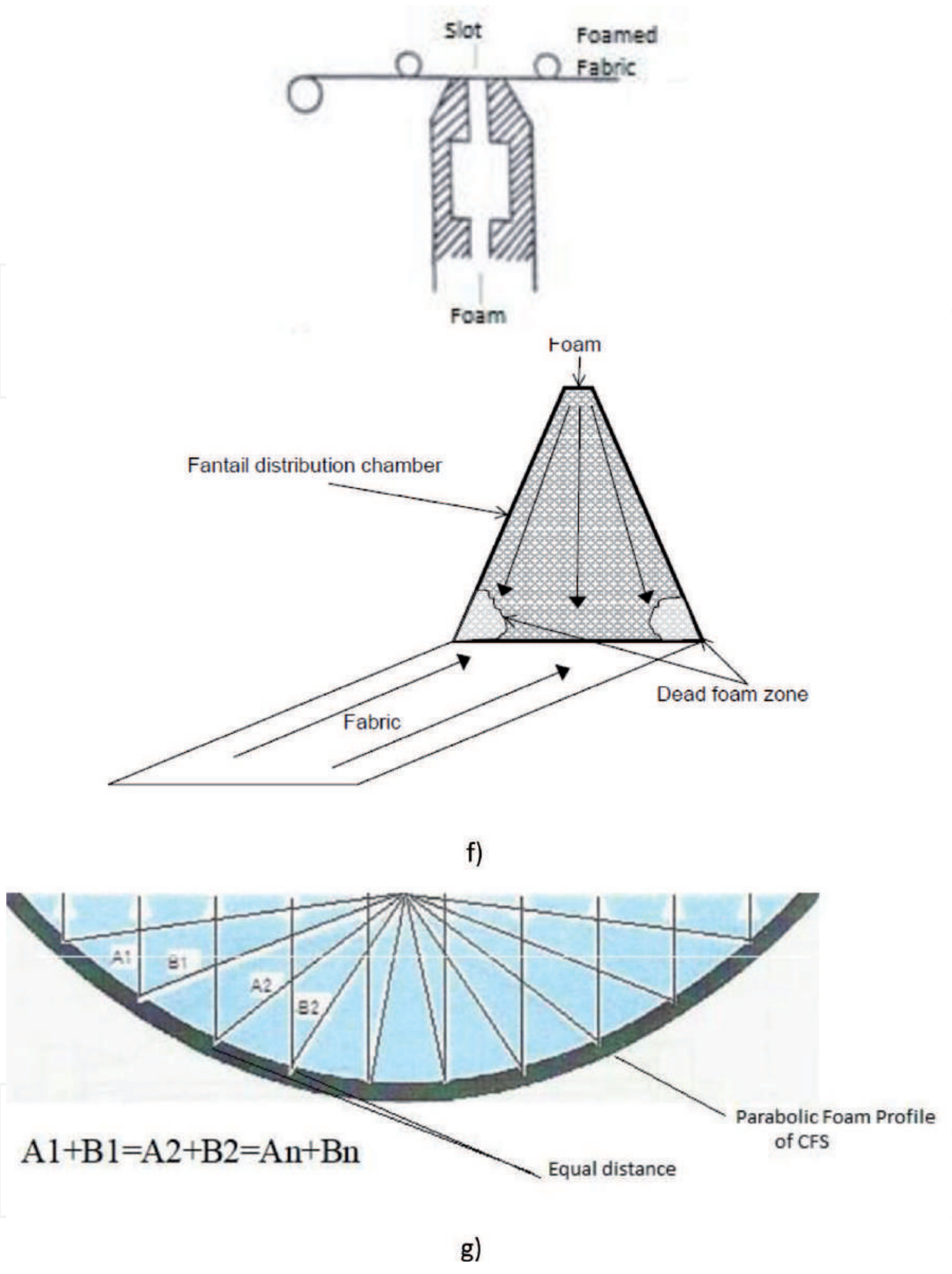

Figure 10.
Types of foam application (f) foam finishing technology (FFT) (g) chemical foaming system (CFS) [24, 26–28].

dual-applicators. Multifunctional fabrics with increased durability against repeated washing and drying processes could be produced. As reported in the literature [24] that many combinations of functionalities such as face side flame retardant and water repellent whereas antibacterial back side of textile materials could be provided via foam finishing application. The most important advantage of this system is providing significant decrease in water consumption (up to 80%) due its lower wet-pick-up system. For cotton-rich fabrics, the wet pickup in foam finishing is typically between 15% and 35%, depending on the process, compared with 60%

to 100% for a conventional pad application [27, 29, 30]. For synthetic fabrics, wet pick up ratio of foam application is in the range of 3–10% whereas it is 35–60% in conventional padding. Moreover, the energy consumed for heating and venting the air is significantly decreased due to lower wet-pick-up values. This reduction in time needed for pre-drying step (could be eliminated), also minimizes the migration of the chemicals. Since the amount of liquor taken is small in foam finishing, excessive swelling of the fibers is not possible. Since the fibers do not swell and the capillary channels do not expand too much, the transferred chemical substance is not carried to the surface with water during drying and remains where it is transferred. This is particularly effective in preventing the reduction of the abrasion resistance in the wrinkle recovery finishing. Since migration, that is, the accumulation of the chemical substance on the surface more than necessary during drying, is effective in the decrease in friction resistance. Foam application also potentially results in less waste water pollution than with traditional application methods. On the contrary of an aqueous pad system, the small liquor volumes required for foam application result in less waste during a changeover [15, 24, 27, 29, 31–34].

Updated versions of foam application systems has offered better solutions to the basic problems encountered with the other low-add-on systems. The main problem of the low-add-on systems is the difficulty of distributing a relatively small quantity of liquor uniformly over a large surface of fabric, especially on hydrophilic fibers. In the case of low-add-on expression systems, a basic limitation is the inability to achieve wet-pick-up levels below the critical application value of the component fibers [7]. When compared to conventional methods, foam finishing provides homogeneous and effective chemical applications via controlled, uniform and repeatable foam formations.

2.6.2 Chemical foaming system (CFS)

If CFS foam machine is examined, it could be clearly seen that uniform and homogenous applications are achieved via performing correct systematic on the distance between the foam generator and applicator.

As shown in the **Figure 11**, the foam diameter increases as the foam formed in the CFS foam generator is transferred from high pressure to the low pressure on the way to the foam applicator. The pressure gradually decreases on the fabric surface and the foam penetrates the fabric. The distance between the foam generator and its applicator is critical for uniform foam formation.

DG: Initially, the radius of the foam produced in the foam generator.

DA: The radius of the foam being transferred from the foam generator to the foam applicator.

DB: The radius of the foam at the foam applicator just before it penetrates to the fabric.

WG: Initially, the area covered by the liquid contained in the foam produced in the foam generator.

WA: The area covered by the liquid in the foam being transferred from the foam generator to the foam applicator.

WB: The area covered by the liquid in the foam just before it penetrates into the fabric, at the foam applicator.

Before the transfer process starts, the state between these parameters is $WG > WA > WB$ and $DG < DA < DB$, while these equations are reversed as the pressure decreases gradually, and $WG < WA < WB$ and $DG > DA > DB$ becomes. Therefore, on the foam applicator, penetration to the fabric takes place evenly with maximum radius and minimum liquid area of the foam [27].

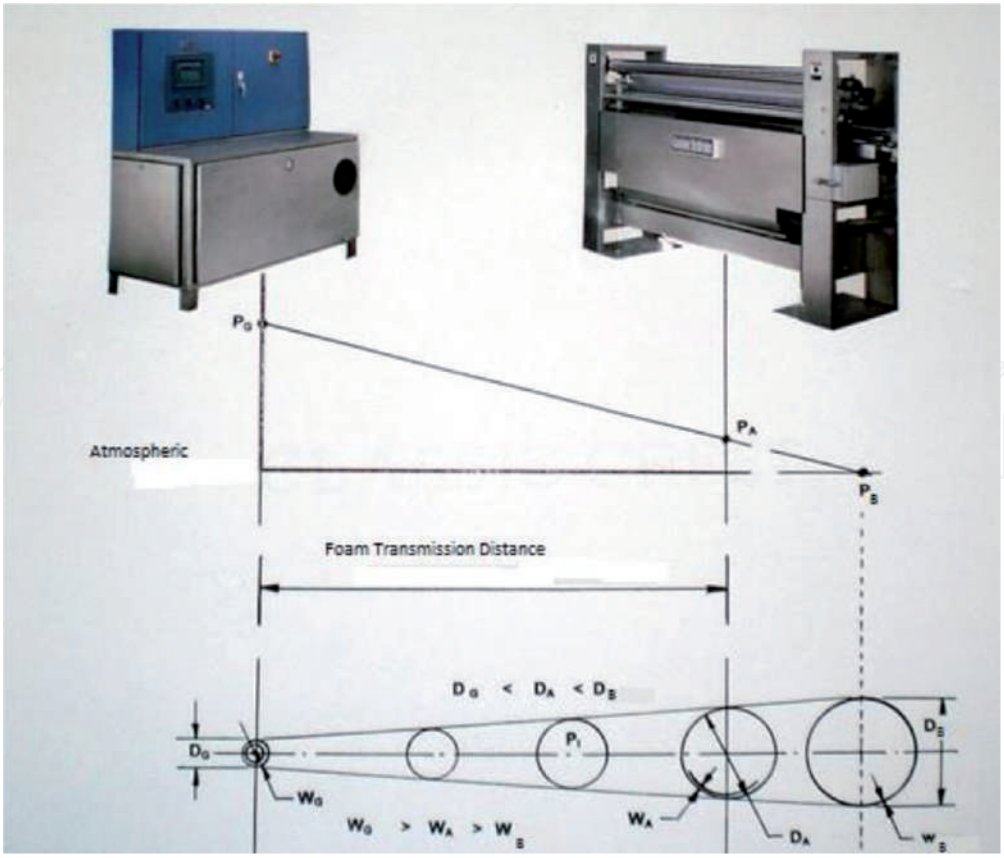

Figure 11.
Chemical foaming system (CFS) [27].

3. Conclusion

Considering the finishing methods used in the textile industry in general, conventional impregnation method is commonly used in the industry due to the low affinity of the chemicals used in the finishing processes. However, it has disadvantages such as high water and energy consumption, inability to apply different functionalities to face and back sides of the material and significant waste load. Extraction method is not included among the preferred methods because the chemicals used have affinity to the fabric, the operation times are long and the amount of water consumed is very high due to the long liquor ratio. Apart from these methods, transfer and coating methods are also available. Transfer methods with various types such as roller transfer or with doctor blades takes place in the minimum application methods. Likewise coating methods is in the low-liquor finishing applications with the types of blade coating, calendar coating, transfer and printing technique. However, both transfer and coating methods are not suitable for low viscosity chemicals. In coating and transferring methods, the effectivity of the application is directly related to the viscosity of the finishing agents, the construction and surface structure of textile material, production method of the material (woven, non-woven or knitted), weight of the textile, speed of the finishing method etc. So, it could be noted that they are not very flexible application techniques in a view of finishing agents and textile materials. Even if the direct spraying method had some problems in the past such as clogging of nozzles or excessive pollution on the machine, with the use of indirect systems such as discs or rotors, it has been much more improved. When the history of the foam application is examined, it could be clearly noticed that significant improvements have been carried out by time in order to make functional or multifunctional (via using dual-applicators) textiles via uniform applications (with developed applicator profiles) which provides reduction in water and energy consumption. Apart from these, there are various lamination techniques that can be used to obtain multifunctionality however; since the lamination process is based on the principle of combining fabric and polymer layers to form a composite material, any factor that prevents adhesion between the structures, low heat resistance of the materials or no resistivity for water and moisture can cause problems during applications.

Apart from these methods, there is also environmentally friendly techniques such as plasma technology, which is used in the textile industry and academic pilot studies, and gives functionality to the fabric with partly ionized gas or monomers without using water [35–37]. With this technology many researches have been carried out to provide functional textiles such as antibacterial cotton fabric supported by silver nanoparticules [38], water repellent and antimicrobial cotton/polyester blend [39], anti-bacterial and anti-static polyester fabric [40]. However, in this technology, the vacuum plasma method, which is quite effective, is a discontinuous method and could not be industrialized because it allows a very low size in terms of fabric length and width. The atmospheric plasma method, which is suitable for industrial use as the operating dimensions, is not as effective as vacuum plasma on porous textile surfaces. Microencapsulation technique, is also one of the effective methods used in textile applications. Microencapsulation technology involves the process by which small particles, mostly bioactive, are encapsulated in a wall consisting of a heterogeneous or homologous polymer matrix, which forms a complex known as a microcapsule [41, 42]. Microencapsulation helps to improve functional textile products such as fabrics with durable fragrances, UV-ray absorbing shirts, thermo-regulation vehicle seats, thermo-changeable dyed apparels, vitamin loaded fabrics as cosmototextiles or military uniforms with microcapsulated insecticides [42]. However, in order to transfer performed microcapsules onto the textile material, the capsulation method is continued with a conventional finishing method frequently (mostly padding) so that two-step applications are carried out with no significant reduction in water and energy consumption. Sol–gel technology, which is a method that can obtain macromolecules by taking advantage of the growth and development of polymers in a solvent, can also be an effective alternative in terms of giving functionality to textile materials. There have been lots of studies on sol–gel functionality such as self-cleaning superhydrophobic films [43], flame retardant and hydrophobic coatings on cotton fabrics [44], hydrophilic, antistatic and antimicrobial cotton and polyester fabrics [45]. However, it should be noted that the requirement of using solvents brings environmental threats and applying some special polymers increase input costs [46]. Nano-technology seems to be a significant alternative for achieving functional and multifunctional textile materials [35] however; in some cases, there have been still some issues of industrialization of nanoparticles because of producing them only in laboratory scale experiments. Studies about using liposomes in dyeing processes [47–49] photocatalytic reactions for bleaching process [50, 51] and layer-by-layer self-assembly technique for producing multifunctional multilayers [52, 53] have also been taken place in the literature but there has been no scientific clue reported in the literature for industrialization of these methods in textile manufactories.

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References

[1] Farhad, S., Saffar-Avval, M., & Younessi-Sinaki, M. (2008). Efficient design of feedwater heaters network in steam power plants using pinch technology and exergy analysis. International journal of energy research, 32(1), 1-11.

[2] Panwar, N. L., Kaushik, S. C., & Kothari, S. (2011). Role of renewable energy sources in environmental protection: A review. Renewable and sustainable energy reviews, 15(3), 1513-1524.

[3] Lu, S., Bai, X., Li, W., & Wang, N. (2019). Impacts of climate change on water resources and grain production. Technological Forecasting and Social Change, 143, 76-84.

[4] Namboodri, C. G., & Duke, M. W. 1979. Foam finishing of cotton-containing textiles. Textile Research Journal, 49(3): 156-162.

[5] Tarakçıoğlu I. 1984. Tekstil terbiye işletmelerinde enerji tüketimi ve tasarrufu. Uludağ Üniversitesi Basım evi, Bursa, 102 s.

[6] Çoban S.1999. Genel tekstil terbiyesi ve bitim işlemleri, E.Ü. Tekstil Konfeksiyon Araştırma Merkezi, İzmir, 314 s.

[7] Elbadawi, A. M., & Pearson, J. S. 2003. Foam technology in textile finishing. Textile Progress, 33(4):1-31.

[8] Schindler, W. D., & Hauser, P. J. (2004). Chemical finishing of textiles. Elsevier.

[9] Choudhury, A. K. R. (2017). Principles of textile finishing. Woodhead Publishing.

[10] Cay, A., Tarakçıoğlu, I., & Hepbasli, A. (2009). Assessment of finishing processes by exhaustion principle for textile fabrics: An exergetic approach. Applied Thermal Engineering, 29(11-12), 2554-2561.

[11] Van der Walt, G. H. J., & Van Rensburg, N. J. J. (1984). A review of low add-on and foam application techniques.

[12] 12.https://www.cottonworks.com/wpcontent/uploads/2018/01/Dyeing_Booklet.pdf

[13] https://www.slideshare.net/sheshir/jigger-dyeing-machine-33040185

[14] https://www.slideshare.net/asifalilakho3/exhaust-dyeing-process

[15] Tarakçıoğlu I. 1998. Tekstil Terbiyesinde Aplikasyon Yöntem ve Makinaları, E.Ü. Basımevi, Bornova, İzmir, 97s.

[16] https://textileinsight.blogspot.com/2014/08/pad-steam-dyeing-machineprocess.html

[17] https://www.shreeshaktikrupa.com/cold-pad-batch/

[18] https://tekstilbilgi.net/pad-jig-yontemi-ile-boyama.html

[19] Madhu, A., & Pal, S. (2012). Low Wet Pick-up Techniques In Textile Finishing. Man-Made Textiles in India, 40(1).

[20] http://parandchemie.ir/pdfs/DR.PETRY-SALES-CONFERENCE 2016/WEKO_denim_PRESENTATION_en.pdf

[21] Fung, W. (2002). Coated and laminated textiles (Vol. 23). Woodhead Publishing.

[22] Kovačević, S., Ujević, D., & Brnada, S. (2010). Coated textile materials. Woven Fabric Engineering, 241.

[23] Shim, E. (2013). Bonding requirements in coating and laminating

of textiles. In Joining Textiles (pp. 309-351). Woodhead Publishing.

[24] Başyiğit Ömeroğulları, Z. (2016). "Improving functional properties of cellulosic based textile materials via foam application" PhD thesis, Uludag University, Institute of Science and Technology, Bursa, TR.

[25] Bafford, R. A., & Namboodri, C. G. 1984. Foam Processing of Textiles. Sixth Annual Industrial Energy Technology Conference Volume I, Houston, TX.

[26] http://iqbaltextile3022.blogspot.com/2009/06/

[27] 27.https://www.gastonsystems.com/system/system.html#:~:text=CFS%20is%20a%20highly%20controlled,nonwovens%2C%20paper%2C%20and%20others.&text=This%2C%20combined%20with%20CFS%20technology,control%20of%20chemical%20penetration%20depth.

[28] http://www.autofoam.co.uk/en/app_std.html

[29] https://www.cottoninc.com/wp-content/uploads/2017/12/TRI-3008-Processing-100-Cotton-Woven-Fabrics-for-Filling-Stretch.pdf

[30] Gregorian, R. S., Namboodri, C. G., Young, R. E., & Baitinger, W. F. 1983. Foam application of phosphonium salt flame retardants. Textile Research Journal, 53(3):148-152.

[31] Song, M. S., Hou, J. B., Lu, Y. H., Lin, J., & Cheng, D. H. (2013). Performance of foam and application in foam finishing of textile. In Advanced materials research (Vol. 821, pp. 661-664). Trans Tech Publications Ltd.

[32] Baker, K. L., Bryant, G. M., Camp, J. G., & Kelsey, W. B. 1982. Foam finishing technology. Textile Research Journal, 52(6):395-403.

[33] Brown, R. L., & Bryant, G. M. 1984. Influence of Resin Add-on and Co-applied Water in Foam Finishing of Cotton Fabric. Textile Research Journal, 54(12): 807-812.

[34] Camp, J. G. 1990. Recent Developments in Foam Application Systems for Nonwoven Substrates. Journal of Industrial Textiles, 19(4): 252-260.

[35] Omerogullari Basyigit Z. 2017. "Functional Finishing For Textiles" Researches On Science And Art In 21st Century Turkey. Book Chapter 257, pp: 2297-2308, Gece Publishing, TR.

[36] Omerogullari Basyigit Z. 2018. "Plasma Applications in Textile" Researches On Science And Art In 21st Century Turkey. Book Chapter 114, pp: 1468-1480. Gece Publishing, TR.

[37] Gulrajani, M. L., & Deepti, G. (2011). Emerging techniques for functional finishing of textiles.

[38] Deng, X., Nikiforov, A., Vujosevic, D., Vuksanovic, V., Mugoša, B., Cvelbar, U. & Leys, C. (2015). Antibacterial activity of nano-silver non-woven fabric prepared by atmospheric pressure plasma deposition. Materials Letters, 149, 95-99.

[39] Davis, R., El-Shafei, A., & Hauser, P. (2011). Use of atmospheric pressure plasma to confer durable water repellent functionality and antimicrobial functionality on cotton/polyester blend. Surface and Coatings Technology, 205(20), 4791-4797.

[40] Zhang, Z., Zhao, Z., Zheng, Z., Liu, S., Mao, S., Li, X., & Li, G. (2019). Functionalization of polyethylene terephthalate fabrics using nitrogen plasma and silk fibroin/chitosan microspheres. Applied Surface Science, 495, 143481.

[41] Muhoza, B., Xia, S., Wang, X., Zhang, X., Li, Y., & Zhang, S. (2020).

Microencapsulation of essential oils by complex coacervation method: preparation, thermal stability, release properties and applications. Critical Reviews in Food Science and Nutrition, 1-20.

[42] Šiler-Marinković, S., Bezbradica, D., & Škundrić, P. (2006). Micro-encapsulation in the textile industry. Chemical Industry and Chemical Engineering Quarterly, 12(1), 58-62.

[43] Zhang, X. F., Zhao, J. P., & Hu, J. M. (2017). Abrasion-Resistant, Hot Water-Repellent and Self-Cleaning Superhydrophobic Surfaces Fabricated by Electrophoresis of Nanoparticles in Electrodeposited Sol–Gel Films. Advanced Materials Interfaces, 4(13), 1700177.

[44] Zhang, D., Williams, B. L., Shrestha, S. B., Nasir, Z., Becher, E. M., Lofink, B. J., & Sun, L. (2017). Flame retardant and hydrophobic coatings on cotton fabrics via sol-gel and self-assembly techniques. Journal of colloid and interface science, 505, 892-899.

[45] Chen, G., Haase, H., & Mahltig, B. (2019). Chitosan-modified silica sol applications for the treatment of textile fabrics: a view on hydrophilic, antistatic and antimicrobial properties. Journal of Sol-Gel Science and Technology, 91(3), 461-470.

[46] Tobiszewski, M., Namieśnik, J., & Pena-Pereira, F. (2017). Environmental risk-based ranking of solvents using the combination of a multimedia model and multi-criteria decision analysis. Green Chemistry, 19(4), 1034-1042.

[47] Barani, H., & Montazer, M. (2008). A review on applications of liposomes in textile processing. Journal of liposome research, 18(3), 249-262.,

[48] Montazer, M., Taghavi, F. A., Toliyat, T., & Moghadam, M. B. (2007), Optimization of dyeing of wool with madder and liposomes by central composite design. Journal of applied polymer science, 106(3), 1614-1621.

[49] Campardelli, R., Trucillo, P., Iorio, M., & Reverchon, E. (2020). Leather dyeing using a new liposome-based process assisted by dense gas technology. Dyes and Pigments, 173, 107985.

[50] GEDİK, G. (2020). Bleaching of Cotton/Lyocell Fabrics with Heterogeneous Photocatalysis with Titanium (IV) Oxide Under UV Light and Investigation of the Effect of Oxygen Radicals on Bleaching Process. 2020 (Volume: 27), 118.

[51] Barros, M. A., Conceição, D. S., Silva, C. G., Sampaio, M. J., & Faria, J. L. (2020). Sustainable Bleaching Process of Raw Cotton by TiO2 Light-Activated Nanoparticles. U. Porto Journal of Engineering, 6(2), 11-21.)

[52] Safi, K., Kant, K., Bramhecha, I., Mathur, P., & Sheikh, J. (2020). Multifunctional modification of cotton using layer-by-layer finishing with chitosan, sodium lignin sulphonate and boric acid. International Journal of Biological Macromolecules.

[53] Lu, L., Hu, C., Zhu, Y., Zhang, H., Li, R., & Xing, Y. (2018). Multi-functional finishing of cotton fabrics by water-based layer-by-layer assembly of metal–organic framework. Cellulose, 25(7), 4223-4238.

Chapter

Surface Design Technique through Tradition Technique

Harozila Ramli and Tajul Shuhaizam Said

Abstract

This aim of this study is to examine the application of tritik technique in creating exquisite batik pattern design. Essentially, tritik is a technique in batik pattern making that is almost similar to the "tie-and-dip" (ikat-dan- celup) technique; however, the subtle difference between the two techniques lies in the aspect of fabric treading, with the former being able to produce elegant and appealing patterns. This study used a qualitative approach using an observation method in which the researchers observed the creation of such art through studio practice. Essentially, the examination of the practice of such a technique was carried out based on direct observation and unstructured interviews, and the collection of textile products. The research findings showed the experimentation of the tritik technique in the textile pattern designs was highly effective, as evidenced by the exquisite aesthetical effects on the surface of the fabrics, such as the formation of elegant lines consisting of dots and of dashed lines and 3-dimensional texture. In addition, the research findings revealed that the quality of fabrics, the type of colors, and sewing polarity heavily influenced such exquisite tritik pattern design. Collectively, all the above elements were intertwined that helped create appealing, beautiful tritik pattern design infused with high aesthetical values.

Keywords: tritik technique, Batik, Textile pattern designs

1. Introduction

Textile art in the Malay world, especially in Malaysia have been detected since the start of the historical development of the culture of the archipelago. Since the Sultanate has recorded about how different types of fabric and textiles is taken as an omen to the status of goods in individual position in society and benchmark the progress of Malay civilization.

According to Raffles in The history of Java [1] has described how different types of clothing and fabrics are unique with the technique of patterning the surface of the fabric such as tie and *tritik*, as well as illustrations of batik patterns produced. Skeat [2] also describe how the Malays use natural coloring during dyeing silk and cotton which are obtained from Singapore.

In a note, Winsteadt [3] Malay Industries Part I, Art and Craft, he also describes the surface design techniques on fabric produced by the Malay community at the time. Techniques that have been applied are such as coloring, weaving, embroidering, embroidering and knitting techniques for the production of textile patterns and ornaments. Obviously tradition surface design of decorative fabric or Malays textile surface have long practiced and it has been developed and passed down from generation to generation until now in the development of traditional cultural arts in Malaysia.

Essentially, batik making is a method of creating beautiful textile materials or cloth involving the use of candles and coloring materials based on natural or synthetic colors. In creating batik, candles are the main medium used to create the required pattern and, at the same time, serve as the medium to separate the colors. To help create artistic batik, several techniques can be used, including tradition technique, the use of *canting*, metal block, wood block, screen, and, lately, dedicated computer software, to create digital batik products.

Tritik technique is one of the traditional decorative techniques that have long been practiced by textile craftsmen in Malaysia. The adaptation of this technique has become one of the uniqueness of batik design in Malaysia apart from the technique of dyeing, canting, and the use of batik blocks and also screen printing as well as the use of brush techniques on fabric.

Tritik is indeed not a new discovery in textile history. This technique has existed for a long time when society began to explore fabrics and colors in dyes for fabric coloring. Instead, there was previously in India called Bandhani and Japan called Shibori, in Malaysia and Indonesia called Tritik. In fact, there is a much older tie-dye motif found in Peru in 500. The designs found include circles and small lines with bright colors, such as red, yellow, blue, and green.

But in Japan and China have developed tie-dye techniques since the sixth century using silk cloth. Silk fabric is evaluated as a suitable material for a more perfect color absorption process. These skills are also likely to have evolved in the Malay Archipelago as a result of trading activities involving the exchange of goods in the past. Skills staining on fabrics, ornaments and decorations technique is adapted according to the nature of Malay culture and become a work of art in the textile design community in the archipelago.

Tritik or *sasirangan* batik is one of the high fashions that help project the uniqueness and beauty in terms of its creation, such as the type of polarity or motifs created with the method of sewing and pull. In the early history of textile, this technique was used by the Banjarmasin society in which the early design of tritik batik only used simple motifs deemed moderately sufficient to meet the fashion needs of the people dwelling in the district of Banjarmasin. However, in tandem with the advancement in fashion designs taking place in the world, tritik batik has undergone a series of innovative transformations through which the patterns and motifs created by such technique have been reshaped and redesigned with diverse geometrical and organic patterns that helps project their artistic beauty.

Moreover, the application and combination of colors also play an important role in establishing the required motif and pattern on the surface of the batik design. Surely, the knowledge and skills in pattern design of fabric surfaces are a critical element in designing exquisite motifs on such surfaces [4].

Consistent with the current trend in fashion designs, the new, contemporary tritik batik, with its exquisite aesthetical effects visibly appearing on the surface of the fabrics, helps make its wearers look elegant and attractive. Despite the uniqueness in such pattern design, tritik technique has gradually being neglected in today's batik pattern design, which is partly attributed to the complicated process involved in making such design.

To help sustain the use of batik in Malaysia as a national attire, the Malaysian government had made it compulsory for the public servant to wear batik shirts or *baju kurung* (women Dress). Apparently, the rapid development of fashions has been instrumental in influencing the design of fashions throughout the world.

Despite such development, however, some of the traditional designs, such as batik blocks, batik drawing, and batik printing, have managed to survive the test of time, with many fashion fans keeping their loyalty with such designs. As such, the use of tritik technique can be re-energized to create batik that has a new appealing design with high aesthetical and artistic values and exquisite pattern design that projects unique beauty. Admittedly, due to the rapid development of the fashion world taking place at an unprecedented rate, the tritik technique has started to decline in its use in the making of batik textile. Unmitigated, such a decline will see such a unique technique becomes obsolete – a thing of the past – in batik-textile making. Obviously, more efforts have to be put in place to address this pressing predicament by encouraging practitioners to adopt the tritik technique in designing intricate batik patterns. Another problem that contributes to the declining use of such a technique lies in the lack of proper learning or training in pattern design of batik textile, especially with respect to the structure of patterns that needs to be discerning learned. For example, the knowledge regarding the closely aligned stitches to create intricate patterns with amazing characteristics, such as sharp teeth, base, *dovo, regulon,* and *gadan*, and the application of red, green, and yellow have to be mastered by practitioners.

Seen from the socio-cultural viewpoint, such a problem is the manifestation of the lack of knowledge among the members of the society, in particular, Art students, with respect to the societal impact of the tritik technique, effecting a decline in the awareness or appreciation of such a culturally enriched method of producing traditional batik. Clearly, to help overcome such a problem, the tritik technique needs to be used in the pattern design process to produce elegant and immaculate patterns, which are on par with those created by other techniques, such as tie-*and-dip* (ikat celup) technique.

Based on a practical studio experimenting with the tritik technique in the making pattern - design process of batik motifs on the surface of a fabric. In addition, the effect of this technique on the surface of the fabric, also has been examined which began from the creation of the Napthol color through the mixing of Diazo salt and Remazol coloring dye to the complete tritik process performed on the fabric. Through practiced studio process, focusing on the process prior to sewing was carried out, the inherent constraints encountered during the process of sewing a particular polar of a pattern and the effects of untying knots on the fabric, also able to identify the outcome of the pattern design of the tritik technique.

Definitely, the selection of suitable fabrics in creating tritik batik is of paramount importance. Obviously, the use of quality fabrics will improve the rate of absorption, enabling the coloring materials to penetrate deeply into the fabrics to produces stunningly attractive, intricate, and appealing effects of the tritik technique. In this regard, the use of suitable fabrics has a profound impact on the effectiveness of the tritik technique that helps the Naphthol color to seep deep into every fabric of the batik materials. To date, several types of fabrics have been widely used with this technique, such as cotton fabric, rayon fabric, and silk fabric, which are clothes made from natural sources. Essentially, such fabrics contain natural fibers with good “working characteristics”, with which the tritik technique can produce amazing effects.

In Malaysia, the majority of people prefer to wear clothes made of cotton. Such a preference is not surprising as cotton can easily absorb sweats produced by the human body in countries in the tropical region of the world, such as Malaysia. In essence, this type of cloths is made from cotton fibers that are used to make short, soft, and fluffy fibers In general, these cotton fibers are used as the primary material in making shirts, robes, bedspreads, and others. Given their delicate characteristics, cotton fabrics are suitable for batik practitioners who manually use their hands with some degree of force in making batik materials (**Figure 1**).

Figure 1.
Cotton fabrics are suitable for batik practitioners.

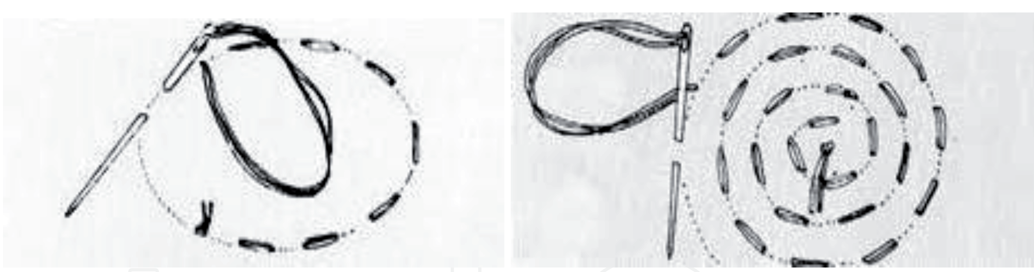

Figure 2.
Illustration of sewing or stitching process in a spiral.

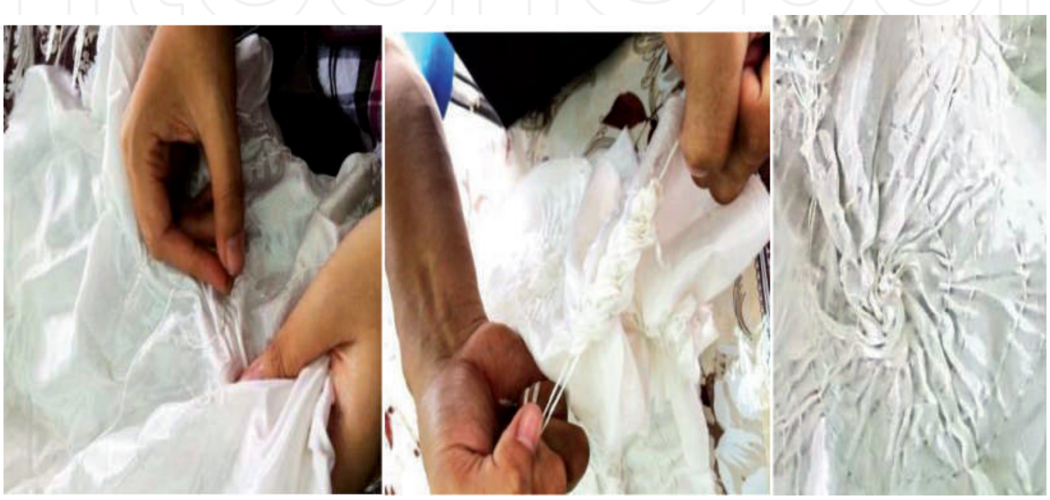

Figure 3.
Sewing process in a spiral moves according to a prescribed spiral pattern.

2. The method of stitching

In general, this type of stitching has a number of diverse sewing techniques, but to create a pattern on the fabric will entail the needle to move in a spiral. Effectively, such a spiral motion of the needle, in which it moves according to a prescribed pattern based generally on a distance of I cm, can help achieve the desired effects.

Furthermore, the threads need to be tightened when the sewing or stitching process has completed. Subsequently, colorings will be swiped over the entire surface of the fabrics that have been completely sewn (**Figures 2** and **3**).

3. The tritik cotton-fabric patterns

The followings are some of the patterns of the cotton cloth created by the effects of the stitching technique used. Clearly, such forms and shapes of the patterns were the results of a sewing or stitching processing a particular direction or polarity, effecting the desired effects that helped create such amazing pattern designs (**Figure 4**).

4. The rayon fabrics

Principally, Rayon is a fabric that can be weaved or merged, depending on its diverse use. In fact, the effectiveness of stitching Rayon is relatively higher than those of other fabric materials, such as *taf* cloth of cotton cloth. In the batik-making industry, the Rayon fabric is categorized as a semi-soft fabric that most batik

Figure 4.
Spiral patterns of the cotton cloth created by the effects of the stitching technique.

Figure 5.
The rayon fabrics.

practitioners find easy to manually work on. As such, the use of this fabric should be emphasized to achieve the desired effects on such fabric (**Figure 5**).

5. The method of stitching

The type of sewing or stitching as shown above is based on horizontal sewing that cuts the surface of the fabric neatly. Ideally, the distance of the stitched fabric

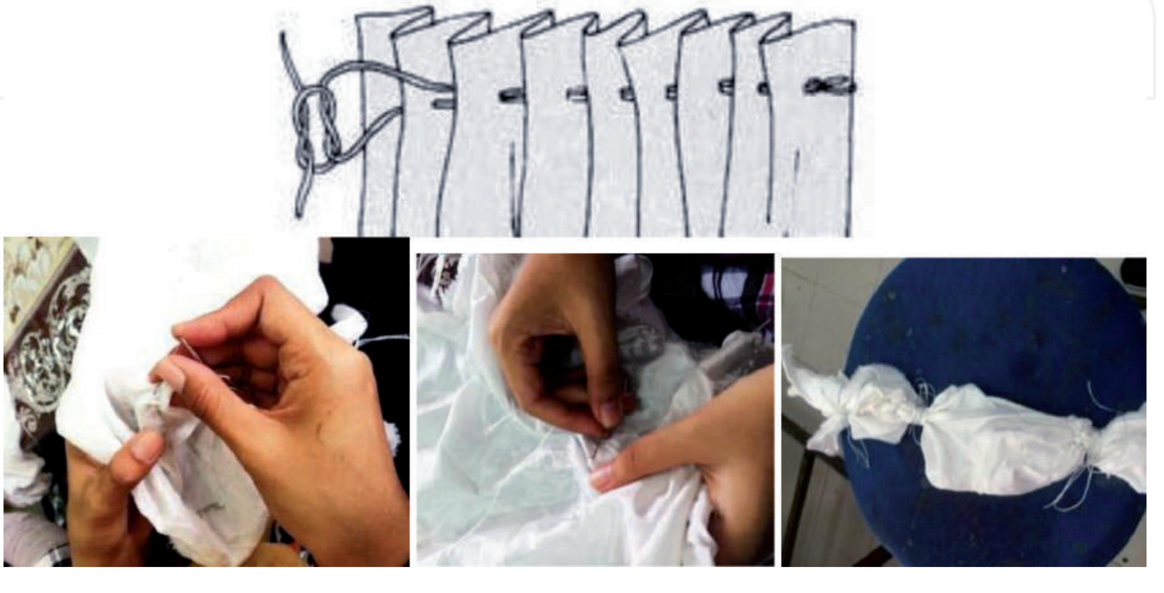

Figure 6.
The process of horizontal sewing performed on a fabric.

should be in the range between 1 cm and 2 cm. obviously, the direction of sewing that is straight and compact will create an amazingly appealing effect. In particular, the end of the cloth must be tied to achieve a better effect (**Figure 6**).

6. The tritik rayon-fabric patterns

As shown in **Figure 7**, the result of using the tritik technique on the Rayon fabrics showed stunning effects, visibly highlighting the effects of colors and stitching on such fabric. Evidently, the stitching the fabric horizontally did not in any way compromise the quality of the fabric. On the contrary, such a stitching method was able to project the undulation of the movement of colors together with the desired pattern on the fabric.

7. The type of satin fabrics

As contended by almost all practitioners, the satin fabric is regarded as the most elegant fabric compared to other types of fabrics, making it a high-class fashion material. This contention is not without reason, as this type of fabric has a surface is delicately soft and glossy, the characteristics that create stunning reflections under the light. In general, satin cloth consists of silk or Rayon, which makes its surface extremely soft. The drawback of this fabric, however, is that it needs constant care, given the delicate nature of its material, which is made up of the softest fibers. To date, satin fabrics have been widely used in many designer fashions throughout the world, notably in developed countries (**Figure 8**).

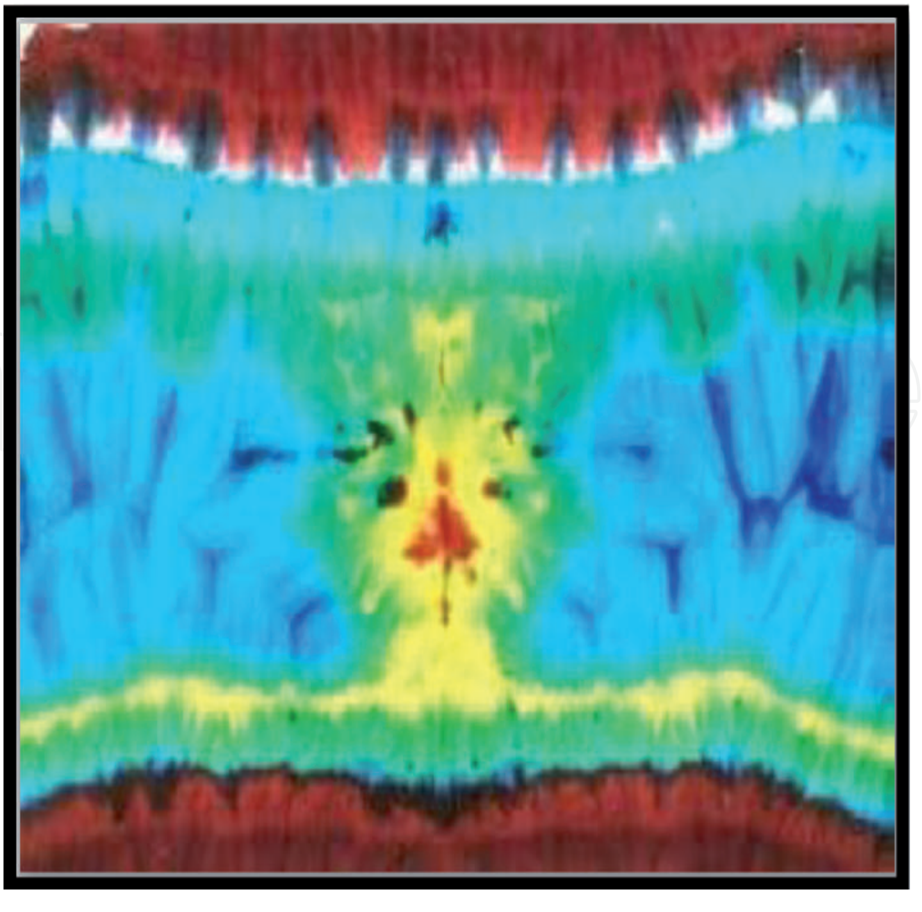

Figure 7.
Tritik technique on the rayon fabrics showed stunning effects, visibly highlighting the effects of colors and stitching on rayon fabric.

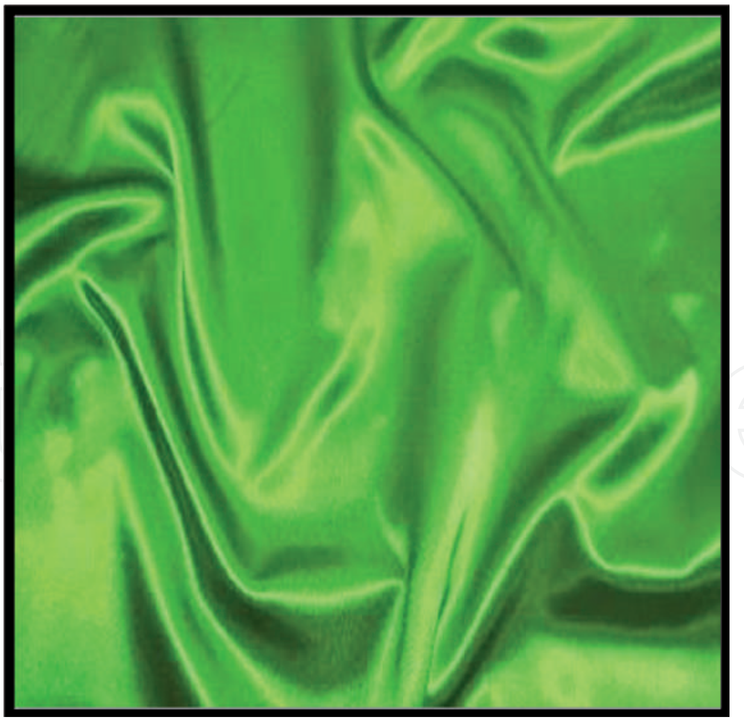

Figure 8.
Satin fabric.

8. The method of stitching

The appropriate configurations of such stitching for such fabrics are circular and horizontal. In this study, the configuration examined was based on circular sewing involving a single direction of movement, of which the closer the distance of the stitches the more attractive the effects on the surface of the fabric.

As shown in the **Figure 9**, spiral stitching based on the close distance among the stitches will create stunningly beautiful effects on the fabric. Furthermore, the edges of the cloth have to be permanently fastened by pulling the thread forcefully to create the desired effects.

9. The tritik satin-fabric patterns

Figure 10 shows the effects of the tritik technique on the surface of the satin fabric. Revealingly, it shows that a well-balanced use of colors can create spectacularly attractive and beautiful effects compared to those that use colors that are too bright or too dull. Through this practical studio-based study, the researchers examined the practice of the tritik technique in the batik-making process involving three types of fabrics, namely cotton fabric, rayon fabric, and satin fabric.

Based on the observations, it can be reasonably argued that each type of fabric has its own unique and beautiful tritik effects, despite using the same sewing or stitching configuration. Surely, such differences in the tritik effects lie in the properties of the fabrics, with each having different thickness and structure of fibers, which produce the unique texture of the fabrics. Clearly, the different types of fibers make some fabrics soft while others coarse, the impact of which will have a profound impact on the rate of absorption and the rate of evaporation of liquids that result in different effects on the patterns of the fabrics. Given such inherent differences, the selection of appropriate fabrics should be treated with caution – in fact, it should be treated as the basis – to help create specular and stunning patterns using the tritik technique.

Figure 9.
Spiral stitching based on the close distance among the stitches will create stunningly beautiful effects on the fabric. Furthermore, the edges of the cloth have to be permanently fastened by pulling the thread forcefully to create the desired effects. The process of spiral stitching performed on a fabric.

Figure 10.
Tritik technique on the surface of the satin fabric.

Moreover, the quality of stitching also depends on the sewing configuration that can help create beautiful effects by controlling the form or the structure of such a pattern. Also observed in this study was that pattern designs in various organic forms or shapes seemed to be the dominant pattern in the tritik technique to produce patterns with high aesthetical values. In addition, the distance between stitches can strongly influence the effects on the patterns made on the fabrics. Likewise, the strength of the knots is also important in creating such attractive patterns.

Evidently, the closer the stitching on the surface of the fabric, the more stunning the patterns will be. Similarly, the tighter the threads are tied, the more spectacular the tritik effects will be in producing beautiful, delicate lines of various sizes and quality. Undeniably, the tying technique and the stitching configuration play an important role in the tritik technique in creating beautiful, unique patterns. In terms of the use of coloring materials, the tritik technique heavily relies on relevant colors to create the desired tritik patterns on fabrics. In fact, such a technique emphasizes well-balanced and judicious use of colors, given that the tritik pattern entails the tone of colors that is neither too strong not too weak.

Clearly, a well-balanced use of colors in the tritik technique can produce patterns that harmoniously blend the chosen color to produce pleasing effects, highlighting a spectacular contrast of colors that enrich the beauty the batik fabric. In this regard, the mixing of Naphthol color and Diazo salt can help produce a color tone that represents the color of the earth's soil. Thus, it cannot be overstated that the coloring effect is an important element in designing beautiful, intricate patterns on the surface of fabrics, which can be carried out by experimenting with colors and sodium silicate. The effect of tritic techniques on fabrics has indirectly created new

Figure 11.
Type of fabrics: Cotton. Technique: Dipping Tritik. Medium: Naphthol color. Soaking duration (in sodium): 6 hours.

patterns with very unique organic and abstract shapes. The effects of color patterning the shapes on the surface of the fabric is one of the characteristic privileges tritik technique that can provide confirmation of the identity of batik fabrics are processed. The followings figure showcase the pattern designs of various fabrics created by the tritik technique (**Figure 11**).

10. Tradition technique *vs* global trending

The experimentation of the tritik technique in designing patterns is a new learning process that effectively has helped create a new, diverse technique in batik textile industry. Specifically, practitioners can use this unique technique, which is slowly being forgotten, to manipulate the method of sewing or stitching threads on the surface of fabrics, which, in principle, the experimentation with ways to create beautiful pieces of fashions with colorful pattern designs (**Figure 12**).

As demonstrated, the effects of decorative arrangements created by the tritik technique is both refreshingly amazing and attractively mesmerizing, with the surface of fabrics infused with design elements and principles that give rise to high aesthetical values of the fabric materials. In addition, both the intended effects and the unintended effects resulting from the application of colors in the tritik technique can help create the desired forms, shapes, lines and spaces on the fabric materials. Furthermore, exploring the techniques and integrating the knowledge and skills pertaining to synthetic coloring materials can pave a way for the improvement in the learning of pattern designs.

According to a study conducted by Bintan Titisari, Kahfiati Kahdar and Intan Rizky Mutiaz in writing an article entitled Development of Dye Sewing Techniques (Tritik) with patterns geometris [5] suggests a very significant finding on how the application of Dye Sewing techniques (Tritik) can be implied in the fashion world. The effect of the use of geometric patterns on political techniques will produce motifs with the effects of direction, depth, and movement (optical illusion) by using the composition of balance, rhythm and harmony. In addition to the presence of effects optical illusions that give the impression of depth, direction and motion, they can be used to create dimensions and illusions in fashion products. The effect of Sewing Techniques (Tritik) from this traditional heritage can also be adapted using

Figure 12.
Type of fabrics: Satin. Technique: Brush-swiping Tritik. Medium: Remazol color. Soaking duration (in sodium): No soaking involved.

Figure 13.
Type of fabrics: Rayon. Technique: Swiping and dipping Tritik. Medium: Naphthol color. Soaking duration (in sodium): No soaking involved. Year 2016.

the latest technology with the help of computer applications and industrial-scale sewing machine technology that can make new contributions in textile technology, for example, geometric patterns using vector graphics editor can be used as preliminary data for development in the CAM (Computer Aided Manufacture) program (**Figure 13**).

The effect of the Sewing Pattern design (Tritik) can also be commercialized in the Fashion industry design where the illusion effect of this geometric design gives a soft finish to the fabric and further highlights the design to visualize the camouflage effect (see **Figures 14–17**). The result of the tritik technique adapted from this traditional technique is an alternative effect that can be designed on the surface of batik fabric. Traditional techniques from hand sewing skills can further highlight the value of the beauty of decorative patterns on batik fabrics.

On the international scene, batik has already taken its place in the contemporary fashion industry. Now the fabric is not only used for traditional clothing, but has also found its way to applications such as haute couture as well as being used in accessories such as handbags [7]. Many popular figures have walked the red carpet proudly wearing batik, from Bill Gates, Nelson Mandela to Barack Obama, and from Beyoncé Knowles to Jessica Alba. The international fashion scene has seen batik designers introduce batik to the world through the mixing of fabrics with modern designs and production methods. For example, Malaysian fashion designer Fern Chua presented handmade batik designs to the world stage through the British Council's global campaign. Highlighting the theme of Crafting Futures, the campaign also brought together fashion and craft designers from around the world to explore and build the future of batik's potential globally. The works of others from the world's batik designers, and many more have also supported batik on the international stage.

Figure 14.
Tritik techniques that can be used as an illusion pattern design for the fashion industry. Photo credit to Titisari et al. [6]

These advances have also influenced well -known designers from other countries to include batik in their design collections. Notably, Belgian-American designer Diane von Furstenberg's batik dress worn by Duchess of Cambridge Kate Middleton; while Angelina Jolie was seen wearing a batik dress by US designer Nicole Miller. Other international designers who also feature batik in their collections include Dries van Noten from Belgium, Ek Throngprassert Thailand, and Milo

Figure 15.
Fashion design that adapts sewing techniques (tritik) in Malaysia.

Figure 16.
Fashion design that adapts sewing techniques (tritik) by SEYMOUR. Photo credit to BLOG DESIGN BY LABINA @ PLEXICOD.

Figure 17.
Fashion design that adapts sewing techniques (tritik) by Humbang Shibori x Purana at JFW 2019. Photo credit to (Fimela.com/Nurwahyunan).

Milavica from Italy. In addition, one of the oldest fashion schools in Italy, Koefia, not only incorporates batik fashion in its curriculum, but also parades its stylish designs on the catwalk. Therefore, the practitioners of batik fashions can capitalize on the effects of the tritik technique to help them create spectacularly stunning and beautiful pattern designs on the surface of the fabrics of batik textile in global. To help realize this aim, it becomes the imperative of the stakeholders and practitioners to rejuvenate such a technique that is capable of creating immaculate and unique pattern designs with high aesthetical values.

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References

[1] Raffles, Thomas Stamford, (1817) The History of Java. London: Parbury and Allen

[2] Skeat, W.W. (1902) "Silk and Cotton Dyeing by Malay". The MBRAS,1,123-127

[3] Winsteadt, R.O. (1925). " Malay Industries Part1: Arts and Craft" in R.J Wilkinson (Ed). Papers on Malay Subjects. Kuala Lumpur: Government Press

[4] Harozila Ramli, Tajul shuhaizam & Siti Salwa (2019). The Beauty of Tritik Technique in Creating Batik-textile Pattern Designs, Journal of Advanced Research in Dynamical and Control Systems 11(05-special issues):1105

[5] Hestri Wulansari (2005). *Tesis PhD: Perancangan Teknik Tritik Dengan Penambahan Struktur Tenun Sebagai Pelengkap Busana.* Surakarta: Universitas Sebelas Maret Surakarta.

[6] Titisari, B., Kahdar, K & Mutiaz, I. R. Pengembangan Teknik Jahit Celup (Tritik) dengan Pola Geometris. ITB J. Visual, Art & Design 6 (2), 131 (2014).

[7] Ira Dhyani Indira (2009). *Batik Ceria*. Jakarta: Puspa Swara

Chapter

Smart Textiles Testing: A Roadmap to Standardized Test Methods for Safety and Quality-Control

Ikra Iftekhar Shuvo, Justine Decaens, Dominic Lachapelle and Patricia I. Dolez

Abstract

Test methods for smart or electronic textiles (e-textiles) are critical to ensure product safety and industrial quality control. This paper starts with a review of three key aspects: (i) commercial e-textile products/technologies, (ii) safety and quality control issues observed or foreseen, and (iii) relevant standards published or in preparation worldwide. A total of twenty-two standards on smart textiles – by CEN TC 248/WG 31, IEC TC 124, ASTM D13.50, and AATCC RA111 technical committees – were identified; they cover five categories of e-textile applications: electrical, thermal, mechanical, optical, and physical environment. Based on the number of e-textile products currently commercially available and issues in terms of safety, efficiency, and durability, there is a critical need for test methods for thermal applications, as well as to a lesser degree, for energy harvesting and chemical and biological applications. The results of this study can be used as a roadmap for the development of new standardized test methods for safety & quality control of smart textiles.

Keywords: smart textiles, wearable electronics, test methods, quality control, safety, efficiency, durability, electronic textiles (e-textiles)

1. Introduction

The smart/electronic textile market has recently exploded, mostly driven by personal healthcare. The term "smart textiles" refers to the "smart functionality" of a product, whereas "electronic textiles" (e-textiles) refer to the "hardware and/or technology" that is responsible for the smart functionality [1]. The market size of smart textiles already reached USD 4.72 billion in 2020 with Asia-Pacific countries leading the chart followed by Americas and Europe [2]. Vista Medical Ltd. (Canada), Myant (Canada), Interactive Wear (Germany), Schoeller Textiles (Switzerland), Intelligent Clothing (England), Google (US), International Fashion Machines (US), Textronics (US), Gentherm Incorporated (US), and Sensoria (US) are the major key players in the smart textile industry.

The convergence between textile substrates and conformable electronics like embedded sensors or actuators has given rise to wearable smart/e-textiles. E-textiles can augment the level of protection, comfort, and physiological performance of humans, with applications in many industries, including medicine, protective clothing, military, and automotive. A few authors have analyzed these current and potential applications. For instance, Honarvar and Latifi described the components, structures, and major application areas of smart e-textiles, including ambulatory measurements for patients with cardiovascular diseases, nonwovens for electromagnetic interference (EMC protection) for security, protective GPS-suits for military, bleeding sensor threads for surgeons, and flexible electronic keypads for dialing phone numbers [3]. Ismar et al. explored the use of e-textiles for futuristic clothes [4]. Dolez et al. analyzed the potential of smart textile technologies for occupational health and safety (OH&S) [5]. Finally, Stoppa et al. described different biomedical smart textile projects conducted within the European Commission's 6th and 7th framework programs: WEALTHY, MyHeart, BIOTEX, PROTEX, STELLA, OFSETH, CONTEXT, WearIT, and PLACE-it [6]. This convergence between clothing and electronics could pose some critical challenges for regulatory bodies, including US Food and Drug Administration (FDA), Health Canada, and National Institute for Occupational Safety and Health (NIOSH). Appropriate quality control methods are a critical tool for them to ensure that e-textiles do not to endanger users' health, safety, and privacy among others.

The lack of standardization of e-textiles is also considered one of the primary restraining factors for industrial growth. Even though the e-textile industries have generally been keen on designing products with improved safety and performance features, their efforts may not have met market expectations due to the current lack of dedicated standardized test methods. The two main disciplines at the root of e-textiles - textiles and electronics - are so much at odds with each other that dedicated standardization methods for smart/e-textiles are critical. However, progress in this area is lagging behind in comparison to the rapid pace of technological innovation. In this chapter, we will highlight critical challenges and provide some suggestions for the development of standardized test methods for smart/e-textiles.

2. Overview of smart/e-textile products and major barriers to market entry

As consumer electronics are marching towards the era of the Internet of Things (IoT), so are smart/e-textiles. Gradually, conformable electronics are embedded within textiles of various configurations to offer an on-body platform for pervasive computing, especially for healthcare and OH&S applications. Examples include a smart trouser for forest workers that can detect the proximity of chain saw and automatically turn it off [5]; industrial protective gloves that alert users of air toxicity by changing their color [5]; power vests to prevent unsafe movements of caregivers while lifting heavy weights [7]; and Myant's recent VOC (volatile organic compound) sensing facemasks to detect airborne infectious agents [8]. Also, smart textiles have been designed for protection against sexual assaults, with the SHE (Society Harnessing Equipment) anti-rape lingerie that can deliver a 3800 kV shock [9]. On a lighter note, Microsoft patented a smart cloth that alerts a user of an incoming text message or daily activity reminders, by generating a mild electric shock to the body [10].

A survey of technologies, solutions, and products based on smart textiles and flexible materials was done in 2017 [5]. The different technologies, solutions, and products in terms of sensors and actuators identified were grouped into seven categories based on the input signal or stimulus for the sensors and the output signal for actuators. These categories are thermal, mechanical, chemical/biological, electrical, physical environment, optical, and power. **Figure 1** shows the distribution of

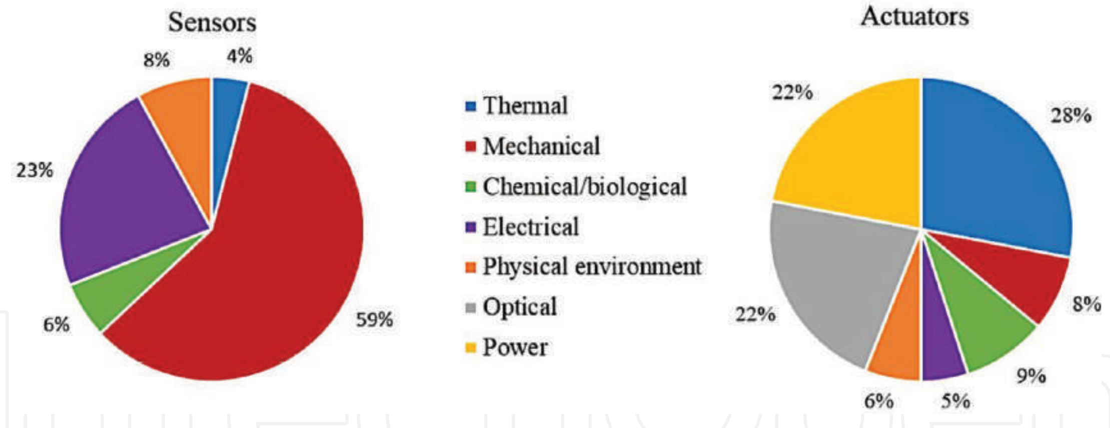


Figure 1.
Distribution of technologies, solutions, and products relevant to smart textiles and flexible materials as a function of the stimulus for sensors (left) and output signal for actuators (right) [5].

the technologies, solutions, and products based on smart textiles and flexible materials identified by the researchers in these different categories. In the case of sensors, the dominant category is associated with a mechanical stimulus, with 59% of the sensors. Electrical sensors account for 23%. In the case of the actuators, thermal, optical, and power outputs represent each about a quarter of the technologies, solutions, and products identified.

However, before the mass adoption of smart/e-textile products is possible, some burning questions need to be addressed: for instance, what is a safe electrical shock, both for user alert and assailant deterrence? Could a malfunctioning smart garment prevent activating a safety emergency shut-off system? What about potential privacy issues associated with the data generated by e-textiles? In an attempt to standardize their assessment of wearable electronic product performance, a group of electrical engineers evaluated the safety performance of wearable energy harvesters based on the device failures and user-related hazards [11]. However, to date, no one has provided a response to the questions customers could legitimately ask for the different applications smart/e-textiles are aiming for.

For instance, according to experts, the lack of standardization and quality control poses the highest barriers to smart textiles entry into the healthcare market (**Figure 2**) [12]. Since wearable electronic components are often worn close to the body, special attention is required to prevent health hazards. There are also potential issues of efficiency associated with the interconnections between the different components. The lack of standardized processes for welding, soldering or glueing for instance can significantly reduce the performance, durability, esthetic, and

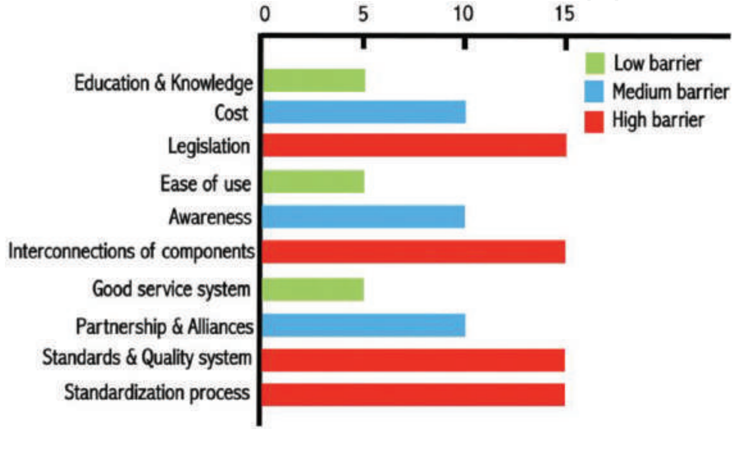


Figure 2.
Barriers to entrance of smart textiles in the healthcare market (based on data from [12]).

hand-feel of the product. Other barriers include product cost, public awareness, lack of education and knowledge [12]. Strategic industrial partnerships and multidisciplinary alliances among key players in textile, electrical, and biomedical engineering can positively impact the product design and test method development processes.

3. Review of different issues reported or foreseen

This section will describe different issues, reported or foreseen, associated with the durability, safety, and efficiency of smart/e-textile products, including health monitoring apparels, protective clothing, automotive actuator textiles, and textile-based physiological sensors.

3.1 Durability

Electrical elements embedded into textile structures to produce e-textiles include electronic circuits, electrodes and printed tracks. They must be extremely rugged, robust, and durable because of their regular exposure to mechanically demanding environments [13]. The issues of durability reported with e-textile products are discussed in the next sections.

3.1.1 During the manufacturing process

A first aspect of durability deals with the e-textile manufacturing process itself. For instance, conductive yarns embroidered on a textile may be damaged by three dominant forces: tension, bending, and shearing [14]. In particular, conductive fibers generally exhibit a low bending radius [15]. However, for flexible display applications, they would be typically subjected to bending radii lower than 1 mm. They also have to withstand friction stresses associated with the embroidery operations. In the case of weaving, fibers must possess the capacity to withstand bending radii as small as 160 μm and 20% tensile strains.

3.1.2 Effect of biomechanical stresses during wear

An apparel product is subjected to large biomechanical stresses during wear, including during donning and doffing. For example, a research conducted with Canadian combat clothing showed that maximum stresses of 2410 and 2900 N/m occur during squatting across the back seat of trousers and coveralls, respectively [16]. Other movements like when bending elbows (for sleeves), bending knees (for trouser legs) or bending over exerted significant stresses on combat clothing of Canadian Forces. If the smart/e-textile product is not robust enough to withstand such biomechanical stresses, they will be easily damaged and experience a loss in functionality like sensing, communication, data-transfer or power supply. Such problems of loss in functionality could cause safety issues for soldiers or first responders in the line of action. Using stretchable connection and electrode designs could allow accommodating body-induced stresses applied on e-textiles. **Figure 3** displays examples of strategies to produce stretchable electro-conductive textiles.

Researchers conducted tensile and bending resistance tests to assess the durability and elastic properties of smart/e-textiles. For example, PEDOT:PSS ((poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate)) dyed cotton and silk yarns exhibited a tensile strength of 260 and 136 MPa with a conductivity of 12 S/cm compared to 305 and 157 MPa for the pristine (uncoated) cotton and silk yarns,

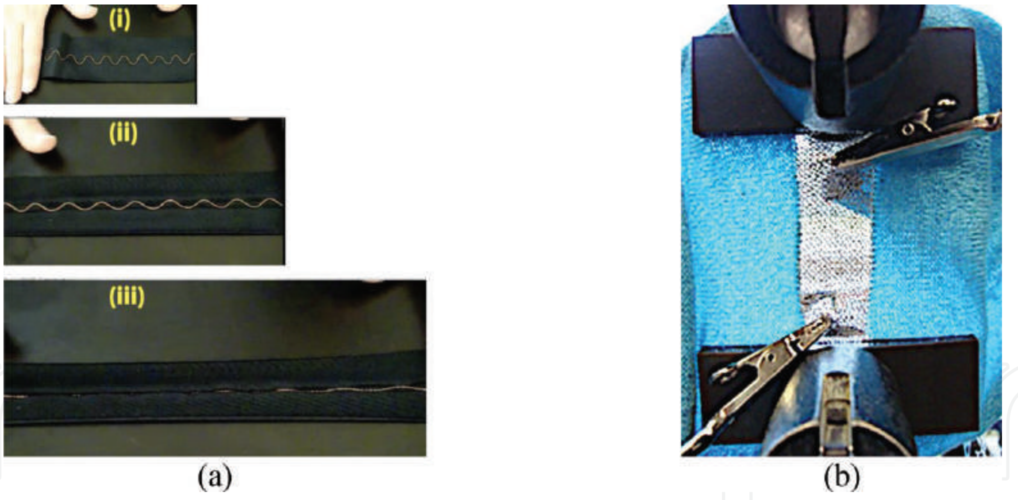


Figure 3.
Examples of stretchable electro-conductive textiles. (a) Elastic behavior of a conductive yarn (white on the pictures) under increasing deformation (i) undeformed, (ii) medium deformation, and (iii) high deformation. The conductivity was maintained even at high deformations. (b) Experimental set-up to measure the electrical resistance of a knitted electrode under stretch in a mechanical test frame.

respectively [17]. The conductive polymer coated silk yarns showed a robust electrical performance, displaying a reduction of conductivity of around 50% after 1000 bending cycles. Using a fabric test tester, Qui et al. measured the durability of a power generating textile fabric [18]; it did not exhibit any measured degradation after 10000 bending cycles of mechanical stimulation, showing superior durability. **Table 1** displays different test methods used by researchers to assess the durability of textile resistive heaters (**Table 1**).

3.1.3 Effect of surface phenomena in service

Besides biomechanical stresses, different surface phenomena such as wear, corrosion, chemical contamination could destroy the transmission functionalities of smart textile components like optical glass fibers [28]. For instance, **Figure 4** illustrates the effect of abrasion on a smart/e-textile webbing (white on the left image (a)) than includes conductive yarns. The multimeter on the right image (b) records the electrical resistance after successive series of abrasion cycles.

To simulate wear behavior, different mechanical tests can be conducted on textiles, for example to measure their abrasion resistance [29]; a lower abrasion resistance would potentially indicate a poor durability of the electrical functionality for conductive tracks on smart textiles. Recent work on a graphene-coated aramid fabric reported a resistance of up to 150 abrading cycles before the complete loss of electrical conductivity [30]. The stability to wear of a power generating textile fabric was analyzed after prolonged use of up to 15 days [18]. The fabric was successful at lighting up an array of LEDs under different dynamic conditions: raising hands, shaking clothes, and human running.

Durability against environmental degradation is another critical factor for smart textiles. For instance, silver-plated textile electrodes may lose their functionality if exposed to air for a longer period because metals are prone to atmospheric corrosion, including silver [31]. When silver is exposed to atmospheric pollution, the surface tarnishes due to a reaction between silver and reduced sulfur compounds in the ambient air [32]. As a result, a dark layer of Ag_2S (silver sulphide) is formed over the silver plating. Sulfur releasing bacteria could also be present in our washing machines, which may lead to a secondary sulfidation of textile silver electrodes [33].

Conductive elements	Test condition	Form factor	Durability test method	Study
Carbon nanotube (CNT) ink	—	Printed element	Tensile strength	[19]
Silver filament	80, 100, and 120 ° C in oven for 264 h	Yarn	Tensile strength	
Silver yarn	65% RH and 20 °C as per EN ISO 2062:2009	Plain, rib, and interlock fabric	Stretchability	[20]
Stainless steel yarn	—	Plain and interlock fabric	Stretchability	[21]
Copper nanowire -polyurethane film	—	Nylon glove with the printed film	Stretchability	[22]
LIG (Laser Induced Graphene) on polyimide film	—	LIG film in contact with copper tape and Ag-paint	Bending test	[23]
Composite ink (graphene-tourmaline- polyurethane)	—	Printed heater on woven cotton wrist band	Abrasion resistance	[24]
CNT-polypyrrole polymer	—	Polymer coated cotton yarn	Bending test	[25]
Multiwalled CNT	—	Coated cotton woven fabric	Bending test	[26]
Carbonized modal knit encapsulated with Ecoflex silicone rubber		Weft knitted fabric	Bending test	[27]

Table 1.
Methods used to assess the durability of resistive heating textiles.

Figure 4.
Abrasion testing on a white webbing with conductive yarns (a). A multimeter measured the change in resistance after successive series of abrasion cycles (b).

Salt from body sweat during workouts or from seawater in marine applications may also corrode metallic elements of smart textiles [34].

3.1.4 Thermal resistance

Resistance to heat is a critical factor for electro-thermal e-textiles, for example heating textiles. The heating components and the material in contact have to be able to sustain the heat generated with in operation without losing their conductivity, strength and other performance, and without getting on fire or melting. For instance, Liu et al. characterized the impact of heat exposure on Ag fabric heaters [35]. The study reviewed the heating performance of three different knitted fabric heaters, viz., plain single jersey (PSF), ribbed stitch (RSF), and interlock knit (ILK), fabricated with silver plating compound yarns (SPCYs) and polyester staple fiber spun yarns (PSFSYs). After 264 h of prolonged heating of the SPCYs in an oven at three different temperatures, 80, 100, and 120 °C, the electrical resistance of the SPCYs were evaluated. The resistance of the heater increased by ∼17% and ∼ 75% after the 264 h aging period at 80 and 100 °C, respectively. After 24 h of aging at 120 °C, the resistance exceeded the measuring range of the multimeter. In addition, the textile structure used may affect the thermal resistance of the system. For example, it was reported that a fabric woven with Ag-coated nylon and cotton yarn powered at 15 V exhibited different degradation temperatures depending on the weave structures: 69.8 °C for plain weave, 80.6 °C for twill weave, and 103.5 °C for sateen [36].

3.1.5 Resistance to washing

Washability is a massive barrier to successful commercialization and widespread adoption of e-textiles. It is a critical concern for e-textile users as the washing and drying processes subject the product to damaging conditions and could eventually destroy the connectivity between the electronic components or the electronic components themselves [37]. Chemical stress (detergent, surfactants), thermal stress (washing/drying temperature), solvent (water), and mechanical stress (e.g., friction, abrasion, flexion, hydro-dynamic pressure, garment twist) are the four dominant forces that could damage electronic components during washing cycles. A protective layer is typically used to protect the smart textile or its electronic components from getting damaged or exposed during laundry. Polyurethane (PU) is largely used as a waterproofing encapsulation layer for e-textiles [38]. It has the great advantage of being flexible and stretchable and can accommodate the stretch of the fabric underneath. Polypropylene thin films have also be laminated to provide protection to metallized polymer films on e-textiles against repetitive washing and abrasion [39]. However, the encapsulation may not be durable. For example, the extremity of metal wires encapsulated in an e-textile product could damage the encapsulation layer due to their intrinsic rigidity and configuration geometry. **Figure 5** shows how the extremity of soldered metal wires pierced through a PU lamination after repeated washing cycles.

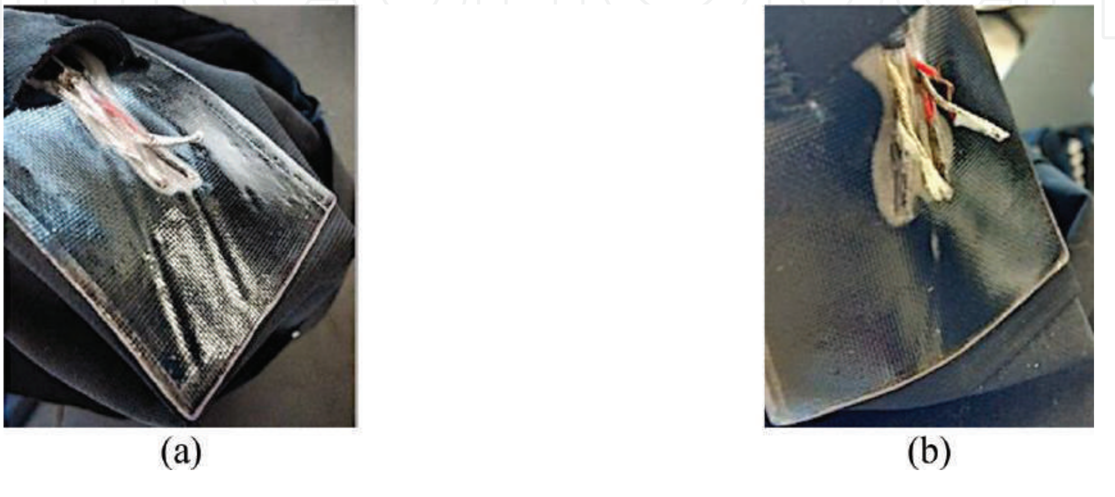


Figure 5.
Soldered wires in a smart/e-textile product piercing through the wash-resistant polyurethane encapsulation layer.

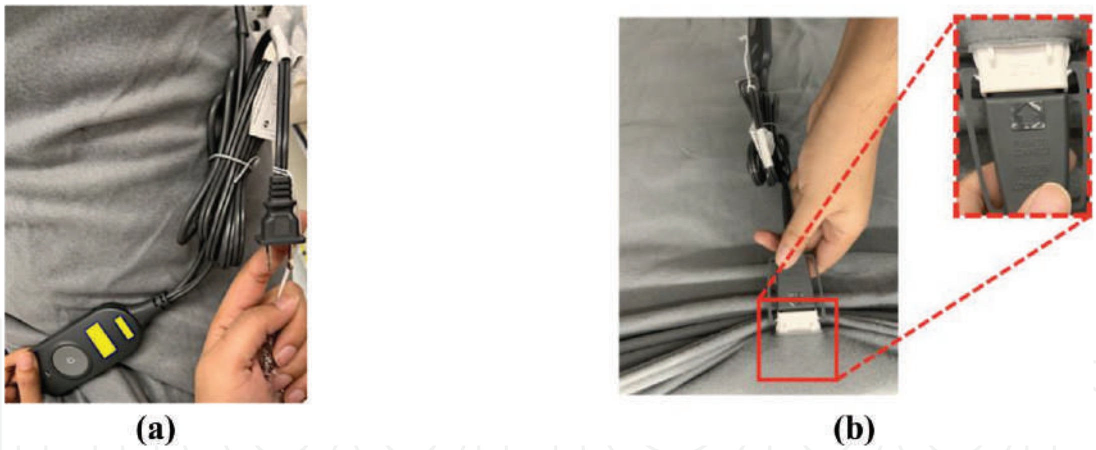


Figure 6.
Resistive heating blanket: (a) electronic control module with wiring for power supply; (b) connection between electronic module and the blanket (identified with the red box). The rigid connector is sewn to the blanket with a single row of stitches (shown in the inset).

Concerns also exist for non-textile rigid elements that are sewn to e-textiles for instance. The laundering process may damage them if they are fragile. They may also hit the flexible conductive interconnects when the textile is tumbled during washing or drying. **Figure 6** displays the example of a resistive heating blanket. The plastic connector between the non-washable electronic modules and the blanket could get damaged when exposed to the mechanical stresses and the elevated temperatures associated with laundering and tumble drying.

Another issue is associated with the tendency of some textile fibers to absorb water. As water swells the hydrophilic fibers, it influences their physical properties [40]. It can also reduce the flexural strength, modulus, strength, hardness, and fracture toughness at the textile fiber-polymer matrix interface [41]. Even hydrophobic fibers can transport moisture by capillary action. The water can reach the different e-textile components and damage them. Electronic modules and batteries are the most sensitive to water ingress, which can instantly and permanently damage them [42, 43]. Proper encapsulation is once again the solution when complete unplugging is not possible [37]. Alternatively, a water-free, air-based laundry system has been designed for smart garments [44].

Product lifetime is very important for consumers. A typical 100% cotton t-shirt provides serviceability for at least 20 washes [45]. Hence, the expectation of consumers is no less for smart textiles, especially due to their high price tag. OMsignal claimed that their smart t-shirt, designed for tracking heart and respiration rate, could undergo 50 wash cycles [46]. However, the company no longer exists. Karaguzel et al. designed a silver ink screen-printed nonwoven electro-textile circuit that could resist up to 25 wash cycles [47]. Cho et al. reported no change in conductivity of an rGO-coated meta-aramid woven fabrics after ten 6-min washing cycles at 40 °C using a Laundero-meter [30]. Similarly, intrinsic conductive polymers like PEDOT:PSS were used to exhaust-dye silk yarns and showed no change in electrical conductivity for up to 4 washing cycles [17]. Laminated and metallized textile yarn electrodes sustained successfully 20 domestic washing cycles according to EN ISO 6330 [39].

Researchers also used prolong washing to demonstrate the stability-to-laundering of smart textiles. Qui et al. observed a constant electrical output (voltage: ~110 V, current: 2 μA) for their piezoelectric energy harvesting fabric based on biomechanical body movements after up to 2 h of continuous washing [18]; only a minor degradation in the output (voltage: ~106 V, current: 1.9 μA) was recorded after 12 h of prolonged washing. The impact of powder detergent (containing conventional chlorine-based bleaching agents), liquid detergent, and sodium percarbonate (an unconventional stain remover based on oxygen bleach) was compared when testing the resistance of Ag-plated nylon electrodes to 30 washing cycles [42]. Detergents with bleaching agents were reported to be more damaging to the Ag-electrodes, as the bleaching agents oxidize the Ag layer, making the conductive layer vulnerable to mechanical rubs and progressive wash cycles. The researchers recommended using liquid detergents, free of any form of bleaching agents, for e-textiles. Recently, researchers from the University of Toronto and the University of Waterloo developed two different electrocardiogram (ECG) electrodes made of silver-coated and carbon-suffused nylon yarns [48]. Although silver-coated ECG electrodes resisted well up to 35 washes, the carbon yarns yielded a longer lifespan and maintained a reasonable signal quality for the ECG biosignals.

3.2 Safety

Safety is the biggest concern for e-textile users because of the fear of electric shocks from embedded electronics. Even though the embedded electronics are responsible for the smart behavior of e-textiles, the safety of the product should not be compromised by the presence of electronic components.

3.2.1 Electric shocks and shorts

Embedded electronics in e-textiles may suffer from short-circuits or mechanical failures, e.g. due to body sweat or ambient moisture, similarly to what is observed for electronic devices in marine environments [49]. Such malfunctioning can cause serious health hazards or fire accidents. For instance, a recall was issue for the Omni-Heat electric jackets of the company Columbia [50]. A manufacturing defect was detected in the heating component of the wrist cuff, which could create an electric short and lead to burn injuries. The electrical insulation of conductive components can be achieved by surrounding the conductive components with an electrically insulating layer, for instance through core spinning, using a tubular intarsia knitting, or by encapsulation in a water-resistant polymer for instance [51].

3.2.2 Exposure to high temperatures

Burns due to exposure to high temperatures is a serious safety concern for users of heating textiles. Skin temperature is around 34-35 °C although it differs slightly between different regions of the human body while the core temperature of the human body is maintained at around 37 °C [52, 53]. **Figure 7** illustrates the effect of exposure of the human skin to different temperatures [54–56]. While the burning pain threshold is at 43 °C, extended exposure of the skin to 45 °C can lead to 2nd and 3rd degree burns. Temperature overshooting or the malfunctioning of heating textiles could cause severe burn injuries, in particular for people with impaired sensations. For instance, a 26-year-old male patient with paraplegia suffered from a hip burn due to a heated car seat while driving a 2004 Jeep Cherokee for 30 minutes [57]. While the patient was unaware that the car seat was preprogrammed to a high setting (~41 °C), it was later revealed that the seat heater malfunctioned and exceeded 41 °C.

Similar unfortunate cases include a 42-year-old post-traumatic paraplegic patient in Germany who required several reconstructive surgeries as a result of burns caused by a heated car seat [58], a 54 old paraplegic patient driving a 1999 Chrysler Town & Country minivan who suffered from blisters in the rear and upper thigh [59], and a 50-year-old diabetic and paraplegic woman who suffered from a

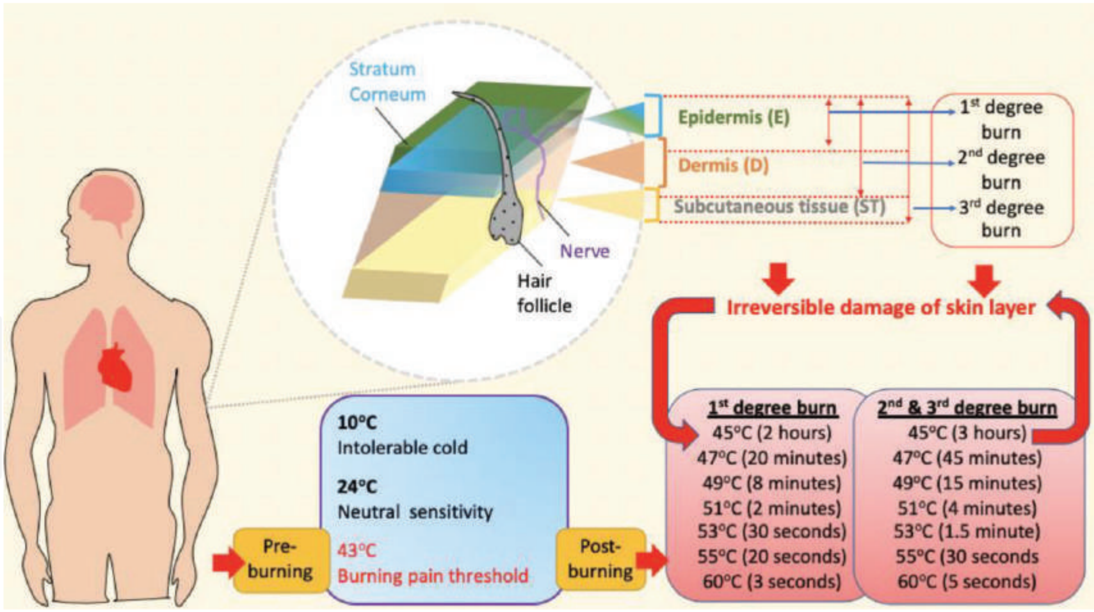


Figure 7.
Resistance of the human skin layers to low and elevated temperatures. Data retrieved from [54–56] (artwork by author).

partial-thickness burn on her medial buttocks [60]. Canada has cold winters and people use heated car seats during the winter; however, most of the heated seats do not display the temperature reached during operation. **Figure 8** displays the example of a North American 2020 full-sized sedan car with its heated car seats and different levels of heat settings; no indication of the actual temperature reached by the heated seats is available. As shown in **Figure 7,** an overheating at 50 °C may cause a 2nd or 3rd degree burn within 4 minutes. Beside medical patients, a temperature overshoot may also increase the risk of fire in the case of apparel articles with poor fire retardancy.

Similar smart heating technologies are also used by diabetic patients. Diabetic patients often suffer from nerve damages, termed as neuropathy, which involves sensory or motor impairment of small and large fibers of the body muscles [61]. The weakness of feet nerves is the most common type of diabetic neuropathy affects. Foot ulcers, sharp or burning pains in feet, and numbness of toes are other neuropathy symptoms [62]. To keep neuropathic pain under a manageable level, patients often undertake different physical therapies, including heat therapies by heating pads (**Figure 9a**) [63]. Since diabetic patients may suffer localized feet numbness and these heating pads are in direct contact with the skin, any temperature overshoot may cause serious skin burn injuries. Unfortunately, different heating textiles like heating blankets, mattress pads or throws (**Figure 9b**) are sold to consumers without proper instructions or clear indications. For instance, the heat regulator does not indicate the level of temperature it generates for its different heat settings (high, medium, low) (**Figures 9c**). Such an approach could harm sensitive skins as

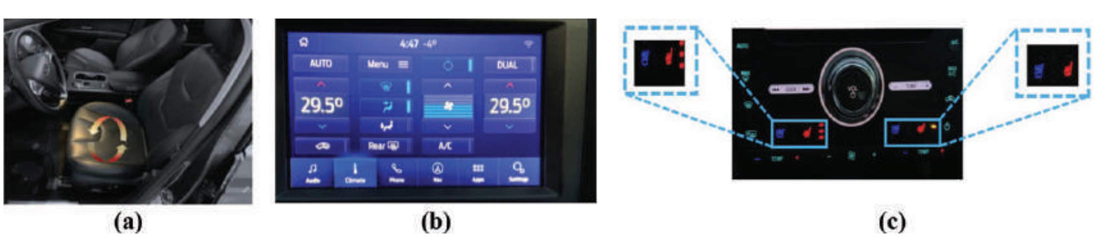


Figure 8.
A full-sized sedan with its heated seat (a) and dashboard control modules with set temperatures (b). The car seat heat indicator is in tally marks (with no reference of actual temperature) (c).

Figure 9.
Examples of heating textile products. (a) a heating pad; (b) a 120 V (A.C.)/60 Hz/ 115 W electronic heating throw made of 100% polyester fiber; (c) heating control module without numerical indication of temperature levels for the three different heat settings (high, medium, low).

the heat tolerance level differs from person to person and patients with diabetes or paraplegia suffer from reduced or impaired sensitive body organs. Operation manuals also miss indications about the temperatures at the different heat settings and warnings about the dangers of prolonged heating times.

In addition, the accumulation of heat over time could also make the users of different electronic wearables feel uncomfortable [64]. Such issue is particularly critical in the case of joule heating textiles where it could lead to burns for the user or instance of fires. Due to the accumulation of heat in the textile over the successive heating/cooling cycles for instance, the temperature may keep on increasing even if the power input remains constant – a phenomenon which was marked in smart nylon gloves embedded with a polyurethane-copper nanowire (PU-CuNW) resistive heating element [22]. Kim et al. reported a temperature increase of 5 °C, from 85 °C to 90 °C, during a 10 h prolong heating period of the smart nylon gloves [22]. This temperature increase over time could potentially be associated with the ~7% increase they observed in the resistance of the conductive element of the PU-CuNW-nylon glove after the 10 h heating period. Thermal inertia may also lead to issues of overheating as the temperature experienced may exceed the set value, which can be associated with a phenomenon of overshooting.

3.2.3 Battery ignition and fire hazards

Recently, the US Homeland Defense and Security Information Analysis Center described the need for integrating multiple energy harvesting textiles on US military protective clothing [65]. Indeed, most wearable electronic systems need to be powered to be able to function. Strategies for textile-based energy harvesting are generally based on triboelectric (based on the friction between pieces of garments during body motion) [66], piezoelectric (from deformation during body motion [67], thermoelectric (using body heat) [68], and photovoltaic (from solar energy) power generation [69]. Recent scientific works also showed the potential of producing biochemical energy from body sweat using textile-based biofuel cell systems [70]. An overview of different energy harvesting textile platforms is illustrated in **Figure 10** for an application for dismounted soldiers.

In addition to energy harvesting, on-body batteries or supercapacitors are needed to store the energy from these energy harvesting fabrics and/or provide some power supply autonomy to the wearable clothing system [71]. However, these integrated batteries could suffer from battery ignition. One such incident was

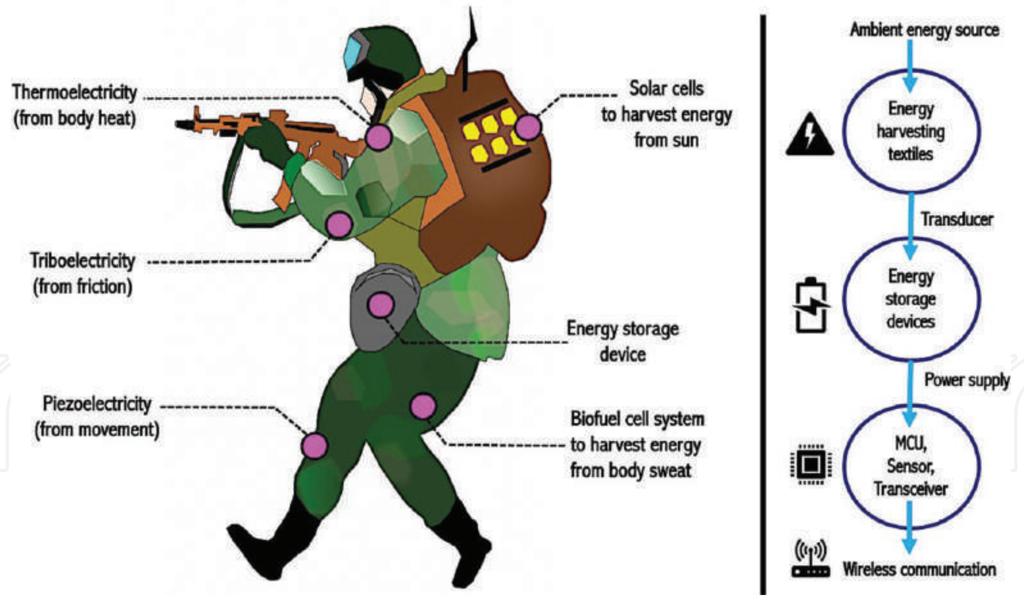


Figure 10.
An overview of energy harvesting systems for autonomous and self-charging protective military clothing with a simplified block diagram for wireless communication platform.

reported by the Department of Police in Arkansas (USA); a smart jacket caught on fire due to the ignition of its built-in battery [72]. Another example concerns the Omni-Heat electric jacket models of the company Columbia [50]. A recall resulted from defective batteries that could overheat and ignite the jacket. Similar incidents could have dramatic consequences, in particular in the military where an increasing number of e-textile systems are being encountered. For instance, in the US, the Future Force Warrior, Scorpion, and Land Warrior programs take advantage of copper and tinsel wire-based textile USB, radiating conductor, and electro-textile cables among others for improved flexibility and real-time information technology in military protective clothing systems [73].

3.2.4 Unstable connectivity

The reliance on smart textiles in case of emergencies is a growing trend for the biomedical, OH&S, and transportation industries. Any inconsistency or flaw in the interconnecting conductive tracks may render the emergency smart textiles dysfunctional, with potential dramatic consequences. Moreover, if the textile antennas or wireless communication system suffer any disruption in the communication protocol, it will make the user vulnerable to life-threatening situations. For example, Smart Enjoy Interact Light (SEIL) backpacks are manufactured for cyclists to avoid traffic accidents by displaying built-in LED lights or by expressing images in real-time [74]. The bag allows the user to show traffic signals like left/right, stop and emergency signs using a wireless controller. Any flaw in the conductive tracks or quality issues with PCBs (printed circuit boards) may disrupt the direct signal transduction, thereby putting the cyclists in danger. Other examples of smart textiles employed for health monitoring and disease prevention by early detection include the Vivago WristCare to monitor and transmit data on a person's health condition 24 hours a day – with benefits beyond the traditional push-button alarm; MARSIAN smart gloves to monitor and wirelessly transmit ANS (nonconscious) activities and real-time physiological (skin microcirculation, respiration rate, etc.) data; SenseWear body armband for measuring physiological parameters (motion, temperature, skin electrical conductance); VTAM biomedical t-shirt for teleassistance in medicine to monitor shock, fall, respiration, temperature, and location; and Vivometric's LifeShirt for ambulatory and plethysmographic respiration monitoring [75].

3.3 Efficiency

Thus far, the current chapter has discussed several aspects associated with the durability and safety of smart/e-textiles. Efficiency covers aspects such as the actuating performance against applied stimulus level or the quality of the biosignal detection in physiological applications. These aspects are also critical for the satisfaction of the smart/e-textile user.

3.3.1 Response time

Response time can be defined as the delay between the input, i.e., the activation by the stimulus, and the output of the smart/e-textiles. In the case of joule heating textiles, the response time can be determined from the time–temperature curves. Researchers have used different parameters to characterize the response time of heating textiles. For instance, R_{90} refers to the time required to reach 90% of the steady state temperature [24]. Xiao et al. reported a decrease in the R_{90} of a heating e-textile based on a carbon black nanoparticle-PU (polyurethane) composite film as the applied voltage was increased [76]. Another parameter used by researchers is the heat time constant (H_{TIME}) [25]. This is also known as response time constant (τ) [77]. The parameter τ characterizes the system's inertia [77]. It is defined as the time required to reach 63.2% of the maximum value, in this case the maximum temperature, according to the following equation (see Eq. (1)):

$$1 - e^{-1} = 1 - 0.3679 = 0.632 \, or \, 63.2\% \tag{1}$$

One solution developed by researchers to improve the reaction/response time of the carbon-based conductive materials is to take advantage of different metal fillers. For example, Ag nanowires were added to graphene oxide to prevent lattice defects during the reduction to rGO [78].

3.3.2 Power efficiency

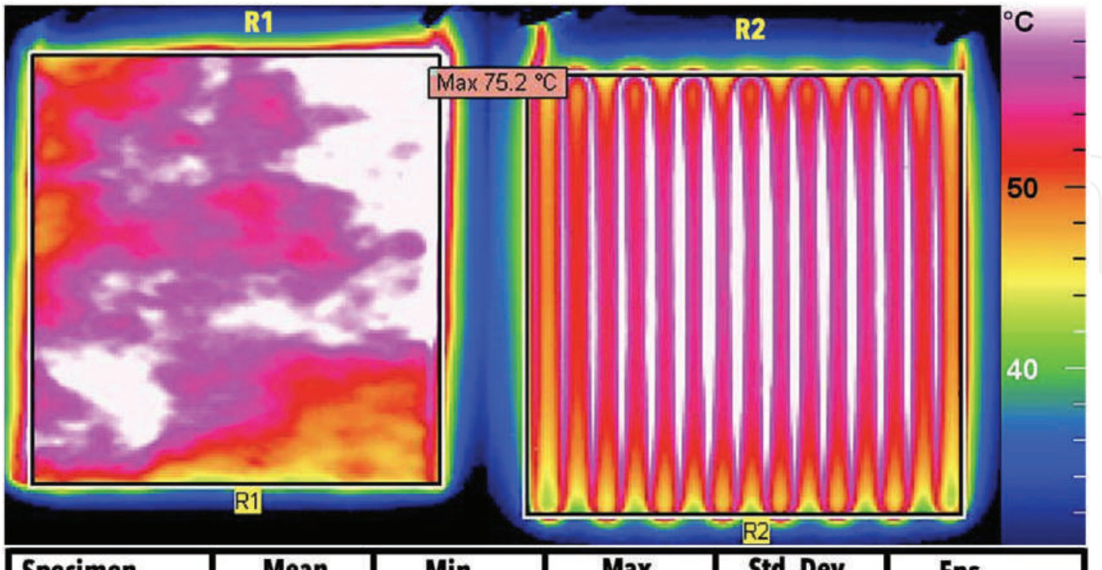
As many smart/e-textiles require power to operate, power efficiency is critical to maximize the wearability of the device. For joule heating textiles, researchers generally express the maximum temperature reached as a function of the applied power density to characterize the heating performance of the heating system, for example flexible graphene heaters for wearable electronics [79]. Work on thermoregulatory devices for cooling and heating applications, stretchable knit heating cotton gloves, and stretchable smart textile heaters based on copper nanowires have relied on heat flux density measurements to quantify the resistive heating performance [22, 24, 25, 80]. However, power efficiency is still a weakness for products currently on the market [5].

3.3.3 Uniformity of actuation

The uniformity of actuation is a critical parameter when considering heating textiles. For example, Hao et al. characterized the uniformity of the heating performance of a cotton woven fabric spray-coated with a graphene nanosheet conductive mixture by showing the temperature distribution from four different perspectives: (a) in the horizontal direction over a span of 4 cm (the length of the heater), (b) in the vertical direction over a span of 2 cm (the width of the heater), (c) observed from the top (sprayed face of the fabric), and (d) the bottom (non-sprayed face) [24]. They also compared the heat distribution in the flat and bent (180°) conditions. The 2D plane surface temperature distribution was uniform in both the horizontal and vertical directions during the 10–60s heating phase, which confirmed the uniform distribution of the conductive coating. However, a small temperature gradient was observed in the periphery of the heating fabric; the authors attributed it to heat loss by convection. The comparison between the sprayed and non-sprayed faces of the fabric showed a 3.5 °C difference, with the sprayed face exhibiting a temperature of 83.8 °C. No significant effect was noticed in the heat distribution when the flexible heater was bent by 180°. As another example of temperature distribution inhomogeneity, **Figure 11** displays the temperature measurement of two different heating fabrics: (i) a nonwoven heater (R1) and (ii) a fabric with heating wires (R2). Different patterns of spatial heat distribution are observed with both types of heating textile structures.

3.3.4 Repeatability/stability of the actuation level

A similar approach was undertaken by several researchers to evaluate the thermal stability of electrothermal textiles during repeated heating–cooling cycles of different amplitudes. The test would involve a series of stepwise or periodic or cyclic applied voltages, with the resulting temperature changes being recorded [76]. Some researchers also used specific actuation patterns. For example, Sun et al. characterized his segregated carbon Nanotube/thermoplastic polyurethane (s-CNT/TPU) heater with three different types of heating–cooling cyclic patterns [19]: (a) ten on/off periodic cycles at 6 V, (b) three cycles of 1.5–3-4.5-6 V step increase followed by an off period, and (c) five on/off periodic cycles at increasing then decreasing voltages (3–4.5-6-4.5-3 V). In general, two types of approaches have been observed among researchers investigating the efficiency of



Specimen	Mean	Min	Max	Std. Dev	Eps
R1	56.3°C	40.2°C	75.2°C	4.68°C	1.00
R2	54.8°C	36.8°C	68.3°C	4.84°C	1.00

Figure 11.
Comparison between the infrared temperature measurement of heating textiles using a conductive nonwoven structure (R1) and a conductive wire (R2).

wearable heaters: (a) cyclic heating–cooling tests at a fixed voltage, and (b) repetitions of the continuous profile of variable voltages.

3.3.5 Quality of biosignal measured

Smart/e-textiles for biomedical applications often incorporate textile sensors or electrodes. The efficiency of these devices depends on the quality of the biosignals recorded. Dry textile sensors suffer from high contact impedance between the skin and the electrodes [81]. This results in high signal distortion and level of noise, lowering the overall efficiency of the biomedical devices. To overcome this challenge, researchers have integrated a water reservoir to continuously dispense moisture vapor to a Ag/Ti-coated polyester yarn embroidered electrode and lower the motion artifacts [82]. However, this system still does not offer a long-term solution as the reservoir dries out after a few hours, disrupting the signal measurement protocols, and thereby, the product efficiency [83]. Ultimately, the efficiency in the linearity of the output signals will have to be improved by reducing the impact of temperature, mechanical vibrations, ambient relative humidity, and other atmospheric factors [84].

3.3.6 Negative impact of moisture

Moisture reduces the performance of all types of batteries, including textile batteries or batteries integrated into smart textiles [43]. Moisture may also cause chemical and physical interferences in the control module of e-textiles, reducing its efficiency before a total failure occurs [85]. Besides the possibility of electric shocks or complete signal loss from corrosion, marine e-textiles could also experience decreased efficiency when exposed to the salt of seawater. As soon as the saltwater propagates the localized corrosion process of textile electrodes or conductive interconnects, it could affect the overall signal quality, lowering the transduction efficiency [49].

3.4 Other issues reported and concerns with the use of smart textiles

3.4.1 Longevity of the power supply source

For the consumer satisfaction, the longevity of the system supplying power to the e-textile, either a battery or an energy harvesting component, is critical. Unfortunately, the same situation experienced in the mobile phone sector will potentially be observed with e-textiles, in particular with batteries and chargers. Components may even reach obsolescence faster due to the combination of specific life cycle factors associated with both the electronics and textile sectors [86].

3.4.2 Maintenance and repairs

Fault detection and maintenance are another critical aspect of e-textiles. Due to their seamless integration into smart textiles, routine maintenance of electronic components can be extremely difficult. Also, any attempt to repair of the defective components may permanently damage the smart textile products.

3.4.3 Electronic component and software upgrades

In an effort towards real-time data analytics, smart textiles provide a platform for portable computing for the consumers, for instance for biosignal and physiological data collection. Any difficulty to update the electronic components, firmware, networking protocols, and software could seriously jeopardize the lifetime of the e-textile product.

3.4.4 E-waste and legislation

E-waste already raises a major challenge. With e-textiles, the situation becomes even worse as they are more integrated, have a shorter life span, and will be more likely disposed of with their batteries [86]. In addition, if people own one cell phone, they have several tee shirts in their wardrobe. E-textiles may lead to contamination of other materials' recycling processes as well the increased release of toxic substances. Hence, proper standardization and appropriate regulations are needed for the safe disposal of this new generation of electronics.

4. Test methods: current state of knowledge and future needs

Several national and international standardization organizations have been working over the last 10 years towards the development of standards for smart/e-textiles. This includes the European Committee for Standardization (CEN) with technical committee CEN TC 248/WG 31, the International Electrotechnical Commission (IEC) with technical committee IEC TC 124, ASTM International with technical committee ASTM D13.50, the International Organization for Standardization with technical committee ISO/TC 38/WG 32, and the American Association of Textile Chemists & Colorists (AATCC) with technical committee AATCC RA111. Several of them have published and/or are working on the development of test methods for smart/e-textiles. A total of 18 published/in-development standard test methods are listed in **Table 2**. They are organized according to the classification shown in **Figure 1**. Four documents relative to terminology are also included in the table.

The distribution of existing sensor and actuator-based textile technologies, solutions, and products by category of input/output signal (**Figure 1**) can be compared with the standard test methods (published and in development) identified (**Figure 12**). While most of the test method development efforts for e-textiles are in the electrical category, which accounts for 55% of the total test methods published and in development, technologies, solutions, and products in the electrical category only represent 28% and 5% of the sensors and actuators, respectively. For their part, mechanical test standards only represent 11% of the total, whereas technologies, solutions, and products in the mechanical category comprise 59% of the sensor-based smart/e-textiles. Also, very few standard test methods exist for thermal, optical and physical environmental aspects of e-textiles, while commercial products in these categories account for a large part of products/technologies in the market. No standards are available yet for power/energy harvesting and chemical/biological e-textiles, while some related products already exist on the market. This situation has led several researchers and research institutions to develop their own test methods [107]. It must be mentioned that test methods characterizing the electrical function were included in the electrical category while they may also, in a certain extent, apply to other categories of smart/e-textiles.

Based on the number of commercial e-textile products currently available and issues reported in terms of safety, efficiency, and durability, there is thus a critical need for test methods for thermal applications, as well as to a lesser degree, for energy (power) harvesting and chemical and biological applications. For this purpose, a trifactor model of performance assessment is illustrated in **Figure 13**.

Test method	Document
Electrical (Total of 10 test method standards, 1 published and 9 in development)	
ASTM WK61479- Durability of textile electrodes exposed to perspiration (in development)	[87]
ASTM WK61480- Durability of textile electrodes after laundering (in development)	[88]
AATCC RA111(a)- Electrical resistance of electronically integrated textiles (in development)*	[89]
AATCC RA111(b)- Electrical resistance changes after home laundering (in development)*	[90]
CEN EN 16812:2016- Linear electrical resistance of conductive tracks*	[91]
IEC 63203–204-1- Washable durability for leisure and sportswear e-textile system (in development)*	[92]
IEC 63203–201-3- Electrical resistance of conductive textiles under simulated microclimate (in development)*	[93]
IEC 63203–250-1- Snap button connectors (in development)*	[94]
IEC 63203–201-1- Basic properties of conductive yarns (in development)*	[95]
IEC 63203–201-2- Basic properties of conductive fabric and insulation materials (in development)*	[96]
Thermal (Total of 4 test standards, 1 published and 3 in development)	
CEN EN 16806–1:2016- PCM - Heat storage and release capacity	[97]
CEN EN 16806–2 PCM- Heat transfer using a dynamic method (in development)	[97]
CEN EN 16806–3 PCM- Determination of the heat transfer between the user and the product (in development)	[97]
IEC 63203–406-1- Measuring skin contact temperature (in development)	[98]
Mechanical (Total of 2 test standards in development)	
IEC 63203–401-1 - Stretchable resistive strain sensor (in development)	[99]
IEC 63203–402-1 – Finger movements in glove-type motion sensors (in development)	[100]
Physical environment (Total of 1 test standard in development)	
IEC 63203–402-2 - Fitness wearables – step counting (in development)	[101]
Optical (Total of 1 test standard in development)	
IEC 63203–301-1 - Electrochromic films for wearable equipment (in development)	[102]
Others (Total of 4 test standards, 2 published and 2 in development)	
ASTM D8248–19- Standard terminology for smart textiles	[103]
ASTM WK61478- New terminology for smart textiles (in development)	[104]
CEN 16298 - Definitions, categorization, applications and standardization needs	[105]
IEC 63203–101-1 – Terminology (in development)	[106]

**Also applies to other categories of products/technologies.*

Table 2.
Standards (existing and in development) test methods for smart textiles.

The product assessment should also take into account the product features, longevity, benefits/cost ratio, and the user experience.

Applying this trifactor model, we have identified the need for more than thirty standard test methods in the specific case of thermal e-textile products (**Tables 3–5**). They include a full-sleeve resistive heating jacket, battery-powered resistive heating boots, resistive heating car seats, battery-powered resistive heating gloves, a

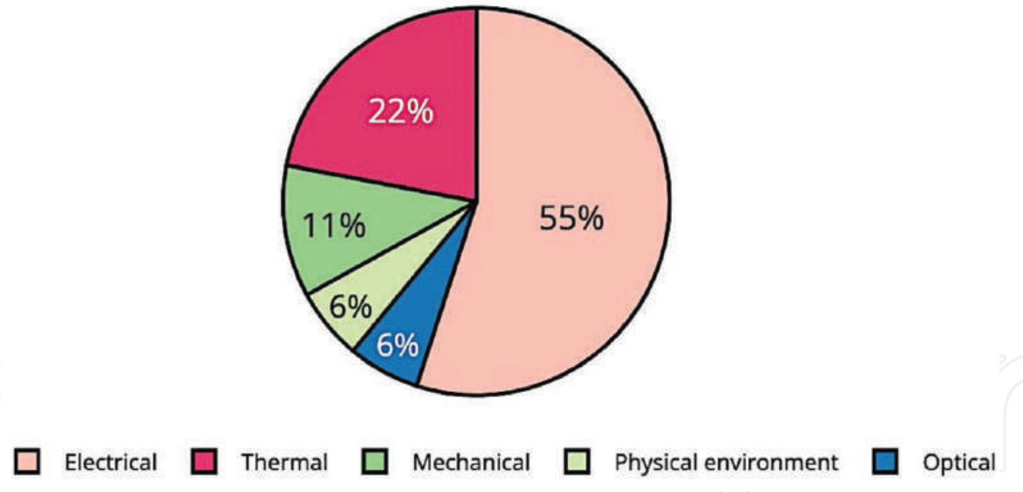


Figure 12.
Existing/in-development standardized test methods for smart textiles as of December 2020.

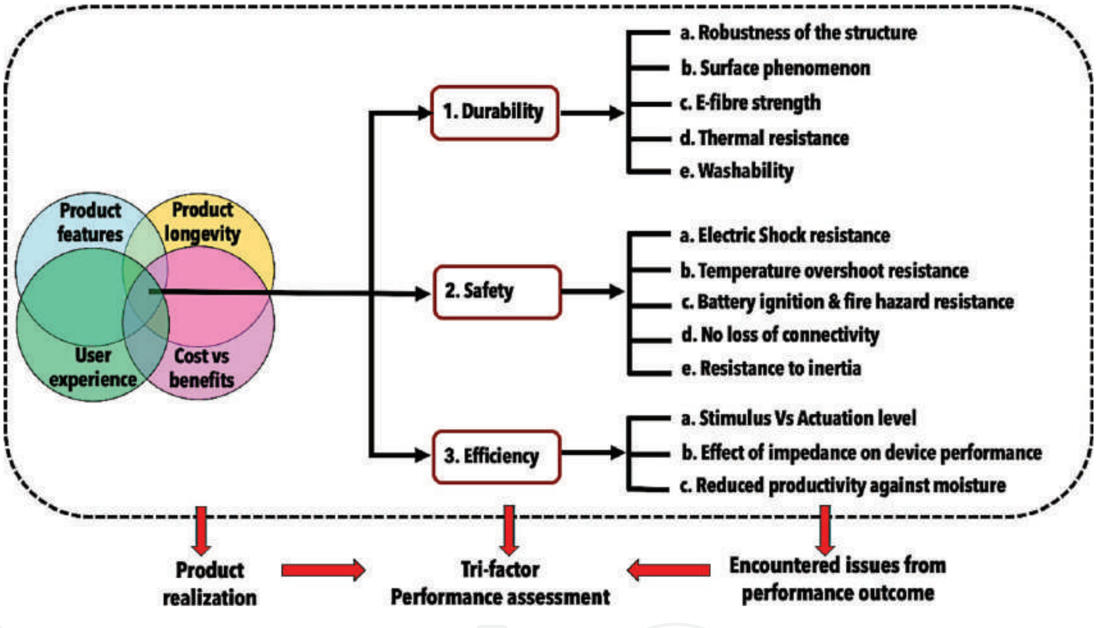


Figure 13.
Tri-factor framework for assessing the performance of smart/e-textiles.

Performance evaluation	Applicable standards
Efficiency of the overall functional/protective clothing system	Not available
Efficiency of the heat transfer system between textile and user (at the component level)	Not available
Efficiency of the induction-charging system	Not available

Table 3.
Test methods needed to evaluate the efficiency of smart/e-textiles.

reflective heating jacket, an air-exchange heating face mask, a cooling vest using water circulation and a Peltier module, and a thermo-regulated jacket with phase change materials. The few standard test methods already published and in development are also included in the tables when relevant: in several cases, the standard would not apply to the case of thermal e-textiles used as an example here. In the

Performance evaluation	Applicable standards
Efficiency of protection against shorts or open circuit, leading to shocks or fire hazards	IEC 63203–201-2 is in development, but it may not apply to high resistance conductive fabrics used for antistatic or heater purposes
Efficiency of controls (i.e., power limit) to avoid over-heating, leading to skin burn or damage	IEC 63203–406-1 ED1 is in development but it appears to be limited to wearable electronic devices
Impact of prolonged heating exposure on the skin and the surrounding environment	Not available
Overshooting of temperature difference between set temperature and experienced temperature by the skin	Not available

Table 4.
Test methods needed to evaluate the safety of smart/e-textiles (include test methods published and in development when relevant).

Performance evaluation	Applicable standards
Electrical resistance of the heater/resistive material to cleaning (washing/ laundering, dry-cleaning, drying)[a,d]	ASTM WK61480 (draft) AATCC RA11 (draft) IEC PN 63203–201-2 (draft)
Electrical resistance of the heating element to exposure of perspiration (from different parts of the body)[a,b,d]	ASTM WK61479 (draft) IEC PN 63203–201-2 (draft)
Electrical resistance of the heating element when subjected to mechanical stresses (tension /compression/ bending / fatigue/ abrasion/cutting /tearing / bodyweight)[a,b,c,d]	IEC PN 63203–201-2 is in development, but it does not appear to cover the aspects of abrasion, cutting, tearing, and fatigue
Electrical resistance of conductive parts to steaming or ironing (after laundering)[a]	Not available
Electrical resistance of the heating element to extreme weather conditions (e.g., rain and snow)[a,b,c,d]	Not available
Electrical resistance of the heating elements after exposure to severe use conditions (hot/cold/high humidity)[a,b,c,d]	Not available
Electrical resistance of the heating elements after exposure to different kinds of liquid (water, coffee, soft drinks)[c,d]	Not available
Electrical resistance of conductive track to cleaning[a,b,c,d]	ASTM WK61480 (draft) AATCC RA11 (draft) IEC PN 63203–201-2 (draft)
Electrical resistance of fasteners (e.g., switch, snaps, power supply) to cleaning[a]	Not available
Electrical resistance of fasteners to power supply to repetitive connection/disconnection for cleaning, i.e., fatigue[a,d]	Not available
Electrical resistance of fasteners to steaming/ironing[a]	Not available
Electrical resistance of fasteners to the power supply to exposure of perspiration (e.g., corrosion)[a]	Not available
Resistance of reflective thermal heating pattern to cleaning (washing/ laundering, dry-cleaning, drying)[e]	Not available
Resistance of reflective thermal heating pattern to body abrasion[e]	Not available

Performance evaluation	Applicable standards
Resistance of reflective thermal heating pattern to perspiration[e]	Not available
Preservation of thermal heat reflection of liner fabric over time i.e., aging behavior[e]	Not available
Resistance of antimicrobial property of ventilator to cleaning (washing/ laundering/ dry-cleaning/ drying)[f]	Not available
Resistance of structural integrity of the ventilator against external compression and abrasion[f]	Not available
Efficiency of the heat recovery of the ventilation system from the exhaled breath[f]	Not available
Efficiency of the transformation mechanism of cold inhaled air into warm air inside the ventilator[f]	Not available
Resistance of structural integrity of the bladder/reservoir to compression and abrasion (with zipper track while detaching)[g]	Not available
Heat storage and release capacity of phase change material (PCM)[h]	CEN EN 16806–1 (Part- 1)
Resistance of PCM and coatings (many contain binders) to washing/ laundering/ dry-cleaning/ drying[h]	Not available
Resistance of PCM and coatings to abrasion[h]	Not available
Resistance of PCM and coatings to perspiration[h]	Not available
Determination of cooling or heat transfer of the PCM (coated or portable packs) technology[h]	CEN EN 16806–1 (Part- 2)
Resistance of PCM and coating to steaming and ironing[h]	Not available
Efficiency of PCM (coated or portable packs) technology over the course of the time i.e., aging behavior (weather conditions)[h]	Not available
Efficiency of PCM (coated or portable packs) technology to fatigue[h]	Not available

[a]*Resistive heating jacket.*
[b]*Resistive heating boot.*
[c]*Resistive heating car seat.*
[d]*Resistive heating gloves.*
[e]*Reflective heating jacket.*
[f]*Air-exchange heating face mask.*
[g]*Cooling vest using water circulation and a Peltier module.*
[h]*Thermo-regulated jacket with phase change material.*

Table 5.
Test methods needed to evaluate the durability of smart/e-textiles (include test methods published and in development when relevant).

case of the durability assessment, the analysis considered the specificities of the application corresponding to the product under consideration.

5. Conclusion

After a brief overview of smart/e-textile products and major barriers to market entry, this chapter discussed different issues reported as well as foreseeable challenges that may result in injuries for instance, with electric shocks, skin burns and fires. Aspects related to the user's satisfaction, for instance in terms of the product longevity and the ability to maintain/repair it, were also covered. In particular, different conditions such as biomechanical stresses applied during use, ambient moisture, and laundering may reduce the life expectancy of the smart textile due to a damage of the conductive interconnects or a reduced actuation, for instance. As the world moves towards an increased adoption of smart e-textiles, such unwanted outcomes can put the lives of healthcare patients, first responders, and soldiers, for instance, at risk.

Due to the lack of dedicated standard test methods, manufacturers of e-textiles are limited in their attempt to control the quality of their products; as a result, they are unable to scale up and have their innovative e-textile technologies and products reach their full potential. It is clear that the issues reported in terms of safety, durability, and efficiency of e-textiles can be mitigated and eliminated through appropriate quality control using standard test methods. Currently, only 18 standard test methods published and in development by CEN, IEC, ASTM, and AATCC technical committees relevant to smart/e-textiles were identified. In some categories of e-textiles, e.g., thermal, chemical, biological, and energy harvesting, few or no test methods exist while several products are already on the market.

Using a trifactor model of performance assessment based on safety, efficiency, and durability, more than 30 standard test methods were identified for thermal e-textiles by considering a series of existing technologies/products: a full-sleeve resistive heating jacket, battery-powered resistive heating boots, resistive heating car seats, battery-powered resistive heating gloves, a reflective heating jacket, an air-exchange heating face mask, a cooling vest using water circulation and a Peltier module, and a thermo-regulated jacket with phase change materials. The development of such product-oriented test methods and their adoption by the manufacturing industries, will facilitate the design process towards a safer, more efficient, and durable smart/e-textile world. Adopting a collaborative and multidisciplinary approach, involving textile, materials, biomedical, and electrical engineers as well as relevant national and international standardization technical committees in textiles and electronics, is key to achieving this.

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References

[1] Köhler AR (2013) Challenges for eco-design of emerging technologies: The case of electronic textiles. Mater Des 51: 51–60. https://doi.org/10.1016/j.matdes.2013.04.012

[2] MarketsAndMarkets (2015) Smart Textiles Market by Type (Passive, Active, Ultra-smart), Function (Sensing, Energy Harvesting, Luminescence & Aesthetics, Thermo-electricity), Industry (Healthcare, Sports & Fitness, Fashion, Military, Automotive), & Geography - Global Forecast to 20

[3] Honarvar MG, Latifi M (2017) Overview of wearable electronics and smart textiles. J Text Inst 108:631–652. https://doi.org/10.1080/00405000.2016.1177870

[4] Ismar E, Kurşun Bahadir S, Kalaoglu F, Koncar V (2020) Futuristic Clothes: Electronic Textiles and Wearable Technologies. Glob Challenges 4:1900092. https://doi.org/10.1002/gch2.201900092

[5] Dolez PI, Decaens J, Buns T, et al (2020) Applications of smart textiles in occupational health and safety. IOP Conf Ser Mater Sci Eng 827:012014. https://doi.org/10.1088/1757-899X/827/1/012014

[6] Stoppa M, Chiolerio A (2014) Wearable Electronics and Smart Textiles: A Critical Review. Sensors 14: 11957–11992. https://doi.org/10.3390/s140711957

[7] Weigelt G (2015) Power vest-Research News. In: Fraunhofer. https://www.fraunhofer.de/en/press/research-news/2015/March/power-vest.html. Accessed 15 Nov 2020

[8] Myant Inc (2020) Myant unveils connected ppe concepts, creating new ways to assess health and performance as part of the skiin interconnected system of biometric garments. In: Myant. https://myant.ca/. Accessed 15 Nov 2020

[9] Graham F (2013) Wearable technology: The bra designed to shock attackers. In: BBC News. https://www.bbc.com/news/business-22110443. Accessed 15 Nov 2020

[10] Sky News (2015) Microsoft May Send Shock Alerts Through Clothes. In: Sky News UK. https://news.sky.com/. Accessed 15 Nov 2020

[11] Hisham AAB, Saad SA, Ahmad MRR, et al (2017) Review of Safety Evaluation of Thermal Wearable Power Harvesting Device. Int J Integr Eng 9:

[12] Schwarz A, Van Langenhove L, Guermonprez P, Deguillemont D (2010) A Roadmap on Smart Textiles. CRC Press

[13] Cherenack K, van Pieterson L (2012) Smart textiles: Challenges and opportunities. J Appl Phys 112:091301. https://doi.org/10.1063/1.4742728

[14] Kok M, de Vries H, Pacheco K, van Heck G (2015) Failure modes of conducting yarns in electronic-textile applications. Text Res J 85:1749–1760. https://doi.org/10.1177/0040517515573405

[15] Cherenack K, Zysset C, Kinkeldei T, et al (2010) Woven Electronic Fibers with Sensing and Display Functions for Smart Textiles. Adv Mater 22:5178–5182. https://doi.org/10.1002/adma.201002159

[16] Crow RM, Dewar MM (1986) Stresses in Clothing as Related to Seam Strength. Text Res J 56:467–473. https://doi.org/10.1177/004051758605600801

[17] Ryan JD, Mengistie DA, Gabrielsson R, et al (2017) Machine-Washable PEDOT:PSS Dyed Silk Yarns for Electronic Textiles. ACS Appl Mater

Interfaces 9:9045–9050. https://doi.org/10.1021/acsami.7b00530

[18] Qiu Q, Zhu M, Li Z, et al (2019) Highly flexible, breathable, tailorable and washable power generation fabrics for wearable electronics. Nano Energy 58:750–758. https://doi.org/10.1016/j.nanoen.2019.02.010

[19] Sun W-J, Xu L, Jia L-C, et al (2019) Highly conductive and stretchable carbon nanotube/thermoplastic polyurethane composite for wearable heater. Compos Sci Technol 181:107695. https://doi.org/10.1016/j.compscitech.2019.107695

[20] Hamdani S, Potluri P, Fernando A (2013) Thermo-Mechanical Behavior of Textile Heating Fabric Based on Silver Coated Polymeric Yarn. Materials (Basel) 6:1072–1089. https://doi.org/10.3390/ma6031072

[21] Hamdani STA, Fernando A, Maqsood M (2016) Thermo-mechanical behavior of stainless steel knitted structures. Heat Mass Transf 52:1861–1870. https://doi.org/10.1007/s00231-015-1707-z

[22] Kim D, Bang J, Lee W, et al (2020) Highly stretchable and oxidation-resistive Cu nanowire heater for replication of the feeling of heat in a virtual world. J Mater Chem A 8:8281–8291. https://doi.org/10.1039/D0TA00380H

[23] Bobinger MR, Romero FJ, Salinas-Castillo A, et al (2019) Flexible and robust laser-induced graphene heaters photothermally scribed on bare polyimide substrates. Carbon N Y 144:116–126. https://doi.org/10.1016/j.carbon.2018.12.010

[24] Hao Y, Tian M, Zhao H, et al (2018) High Efficiency Electrothermal Graphene/Tourmaline Composite Fabric Joule Heater with Durable Abrasion Resistance via a Spray Coating Route. Ind Eng Chem Res 57:13437–13448. https://doi.org/10.1021/acs.iecr.8b03628

[25] Lima RMAP, Alcaraz-Espinoza JJ, da Silva FAG, de Oliveira HP (2018) Multifunctional Wearable Electronic Textiles Using Cotton Fibers with Polypyrrole and Carbon Nanotubes. ACS Appl Mater Interfaces 10:13783–13795. https://doi.org/10.1021/acsami.8b04695

[26] Rahman MJ, Mieno T (2015) Conductive Cotton Textile from Safely Functionalized Carbon Nanotubes. J Nanomater 2015:1–10. https://doi.org/10.1155/2015/978484

[27] Zhang M, Wang C, Liang X, et al (2017) Weft-Knitted Fabric for a Highly Stretchable and Low-Voltage Wearable Heater. Adv Electron Mater 3:1700193. https://doi.org/10.1002/aelm.201700193

[28] Bosowski P, Hoerr M, Mecnika V, et al (2015) Design and manufacture of textile-based sensors. In: Electronic Textiles. Elsevier, pp 75–107

[29] zdil N, Zelik G, Spren G (2012) Analysis of Abrasion Characteristics in Textiles. In: Abrasion Resistance of Materials. InTech

[30] Cho C, Elias A, Batcheller J, et al (2019) Electrical conduction of reduced graphene oxide coated meta-aramid textile and its evolution under aging conditions. J Ind Text 152808371986938. https://doi.org/10.1177/1528083719869387

[31] Matikainen A, Nuutinen T, Itkonen T, et al (2016) Atmospheric oxidation and carbon contamination of silver and its effect on surface-enhanced Raman spectroscopy (SERS). Sci Rep 6:37192. https://doi.org/10.1038/srep37192

[32] Palomar T, Ramírez Barat B, García E, Cano E (2016) A comparative

study of cleaning methods for tarnished silver. J Cult Herit 17:20–26. https://doi.org/10.1016/j.culher.2015.07.012

[33] Denawaka CJ, Fowlis IA, Dean JR (2016) Source, impact and removal of malodour from soiled clothing. J Chromatogr A 1438:216–225. https://doi.org/10.1016/j.chroma.2016.02.037

[34] MacLeod ID, Stambolov T (1987) The Corrosion and Conservation of Metallic Antiquities and Works of Art. Stud Conserv 32:138. https://doi.org/10.2307/1506218

[35] Liu H, Li J, Chen L, et al (2016) Thermal-electronic behaviors investigation of knitted heating fabrics based on silver plating compound yarns. Text Res J 86:1398–1412. https://doi.org/10.1177/0040517515612359

[36] Sezgin H, Bahadir SK, Boke YE, Kalaoglu F (2016) Thermal analysis of e-textile structures using full-factorial experimental design method. J Ind Text 45:752–764. https://doi.org/10.1177/1528083714540699

[37] Tao X, Koncar V, Huang T-H, et al (2017) How to Make Reliable, Washable, and Wearable Textronic Devices. Sensors 17:673. https://doi.org/10.3390/s17040673

[38] Yang K, Torah R, Wei Y, et al (2013) Waterproof and durable screen printed silver conductive tracks on textiles. Text Res J 83:2023–2031. https://doi.org/10.1177/0040517513490063

[39] Altaş S, Yılmaz E, Adman N (2020) Improving the repetitive washing and abrasion resistance properties of fabrics produced with metallized yarns. J Ind Text 152808372094296. https://doi.org/10.1177/1528083720942961

[40] Booth JE (1964) Principles of textile testing: an introduction to physical methods of testing textile fibres, yarns, and fabrics. Chemical Pub. Co.

[41] Alomayri T, Assaedi H, Shaikh FUA, Low IM (2014) Effect of water absorption on the mechanical properties of cotton fabric-reinforced geopolymer composites. J Asian Ceram Soc 2:223–230. https://doi.org/10.1016/j.jascer.2014.05.005

[42] Gaubert V, Gidik H, Bodart N, Koncar V (2020) Investigating the Impact of Washing Cycles on Silver-Plated Textile Electrodes: A Complete Study. Sensors 20:1739. https://doi.org/10.3390/s20061739

[43] Nayak R, Wang L, Padhye R (2015) Electronic textiles for military personnel. In: Electronic Textiles. Elsevier, pp 239–256

[44] LONGINOTTI-BUITONI G, BOVIO D (2020) Laundry system for smart garments

[45] Badgett J (2019) An Evaluation of the Quality of Men's 100% Cotton Jersey Knit T-Shirts. J Text Sci Fash Technol 3:. https://doi.org/10.33552/JTSFT.2019.03.000557

[46] Metz R (2014) This Shirt Is (Really) Sensitive. In: MIT Technol. Rev. https://www.technologyreview.com/s/527136/this-shirt-is-really-sensitive/

[47] Karaguzel B, Merritt CR, Kang T, et al (2009) Flexible, durable printed electrical circuits. J Text Inst 100:1–9. https://doi.org/10.1080/00405000802390147

[48] Eskandarian L, Lam E, Rupnow C, et al (2020) Robust and Multifunctional Conductive Yarns for Biomedical Textile Computing. ACS Appl Electron Mater 2:1554–1566. https://doi.org/10.1021/acsaelm.0c00171

[49] Mariello M, Guido F, Mastronardi VM, et al (2019) Reliability of Protective Coatings for Flexible Piezoelectric Transducers in Aqueous Environments. Micromachines 10:739. https://doi.org/10.3390/mi10110739

[50] Murph D (2013) Columbia recalls Omni-Heat electric jackets due to burn hazard (or, for working too well). Engadget

[51] Castano LM, Flatau AB (2014) Smart fabric sensors and e-textile technologies: a review. Smart Mater Struct 23:053001. https://doi.org/10.1088/0964-1726/23/5/053001

[52] Starner T, Maguire Y (1998) A heat dissipation tutorial for wearable computers. In: Digest of Papers. Second International Symposium on Wearable Computers (Cat. No.98EX215). IEEE Comput. Soc, pp 140–148

[53] Kroemer AD, Kroemer KH. (2016) Office ergonomics. CRC Press, Second edition. | Boca Raton [Florida] : Taylor & Francis, CRC

[54] Gagge AP, Gonzalez RR (2011) Mechanisms of heat exchange: biophysics and physiology. In: Comprehensive Physiology. John Wiley & Sons, Inc., Hoboken, NJ, USA

[55] Iftimia N, Ferguson RD, Mujat M, et al (2013) Combined reflectance confocal microscopy/optical coherence tomography imaging for skin burn assessment. Biomed Opt Express 4:680. https://doi.org/10.1364/BOE.4.000680

[56] Moritz AR, Henriques FC (1947) Studies of thermal injury: ii. the relative importance of time and surface temperature in the causation of cutaneous burns. Am J Pathol 23:695–720

[57] Benjamin C, Gittler M, Lee R (2011) Burn from car seat heater in a man with paraplegia: case report. J Spinal Cord Med 34:332–334. https://doi.org/10.1179/2045772311Y.0000000005

[58] Demir E, O'Dey D m., Fuchs PC, et al (2006) Die Autositzheizung — eine potenzielle Verbrennungsgefahr für den Querschnittsgelähmten. Nervenarzt 77: 201–203. https://doi.org/10.1007/s00115-005-1960-3

[59] Vogel B (2008) Escaping the Hot Seat. New Mobil.

[60] Rakowski KRM, Sivathasan N, Sivathasan N (2011) Pain in your buttocks? Check your heated car seat isn't burning you. Spinal Cord 49:672–672. https://doi.org/10.1038/sc.2010.115

[61] Bansal V (2006) Diabetic neuropathy. Postgrad Med J 82:95–100. https://doi.org/10.1136/pgmj.2005.036137

[62] Healthline (2018) Find the Right Diabetic Socks. In: Healthline. https://www.healthline.com/health/find-right-diabetic-socks

[63] Tufts Medical Center (2020) Peripheral Neuropathy. In: Tufts Med. Cent. https://hhma.org/healthad visor/aha-perineur-crs/#:~:text=Put moist heat on the,any type of hot pad.

[64] Mbise E, Dias T, Hurley W (2015) Design and manufacture of heated textiles. In: Electronic Textiles. Elsevier, pp 117–132

[65] Swanner J, Bito J, Nichols G, et al (2017) Integrating Multiple Energy Harvesting Systems for Department of Defense Applications. In: EESAT Conference - Evolution & Revolution

[66] Choi AY, Lee CJ, Park J, et al (2017) Corrugated Textile based Triboelectric Generator for Wearable Energy Harvesting. Sci Rep 7:45583. https://doi.org/10.1038/srep45583

[67] Matsouka D, Vassiliadis S, Bayramol DV (2018) Piezoelectric textile fibres for wearable energy harvesting systems. Mater Res Express 5:065508. https://doi.org/10.1088/2053-1591/aac928

[68] Sun T, Zhou B, Zheng Q, et al (2020) Stretchable fabric generates

electric power from woven thermoelectric fibers. Nat Commun 11: 572. https://doi.org/10.1038/s41467-020-14399-6

[69] Nocito C, Koncar V (2016) Flexible photovoltaic cells embedded into textile structures. In: Smart Textiles and their Applications. Elsevier, pp 401–422

[70] Lv J, Jeerapan I, Tehrani F, et al (2018) Sweat-based wearable energy harvesting-storage hybrid textile devices. Energy Environ Sci 11:3431–3442. https://doi.org/10.1039/C8EE02792G

[71] Kim S, Vyas R, Bito J, et al (2014) Ambient RF Energy-Harvesting Technologies for Self-Sustainable Standalone Wireless Sensor Platforms. Proc IEEE 102:1649–1666. https://doi.org/10.1109/JPROC.2014.2357031

[72] KFSM-TV (2017) Springdale Woman's Heated Jacket Bursts Into Flames After Battery Ignites. 5 News

[73] Carole W, Justyna T, Patricia W, et al (2005) Development of Electronic Textiles to Transport Data and Power in Future U.S. Military Protective Clothing Systems. J ASTM Int 2:

[74] Chun J, Lee M (2016) Developing a SEIL (Smart Enjoy Interact Light) bag utilizing LED display. Int J Cloth Sci Technol 28:. https://doi.org/10.1108/IJCST-02-2015-0026

[75] Axisa F, Schmitt PM, Gehin C, et al (2005) Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention. IEEE Trans Inf Technol Biomed 9:325–336. https://doi.org/10.1109/TITB.2005.854505

[76] Xiao Z, Sheng C, Xia Y, et al (2019) Electrical heating behavior of flexible thermoplastic polyurethane/Super-P nanoparticle composite films for advanced wearable heaters. J Ind Eng Chem 71:293–300. https://doi.org/10.1016/j.jiec.2018.11.038

[77] Skogestad S (2008) Chemical and Energy Process Engineering. CRC Press

[78] Lai Y-T, Tai N-H (2015) One-Step Process for High-Performance, Adhesive, Flexible Transparent Conductive Films Based on p-Type Reduced Graphene Oxides and Silver Nanowires. ACS Appl Mater Interfaces 7:18553–18559. https://doi.org/10.1021/acsami.5b04875

[79] Huang Y, Tao L-Q, Yu J, et al (2020) Improved Performance of Flexible Graphene Heater Based on Repeated Laser Writing. IEEE Electron Device Lett 41:501–504. https://doi.org/10.1109/LED.2020.2965585

[80] Hong S, Gu Y, Seo JK, et al (2019) Wearable thermoelectrics for personalized thermoregulation. Sci Adv 5:eaaw0536. https://doi.org/10.1126/sciadv.aaw0536

[81] Pani D, Dessi A, Saenz-Cogollo JF, et al (2016) Fully Textile, PEDOT:PSS Based Electrodes for Wearable ECG Monitoring Systems. IEEE Trans Biomed Eng 63:540–549. https://doi.org/10.1109/TBME.2015.2465936

[82] Weder M, Hegemann D, Amberg M, et al (2015) Embroidered Electrode with Silver/Titanium Coating for Long-Term ECG Monitoring. Sensors 15:1750–1759. https://doi.org/10.3390/s150101750

[83] Soroudi A, Hernández N, Wipenmyr J, Nierstrasz V (2019) Surface modification of textile electrodes to improve electrocardiography signals in wearable smart garment. J Mater Sci Mater Electron 30:16666–16675. https://doi.org/10.1007/s10854-019-02047-9

[84] Nasiri S, Khosravani MR (2020) Progress and challenges in fabrication of

wearable sensors for health monitoring. Sensors Actuators A Phys 312:112105. https://doi.org/10.1016/j.sna.2020.112105

[85] Suh M (2015) Wearable sensors for athletes. In: Electronic Textiles. Elsevier, pp 257–273

[86] Köhler AR, Hilty LM, Bakker C (2011) Prospective Impacts of Electronic Textiles on Recycling and Disposal. J Ind Ecol 15:496–511. https://doi.org/10.1111/j.1530-9290.2011.00358.x

[87] Draft ASTM WK61479 (2018) New test method for durability of smart garment textile electrodes exposed to perspiration

[88] Draft ASTM WK61480 (2018) New test method for durability of smart garment textile electrodes after laundering

[89] Draft AATCC RA111(a) (2019) Electrical resistance of electronically-integrated textiles

[90] Draft AATCC RA111(b) (2019) Electrical resistance changes of electronically-integrated textiles after home laundering

[91] CEN EN 16812 (2016) Textiles and textile products - electrically conductive textiles - determination of the linear electrical resistance of conductive tracks

[92] Draft IEC 63203–204-1 (2019) Wearable electronic devices and technologies – part 204–1: electronic textile – washable durability test method for leisure and sportswear e-textile system

[93] Draft IEC 63203–201-3 (2019) Wearable electronic devices and technologies - Part 201–3: Electronic Textile - Determination of electrical resistance of conductive textiles under simulated microclimate

[94] Draft IEC 63203–250-1 (2018) Wearable electronic devices and technologies – part 250–1: electronic textile –snap button connectors between e-textile and detachable electronic devices

[95] Draft IEC 63203–201-1 (2018) Wearable electronic devices and technologies – part 201–1: electronic textile – measurement methods for basic properties of conductive yarns

[96] Draft IEC 63203–201-2 Wearable electronic devices and technologies – part 201–2: electronic textile – measurement methods for basic properties of conductive fabric and insulation materials

[97] CEN EN 16806–1 (2016) Textiles and textile products - textiles containing phase change materials (pcm) - part 1: determination of the heat storage and release capacity

[98] Draft IEC 63203–406-1 (2019) Wearable electronic devices and technologies - Part 406–1: Test methods of on-body wearable electronic devices for measuring skin contact temperature

[99] Draft IEC 63203–401-1 (2019) Wearable electronic devices and technologies - Part 401–1: Devices and Systems – Functional elements - Evaluation method of the stretchable resistive strain sensor

[100] Draft IEC 63203–402-1 (2019) Wearable electronic devices and technologies – part 402–1: devices and systems – accessory – test methods of glove-type motion sensors for measuring finger movements

[101] Draft IEC 63203–402-2 (2019) Wearable electronic devices and technologies – part 402–2: performance measurement of fitness wearables – step counting

[102] Draft IEC 63203–301-1 (2019) Wearable electronic devices and technologies - Part 301–1: Test method

of electrochromic films for wearable equipment

[103] ASTM D8248 (2019) Standard Terminology for smart textiles

[104] Draft ASTM WK61478 (2017) New terminology for smart textiles

[105] CEN 16298 (2011) Textiles and textile products - smart textiles - definitions, categorization, applications and standardization needs

[106] Draft IEC 63203–101-1 (2019) Wearable electronic devices and technologies – Part 101–1: Terminology

[107] Decaens J, Vermeersch O (2018) Specific testing for smart textiles. In: Advanced Characterization and Testing of Textiles. Elsevier, pp 351–374