ELSEVIER

Volume 3: Medical Textiles from Natural Resources

Chapter 23: Research, development, and future trends for medical textile products

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Abstract

Medical textiles are functional textiles resulting from production technologies, materials, and medicines which make them technically sophisticated products for different biomedical applications concerning their potential.

Medical textiles can be classified as non-implantable (i.e., dressings and gauze), implantable (i.e., artificial arteries, sutures, vascular grafts), intelligent textiles (i.e., for thermoregulating, shape), extracorporeal devices (i.e., artificial organs) and health/hygiene products. Recurrent fibers in functional medical textiles must be non-toxic, non-allergenic or carcinogenic. Parameters such as strength, flexibility, absorption, or biodegradability may be desired for products with specific functionalities.

This chapter focuses on the progress of medical textiles from natural resources, their functional modifications, and their added-value potential applications. A description is provided on the technologies, from bio-based medical textiles to the development of medical textiles with high absorption, antimicrobial, drug release, protection, and other highly valuable functions in biomedical materials or tissue regeneration.

Keywords: medical textiles, tissue regeneration, bio-based, sustainability

Chapter contents

1. Introduction (Section Heading)

The high-tech advances in medical textiles have been pitched to the most challenging health needs in an awareness search for natural-based, green, and eco-friendly alternatives. The medical textiles may cover the main areas of basic biomaterials, health and hygiene products, infection control and barrier materials, bandages and pressure clothing, wound care materials, medical devices, implantable and smart technologies (Canyon Hydro et al., 2013).

Over the past years, smart and functional textiles, including responsive textiles, have been developed very fast. Responsive textiles (intrinsic or generated by smart coatings) interact with their environment by responding to specific stimuli. The response derived from the stimuli can be one to evoke a functional, protective, or warning signal (Hu et al., 2012). Abundant stimuli-responsive materials can change their configuration or physical properties, responding to small changes in stimuli such as pH, moisture/water, light, heat, and electricity (e-textiles) (De Smet & Vanneste, 2019).

Traditional circular economy concepts have focused on moving away from end-of-life treatment options, such as waste-to-energy recovery pathways. In this sense, they have been oriented towards higher recovery rates in textile recycling, as well as in the upcycling of textile waste with durable characteristics and high added value for secondary product platforms (Hildebrandt et al., 2021). Today, increasingly accepted definitions of circular economy are applied from a life cycle perspective. Incorporating lifecycle management strategies into circular economy concept, there are opportunities to involve more efficient use of agri-food waste streams in emerging chains of the bio-textile industry. In this sense, promoting the more efficient use of agricultural waste streams and an improved design for recycling finished textile products in an attempt at sustainability (Hildebrandt et al., 2021).

Various textile features such as their flexibility, light-weight, wide range of dimensions, surface, physical, and structural properties made these constructs favourable to be used in different medical applications (Davies, 2018). Textile fabrics have been extensively used as drug delivery systems in wound dressings, synthetic skin graft substitutes, scaffolds for tissue repair and regeneration, and other applications (Ratner et al., 2004). Textile fibers are categorized into natural and man-made groups based on their origin or the way they have been produced. Natural fibers are developed or occur in fiber shape, which refers to naturally occurring fibers found in animals, minerals and vegetable sources (McIntyre & Daniels, 1995). On the other hand, man-made textile fibers or chemical fibers are those whose chemical composition, structure, and properties are significantly modified during the manufacturing process in which the physical and chemical properties of the initial material are altered notably during processing (McIntyre & Daniels, 1995). In another perspective, bio textiles are non-viable, permanent or temporary, fibrous textile structures composed from synthetic or natural materials designed specifically for biological environments, where their profile depends on biocompatibility and biostability with cells and biological fluids(King & Chung, 2013). May be used either in an internal (inside the body) or external (outside the body) as a medical device for prevention/diagnosis, or treatment of an injury or disease, improving the health, medical condition, comfort and wellness of the patient (King & Chung, 2013).

Nonetheless, the first stage to create a bio textile medical device is to generate textile fibers. Fibers can be spun in various ways to create monofilaments or multifilament yarns. One common application of bio textiles and fiber technology is the development of wound dressings (Tessier, 2013). Wound dressings act as a physical barrier to avoid infection and foment moisture absorption and blood coagulation (Chang et al., 2020). The electrospinning method is considered the most effective method for producing suitable nanofibers for wound dressing because this technique is also adequate to deliver bioactive compounds in the long-term to local tissues at the wound local (Croitoru et al., 2020; Serôdio et al., 2019). Currently, the design of wound dressings have reached higher standards and is based on the concept of generating an optimal environment, which main goals are accelerating wound healing, skin regeneration, oxygen exchange and preventing microbial colonisation (Felgueiras & Amorim, 2017). So, studies have focused on developing textile dressings that release antimicrobial agents able to stimulate the healing process and prevent or treat wound infections. Moreover, there is a growing concern related to multidrug-resistant bacteria that arise due to the continuous administration of antibiotics (Croitoru et al., 2020). Therefore, researchers have been developing modern wound dressings materials made of nanostructure fibers that can be loaded with natural compounds showing antimicrobial, antioxidant and anti-inflammatory activities to accelerate the healing process of the wounds (Croitoru et al., 2020).

Fibers and textiles have probably been used for medical applications since human beings learned to produce tools, mainly for wound care applications like sutures and wound dressings (Doser & Planck, 2011). In contrast, it is not widely known that textile structures are used as permanent implants. Dacron® has been one of the first textile materials to be used as vascular grafts (woven and knitted). In recent years textiles have even become an interesting material in the new field of regenerative medicine, which revolutionises many traditional therapies (Gu et al., 2019). Fibers constitute the human body (mainly collagen within the connective tissue, but muscles, tendons and nerves are fibrous). So cells used to handling these structures may also integrate into organoids by promising printable technologies (Gu et al., 2019).

In this chapter, recent revolutions in the manufacturing of bio textiles and their emerging applications for tissue engineering and regenerative medicine will be revised.

2. Overview and research challenges for medical textile products (Section Heading)

Textiles and medical devices have been the subject of active research over time, despite the high regulation that restricts the implementation of new technologies until proven safe for the patient in a specific indication. Still, technological advances continue to be developed to cover new applications in the medical field, such as fibre-based drug-releasing systems, three-dimensional (3D) structures, sensors to give intelligence to medical devices, smart and responsive textiles, and implantable textiles in regenerative medicine (Iqbal et al., 2021). Among these emerging advances, there is a transversal trend in the textile sector towards the development of sustainable bio-based technologies with increased environmental concerns. Therefore, industry challenges must be addressed first to the patient, nurses and surgeon's needs, providing products with improved features, ecological philosophy, and at a reasonable price and cost to enable viability to the health system (Iqbal et al., 2021).

The economic impact of medical textiles is now significant and is growing steadily. The U.S. International Trade Administration (ITA) estimates that in 2017, the global medical device market was about $ 16 billion worldwide ($ 4.5 billion in Europe) with a growth of $ 23.3 billion by 2025, according to a new report conducted by Grand View Research, Inc. (*Medical Textiles Market Size Worth $23.3 Billion By 2025*, 2019). This increase is mostly associated with awareness of best health practices, continued technological advances, a regulatory framework that requires the use of medical textiles and the increase of the geriatric population (*Medical Textiles Market Size Worth $23.3 Billion By 2025*, 2019). The global Biotextiles market, a subset of medical textiles used in surgery that includes implantable devices (i.e. surgical sutures, herniated tissue repair, vascular and endovascular prostheses, artificial skin, anterior cruciate ligament (ACL) prostheses and artificial heart parts) in 2017 represented about the U.S. $ 5.5 billion (34% of medical textiles) and is estimated to have reached $ 6.4 billion in 2020 (Strouse, 2001).

Research in this field requires an understanding of the latest extremely powerful and promising technologies related to textiles, regarding technologies for polymer synthesis, fibre spinning, surface modification, nano/microtechnologies, information technology to develop interactive and wearable medical textiles and new notions in biological sciences, in creative understanding architecture of these disciplines (Textiles & Carolina, 2003). Figure 1 is embodied the most common applications of medical textiles and the different fibre-based types in a schematic work-sum.

The combination of drugs and fibres has resulted in extensive research, mainly to develop textiles with long-lasting antimicrobial properties, to avoid resistant microorganisms. Antimicrobial medical textiles are particularly crucial in a hospital setting or as medical devices for healthcare or hygiene. Common contaminating species include *Escherichia coli, Klebsiella pneumonia, Pseudomonas aeruginosa, Staphylococcus aureus* and *Acinetobacter baumannii*, which can cause opportunistic and severe infections in humans. These types of textiles can be used in operating rooms or hospital wards (sheets and curtains to prevent infections) for safety, hygiene and care for employees and patients. The textiles can be used primarily as absorbents, protection and coverage for diseased or injured parts, as antimicrobial dressings. Methods to achieve such properties may include various strategies such as leaching the antimicrobial compounds in the polymer, use of fibres with antimicrobial properties, modifying the surface of the fibres by graft reactions or by physical methods (Canyon Hydro et al., 2013). There are several synthetic molecules commonly used as metals, quaternary ammonium compounds, triclosan, chlorhexidine, N-halamines and conjugated polymers. Natural antimicrobials can be obtained from plants as extracts (for example, polyphenols, essential oils or dyes), or they can be antimicrobial peptides or antimicrobial polysaccharides such chitosan (Canyon Hydro et al., 2013; Márquez et al., 2017). Those used as implantable are even more restricted due to the associated risks (i.e., silver, triclosan and chlorhexidine apart from antibiotics).

In a system linked with bioactive properties, nanocomposites may offer greater interest from a scientific and technological point of view due to their distinct and applicable structural properties. Nanocomposites can be well-defined as a combination of materials of different geometric architectures that exhibit unique collective assets (Eltarahony et al., 2021). In biomedical implants, the term bio-nano composites is adopted, which corresponds to the mixture of organic fillers with polymeric matrices (Gunn & Zhang, 2010). The development of these new "nanomaterials" was driven to overcome the limitation of soles or mono-nanoparticles (N.P.s) and to improve their properties for enhanced functionalities, such as their incorporation in medical devices with different bioactive properties (Eltarahony et al., 2021). The progress of nanocomposites for the manufacture of medical devices, such as prosthetics, implants, drug delivery and tissue engineering, has reached a significant blow in the technological and biomedicine fields (Ngo et al., 2018). In add-on, nanocomposites can be bioinspired to exhibit advanced functionality, such as adhesive films, super-hydrophobicity and photonic coatings, or to imitate a specific biological function (Velu et al., 2019; T. Zhang et al., 2013). Many nanomaterials are biocompatible and biodegradable, which makes them particularly desirable for bioprinting applications and the subsequent boost of the desired properties in the final product (Lligadas et al., 2013; Velu et al., 2019). In general, matrices include natural polymers, such as collagen, gelatine, enzymes, polypeptides and polynucleic acids. Metal nanocomposites can be metal-metal, metal oxide-metal oxide, metal-metal oxide, metal-polymer and metal-polymer oxide (Eltarahony et al., 2021). Optimising the proper physical, chemical, shape, size, aspect ratio of nanoscale resources, mechanical and optical properties influence the use of nanoscale filling and is the main challenge for improving biomaterials and 3D printing (De et al., 2008).

3D printing is driving forward for major innovations in engineering, textile manufacturing, art, design, and the ultimate health application (Wallin et al., 2020). The available systems use one of the following processes: sintering of powder materials, photopolymerisation of liquid monomer, thermal or chemical processes and printing materials, such as chemical powder binder (Turon, 2017). In health, 3D printing can also be the engine of imaging techniques used to develop custom scaffolding enabling technology for tissue engineering. New technologies have been developed to establish arrays with living cells to form organ/tissue structures to print scaffolds that are biocompatible for the regeneration of human organs and tissues. Currently, three main types of 3D bioprinting techniques can be defined: inkjet bioprinting, microextrusion bioprinting and laser-assisted bioprinting (Turon, 2017). Research has been directed at improving the resolution, speed, reproducibility, viability, and biocompatibility of the biological process of making living structures. In the clinical field, it is also necessary to increase the manufacturing speed for the creation of larger structures while improving the viability, functionality and tissue oxygenation (Jongmin Kim et al., 2020; Murphy & Atala, 2014). Recent data employed commercial liquid silicone rubber materials as inks for extrusion-based three-dimensional (3D) printing to obtain more complex, unmoldable geometries (Yirmibesoglu et al., 2018). However, the gelation kinetics and rheological properties of these inks limit the print fidelity for both high aspect ratio structures and overhanging features. Some strategies are regarding interpenetrating polymer networks (IPN) or double networks (D.N.s), namely in a family of silicone (SilDNs) composed of a weak but 3D-printable silicone network that ensnares the precursors to a commercially available mechanically robust silicone (Wallin et al., 2020).

Electronic products in medical textiles are giving rise to a new range of “wearables” and textile fibres that find diverse applications in medicine. They are fibrous tissues and structures with sensors that can transmit fundamental information and assist health professionals (such as surgeons and nurses) in monitoring relevant, useful parameters of the patient (Jayoung Kim et al., 2019). They can be epidermal-based wearables, flexible wearables, and textile-based wearables and be employed for different body parts, e.g., head-based wearables, eye-based wearables, and wrist-based wearables (Jayoung Kim et al., 2019). Additionally, these materials can be used to deliver drugs in a controlled and efficient manner compared to traditional drug delivery systems (Yadav et al., 2019). Medical wearables can detect different parameters, biopotentials and life-threatening conditions, collect biometric data to aid in patient diagnosis, and even administer pain-relieving medications (i.e., cardiac monitoring, baby monitoring and pain management) (*Medical Textiles - What’s next*, 2016). Recent advancements in these materials include biocompatible flexible materials, for example, polyethene naphthalate, polyethene terephthalate (PET), Ecoflex, and Polydimethylsiloxane (PDMS), silicone-based materials, and thin-film polymers, for example, parylene (Salim & Lim, 2019; Stylios, 2020). It is important to highlight the diaries and numerous technical challenges that health professionals face (i.e., opportunistic surgical infections, minimally invasive surgery, robotisation, digitalisation, etc.) while dealing with management challenges (cost, patient safety, reduction and improvement of surgical results). In this segment, the industry's challenges are directly related to new technologies and to meet these same challenges. Business models must be tailored to address the needs of nurses and surgeons, providing efficient products at a reasonable ratio price/cost toward health care system sustainable, while at the same time meeting the growing requirements of a global and highly regulated system.

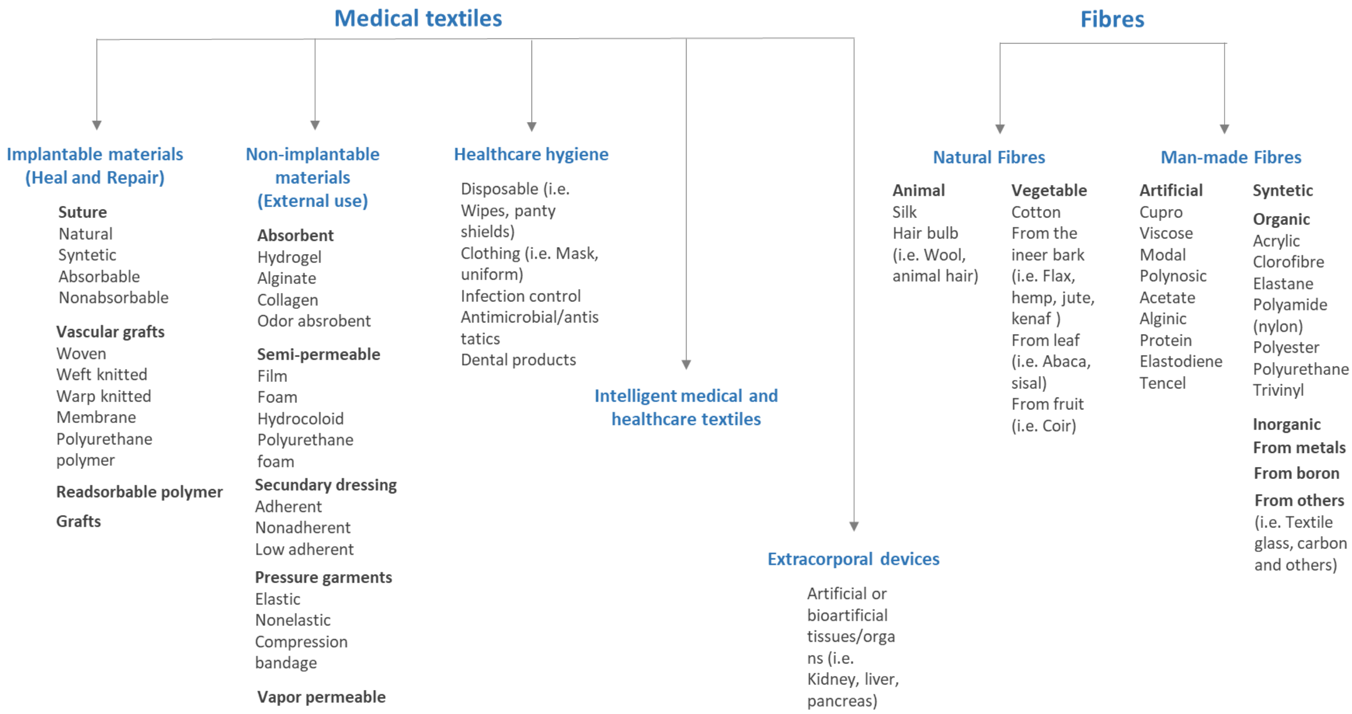

Figure 1. Scheme of medical textiles applications and fibres types (adapted from Azam A. et al. 2016 (Azam Ali & Shavandi, 2016))

3. High-tech advances in functional medical textile materials: development and design (Section Heading)

Wearable technology based on electronic textiles (e-textiles) has demonstrated massive potential for several applications in recent years (Liu et al., 2019), such as the design of smart-textiles for biomedical clothing for monitoring, diagnosing and treating medical conditions (Coyle et al., 2010), wireless cardiac signal monitoring in sports, recovery (Shyamkumar et al., 2014), and integration of military clothing, fabric antennas to support networks and communications (Winterhalter et al., 2005) (Figure 2). However, for all these e-textile applications, the biggest challenge remains the supply of energy. The functionalisation of textiles, namely electronics, is one of the most high-tech fields in the textile industry. However, it poses challenges due to the complex structures formed by various fibres using many different manufacturing techniques. The fabrics themselves also place restrictions/barriers in the implementation of the technologies that can be used (for example, limiting process temperatures), and the surface roughness also represents a challenging substrate for the deposition of the functional film. The integration of electronics in textiles requires the modification, manufacture of devices directly on the textile fibre itself, using high-performance materials that allow continuous and differentiated incorporation into fabrics (Winterhalter et al., 2005).

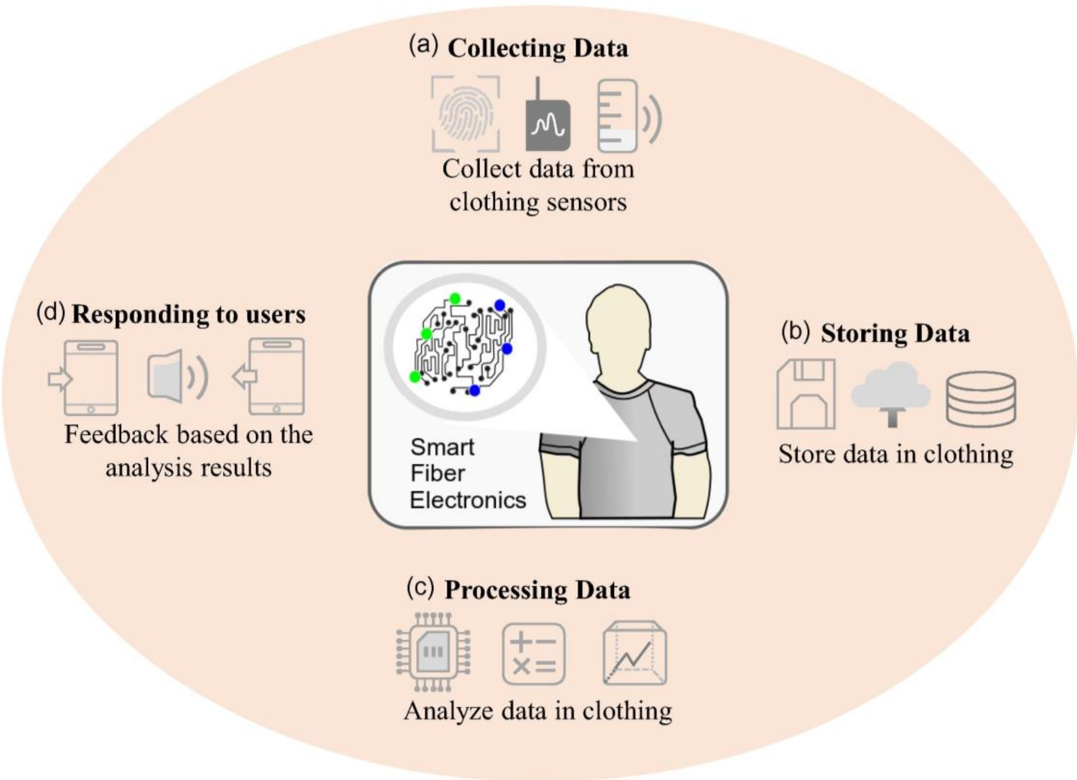

Figure 2. The conceptual idea of smart electronic textiles (copyright Materials Today 2020) (Yan et al., 2020)

Recent research has highlighted the possibilities of developing wearable sensor networks in textile materials, namely as drug delivery devices in our body, connected to such technology in a structure for remote diagnosis versus therapy, obtained with additional self-regulatory resources (Armgarth et al., 2021). The fibres are assembled into fabrics using textile processes, and each thread operates as an independent functional unit, individually designed to allow the on-demand release of a specific drug. The platform may be connected to a microcontroller that can wirelessly transfer commands from an external source, such as a smartphone. Mostafalu and his colleagues (Mostafalu et al., 2017) designed an actively controlled wound dressing manufactured using composite fibres with a central electric heater coated with a layer of hydrogel containing thermo-responsive drug carriers. In this case, the effectiveness was demonstrated through the controlled release of antibiotics and vascular endothelial growth factor (VEGF), which allowed the elimination of bacterial infection and induced angiogenesis in vitro. The effectiveness of VEGF release was improved in the healing rate and was also demonstrated *in vivo*. Xu et al. 2019 (Xu et al., 2019) developed a textile coil near field communication (NFC), dealing with small fabric deformations to create an antenna resonating at 13.56 MHz. However, the classic capacitor makes the antenna not entirely textile and requires few connection points. In a different point of view, (Garnier et al., 2021) developed a fully textile NFC combiner to transfer data and power between a device (i.e. smartphone and sensors) without any electronic components. It precisely describes textile NFC multiple combiners composed of textile NFC antennas linked by two-wire transmission lines. This configuration allows the supply of a power source and a wireless connection for smart biomedical textiles.

Torres Alonso et al. (2018) showed the design of functional devices enabled for graphene made directly from textile fibres and obtained by weaving graphene electronic fibres into a fabric. In this sense, touch sensors and light-emitting devices were produced using a roll-to-roll compatible standardisation technique, opening new possibilities for woven textile electronics. The display of fabric-enabled pixels for position-sensitive screens and functions is a way to new electronic, wearable electronics and smart textiles applications. Fibres that harvest mechanical energy via the triboelectric effect are excellent candidates as power sources for wearable electronics and functional textiles. Dong et al. (2020) demonstrated the scalable fabrication of elastic, microstructured triboelectric fibres with efficiencies comparable to planar systems. The authors used advanced elastomer fibres that combine a micro-textured surface with the integration of several liquid metal electrodes in a thermal stretching process. These fibers exhibited high electrical outputs, which managed to sustain deformations of up to 560%. In addition to energy capture, the fibers demonstrated self-powered respiratory monitoring and gesture detection abilities, making this triboelectric fiber platform an exciting opportunity for multifunctional wearable systems and smart textiles. As an outcome, these thermally stretched, soft and microstructured fibers can face the tasks associated with integrating efficient and discrete feeding units in implants, wearable devices, and advanced textiles.

A novel fabrication process for a monolithic-structured solid-state dye sensitised solar cell (ssDSSC) on textile using all solution-based processes was performed using woven photovoltaic (P.V.) yarns. Liu et al. (2019). For this purpose, glass fiber textile was used as the target substrate for the printed ssDSSC that contain multiple layers of electrodes. The printed ssDSSC on textile have been successfully demonstrated and compared with a reference device made with the same processes on a glass substrate. This approach proved to be potentially suitable for the integration of photovoltaic devices in high-temperature, low-cost textiles. In addition to the range of applications, further research is needed to reduce the processing temperature to allow the device to be manufactured on standard fabric substrates. In another way, Zhang et al. (2016) reported DSSC textiles manufactured using polybutylene terephthalate (PBT) polymer yarns woven into different fabric structures. For this, a liquid electrolyte was used, and a PCE of 1.3% was achieved for a single fiber, which is the largest report so far for fiber-based DSSCs. This study represented a challenge in large area applications to connect a series of crossed cylindrical yarn solar cells that were woven into the textiles.

Printing techniques are established and simple processing techniques for adding functionality to any conventional (non-electronic) fabric and for making e-textiles. Three different printing techniques are compatible with conventional fabrics and e-textiles, i.e. screen printing, drop-casting and spray coating (Liu et al., 2019). Screen-printing is a common approach for standardising textiles with inks of different colours adhering to the yarn fiber and can withstand washing and friction (Liu et al., 2019). Drop moulding can be performed using dispensing equipment to deposit both an isolated drop and a continuous liquid film, automated in inkjet printing (Clancy et al., 2016). Spray coating is a mat coating process used in the textile industry to deposit continuous films on large areas of fabric (Liu et al., 2019). There is a trend regarding these techniques and an ongoing research task force to achieve the uniformity and consistency required for functional electronic devices over a large surface area on different textile surfaces.

Biofabrication techniques present an interesting intersection with textile structures from 3DP (3D printing) technologies, given the need to develop fibrous scaffolds that can allow for patient-specific geometries to facilitate the production of customised tissue structures (Cheng et al., 2016). 3D scaffolds provide a model that may further enhance cell attachment and tissue regeneration, which therefore requires a porous and interconnected network. This feature is seen in conventional woven textile structures as well (Ceretti et al., 2017). However, scaffolds made from soft biocompatible materials have the necessary geometry, mechanical stability, and anisotropic mechanical properties that are very valid for forming connective tissues (Jordahl et al., 2018). In addition to the biological applications, 3DP techniques for making heterogeneous/anisotropic structures may also be manipulated to design other multifaceted structures for single applications, such as biomimetic surfaces and multidirectional 3D preforms. (Jordahl et al., 2018). Still, 3DP is a rapidly evolving field of research, with massive challenges, but with enormous potential to transform modern medicine and healthcare, particularly in the tissue engineering domain and combined with other high-technologies for the textiles industry.

4. Bio-based medical textiles and their key applications (Section Heading)

The tissue engineering and regenerative medicine field is a multidisciplinary area that connects the principles of cellular biology, biomaterials and engineering to replace or repair damaged tissues by generating a space that allows cells to grow and proliferate (Bedian et al., 2017). Also, another aim has been the conception of whole new tissues and organs, which comprises the simulation or mimicry of the extracellular matrix (Bedian et al., 2017). In the engineering of functional tissues, constructs with controlled mechanical properties, microstructure, and cellular distribution play a critical role (Akbari et al., 2016). In this sense, bio textiles, or medical textiles, have great potential for tissue engineering and regenerative medicine applications. Biotextiles are fibrous fabrics with well-defined structures produced from synthetic or natural materials applied for the prevention, treatment and diagnosis of injury or disease (Chang et al., 2020). The versatility of textile structures allows adapting their architecture by monitoring the fiber size and orientation, porosity, and surface topography.

Moreover, it allows a high degree of reproducibility, and it is possible to scale the processes to the industrial level. Several applications of such structures have been explored with the emergence of textile technologies as biofabrication methods for producing biofabrics and tissue constructs (Akbari et al., 2016). The bio-based medical textiles have been mostly applied for wound dressings, cardiovascular and musculoskeletal tissue engineering, and wearable electronics. Recent studies have also reported the use of bio textiles for neural tissue engineering, engineering of bladder and for drug delivery applications (Akbari et al., 2016). Medical textiles are used as part of systems for *ex vivo* manipulation of media and cells, as biodurable or biodegradable components of implantable medical devices and for *in vitro* cell culture and testing (Chang et al., 2020). Hereafter, current advances in the manufacturing of bio textiles and their emerging applications for tissue engineering and regenerative medicine will be explored.

4.1. *Smart and responsive textile coatings* (Subsection Heading)

The traditional protective role of textiles has been passive, restricted to choosing the right material for certain physical conditions of the body and the environment, always to keep the user comfortable and healthy. In the last decade, this conception has been overcome with that of its increasingly wide application in the biomedical industry. For example, stimulus-sensitive textiles can offer a deformation force that can be applied in medical applications. Smart orthopaedic textiles can be applied in corrective aids. Stimulus sensitive textiles with volume and shape changes can also be used in skincare products with the controllable release of nutrients or medications.

In materials engineering, smart technology is creating a sea change today. Because no commonly accepted definition characterises smart materials, this situation leads to ambiguities in the classification of materials in this group. The term "smart" is also frequently used in parallel with others such as "reactive", "receptive", and "adaptive". Regardless of how the term is used, it generally refers to a material that reacts (response or changes) to defined influences (impulses or stimuli) from the local environment (exterior or interior) (Jocic, 2016). Therefore, smart textiles are generally defined as textile materials or products that can detect and interpret changes in their local environment and respond appropriately. (Baghdachi, 2009) When considering biomedical textiles, the term "local environment" encompasses environmental conditions (exterior) and bodily functions (interior).

Today, there is functional finishing technology, including smart coatings. This is considered a specific technology capable of providing an active regulation function to textile materials. A functional coating is a system that has the classic properties of a coating (that is, decoration and protection) and additional functionality that can be provided, for example, by thermal insulation, moisture management, repellent, antimicrobial or fire-retardant properties if it is considered only the textile aspect (Salaün, 2016). Therefore, a functional coating can be sensitive to environmental changes and can respond permanently to a stimulus. The functional finishing approach is possible because of the enormous growth of assistive technologies, mainly in the areas of surface modification techniques, stimulus-sensitive polymers, phase change materials (PCM), and shape memory polymers (SMP). By redesigning the surface of the textile material, operating at a microscopic level, a new textile material with high added value can be created, containing fibers that maintain advantageous conventional properties (e.g. mechanical strength, flexibility) but with advanced functionalities and the ability to environmental response implemented by smart coating. This approach allows producers to continue using conventional textile fibers and, by modifying a very thin surface layer of the material, create modern smart textiles that are expected to react and interact with a wide range of stimuli and situations (Salaün, 2016).

Thermosensitive polymers are widely studied and can be used in different applications, such as medical devices (Gandhi et al., 2015; Ward & Georgiou, 2011), sensors (Kunzelman et al., 2008), surgical adhesive (Lu et al., 2017), and in textiles. (De Smet & Vanneste, 2019) The largest group of heat-sensitive polymers are SMPs. SMPs show changes in mechanical and thermochemical properties along with glass transition temperature or melting point temperature (Hayashi et al., 1993). The switching temperature of the SMPs can be customised and can be set to body temperature. Superior processability, smooth mechanical properties, and high deformability make SMPs suitable for textile applications (Hu et al., 2012). In addition to reversible changes in mechanical properties, SMPs show reversible changes in moisture permeability below and above the glass transition temperature. SMPs, which have a glass transition temperature around human body temperature, are used in smart breathable liners: below body temperature, the coated fabric is less permeable to water vapour and retains body heat, above from body temperature, the water vapour permeability of the coated fabric increases and allows heat transfer. Therefore, smart breathable liners with SMP help keep body temperature constant (Hayashi et al., 1993; Hu et al., 2012). Poly (N-isopropyl acrylamide) (PNIPAm) exhibits a reversible change from hydrophilic to hydrophobic at the transition temperature. Above the transition temperature, the hydrogen bonds between water molecules and amide groups weaken, the water dissociates, and heat is absorbed (Jassal et al., 2006).

Textiles containing microcapsules can be considered the latest generation of smart textiles because they provide new properties and added value. It has its function depending on the type of microcapsules embedded within the fabric or fibers. Microencapsulated materials are commercially available from many companies (Van Parys, 2006) for various application areas to offer the potential for use in smart textiles. For example, applications include the use of PCM and cooling agents; delivery systems for cosmetic-textiles (including fragrance release, aromatherapy agents, skin moisturising or cooling agents, controlled release of vitamins or other agents absorbed through the skin, etc.), antimicrobials, biocides, and insect repellents; fire-retardant compounds (Boh & Knez, 2006). In addition, the microcapsules can be used as biosensors.

However, this field so wide and full of possibilities also faces the need for a deep design and study for each case. Stimulus sensitive materials can be implemented in textiles by finishing and coating; however, by incorporating materials that respond to stimuli into coatings, the response can be changed, weakened, or inhibited.

4.2. Natural antimicrobial textile dressings to manage healing and wound infection (Subsection Heading)

Skin is the largest organ in the human body which acts as a natural barrier, so have an important function against environmental aggressions. Nevertheless, skin can be damaged by external factors causing wounds (Li et al., 2020). Wound management is crucial to combat several complications that may arise during the healing process, including microbial infections. An ideal dressing should act as a barrier against microorganisms and afford a moist environment at the wound interface, eliminate additional exudates and allow the exchange of gas. Traditional dressings mostly include lint, cotton wool, gauzes and bandages with different degrees of absorbency (Farokhi et al., 2018). It is important to highlight that a warm and moist wound healing environment can promote microbial growth and consequently extend the inflammatory stage and cause infection. Thus, the development of textile dressings with desirable antimicrobial properties is important to prevent chronic wounds. Diversity of antimicrobial compounds has been used to inhibit the growth and spread of bacteria, such as antibiotics, metals, metals salts, among others. However, textile dressings incorporated with these antimicrobial agents have some drawbacks that constrain their application, including bacterial resistance, cytotoxicity, adverse effects and high costs (Li et al., 2020). Therefore, extensive research has been conducted on natural-based agents for skin tissue engineering due to their efficient and broad-spectrum antimicrobial properties. The design and creation of bioactive nanofibrous textiles through electrospinning has gained more attention because this is an effective, easy and cost-efficient method generating a diversity of polymeric 2D or 3D scaffolds for body tissue implantation (Croitoru et al., 2020). The electrospun nanofibrous textiles can act as a physical barrier that protects the wound from exogenous microorganisms or can also incorporate natural antimicrobials substances, such as chitosan, honey, or plant-derived compounds.

Chitosan, a natural polysaccharide derived from the deacetylation of chitin, has been widely used due to its biocompatibility, biodegradability and recognised antimicrobial action against several bacterial strains, yeasts and filamentous fungi (Farokhi et al., 2018). The antimicrobial activity is influenced by various features, such as the chitosan molecular weight, polymerisation degree, deacetylation degree and pH of the medium (Periolatto et al., 2017). There are different mechanisms suggested explaining the antimicrobial action of chitosan. The most accepted by the scientific community is the one that proposed that the electrostatic interactions occurring between the amine groups of glucosamines of chitosan (positively charged groups) and the surface components presented on the bacterial cell wall (negatively charged groups) affect the permeability of the cell wall and subsequently inhibit the microbial growth (Simões et al., 2018). Additionally, the mechanisms of wound healing using chitosan accelerate the production of collagen by fibroblast cells to ameliorate the tensile strength at the wound site (Farokhi et al., 2018). In this sense, Figueira et al. (2016) developed a polycaprolactone-hyaluronic acid/chitosan-zein electrospun bilayer nanofibrous membrane to be applied as a skin substitute. The top layer of the membrane had the function to protect against external threats, while the bottom layer comprised chitosan and zein loaded with salicylic acid had the role in conferring anti-inflammatory and antimicrobial activity. This bilayered electrospun membrane revealed inhibitory effects against *Staphyloccocus aureus* (99% of inhibition), in addition, exhibited cell migration, adhesion and proliferation of human fibroblast cells. Fang and collaborators (Fang et al., 2020) also produced a chitosan-vaseline gauze dressing that demonstrated bacterial inhibition efficacy against *S. aureus* and *Escherichia coli* while increased angiogenesis and enhanced microvascular density in murine models.

Honey is another interesting example of an antimicrobial compound combining anti-inflammatory effects that can also stimulate tissue repair and reduce pain (Farokhi et al., 2018). The antimicrobial action has been associated with its acidity (range of 3.4-6.1), low water content (< 20%) and presence of antimicrobial elements such as hydrogen peroxide and phenolic acids. Its acidic feature supports macrophages to eradicate bacteria and prevent microbial biofilm production. The low water content and high osmolarity offer an adverse environment for microorganism growth because water molecules are chemically linked to the sugar molecules. Ultimately, hydrogen peroxide is a crucial component because it can react with the cell wall, lipids, proteins and nucleic acids present in the bacteria inhibiting their growth (Negut et al., 2018; Simões et al., 2018). Nevertheless, in the presence of catalase, an enzyme that degrades the hydrogen peroxide, honey shows a diminished antimicrobial activity. So, only honey with certified activities is proposed to be applied in medical fields. Therein, manuka honey which is obtained from the manuka tree contains a non-peroxide component that is able to maintain antimicrobial activity in biological fluids (Negut et al., 2018; Simões et al., 2018). Therefore, honey is a well-known natural healing agent and has been reintroduced to modern clinical wound care. Nanofibers containing manuka honey produced by electrospinning showed antibacterial effects (*E. coli*, *S. aureus* and *P. aeruginosa*) and had the ability of wound repair on mice without causing any adverse effects (Yang et al., 2017). Honey incorporated into alginate/polyvinyl alcohol-based electrospun nanofibrous membranes showed the ability to control the overproduction of reactive oxygen species and also to inhibit *S. aureus* and *E. coli* being promising for wound dressing (Tang et al., 2019).

Plants have received attention as the main source of natural antimicrobials. Compounds extracted from different parts of plants have demonstrated antimicrobial properties, such as tannin, flavonoids and quinonoid but also alkaloids, saponins, terpenoids and phenolic compounds. (Periolatto et al., 2017). Curcumin is an example of a herbal polyphenolic compound extracted from *Curcuma longa* rhizome with potential wound-healing properties due to its anti-inflammatory, antibacterial and antioxidant potential. Oxidative stress is one reason for the slow wound healing process, so antioxidant therapy allows the eradication of reactive oxygen species, enhancing the healing process of chronic wounds (Alven et al., 2020). Thereby, electrospun nanofibers loaded with curcumin showed the capability to inhibit methicillin-resistant *S. aureus* and extended-spectrum β-lactamase bacteria. Simultaneously, *in vivo* wound healing experiments showed that nanofibers completely closed wounds of diabetic rats in 15 days, while the control only reduced the wound area by approximately 20% (Mohammadi et al., 2016).

Essential oils, also called volatile natural mixtures, may represent 5% of the plant dry matter and could be extracted from roots, rhizomes, leaves, bark, branches, flowers, fruits, and seeds (Baptista-Silva et al., 2020). Essential oils can protect a broad spectrum of microorganisms usually attributed to phenolic compounds. The quantity and the presence of these compounds in essential oils depend on the extraction procedure (hydrodistillation, dry distillation, steam distillation or mechanical cold pressing) and the sample source (Baptista-Silva et al., 2020; Negut et al., 2018). Essential oils can attack the lipids present on the cell wall of the bacteria and the phospholipids available in the cell membranes, inducing an increased permeability and consequently to cell lysis. Furthermore, essential oils can disturb the function of the cytoplasmic membrane by disrupting the passage of nutrients through the cell membrane (Simões et al., 2018). Therefore, the application of essential oils on medical textiles has increased in recent times, being suitable compounds for wound dressing applications due to their well-known antimicrobial, antioxidant, and anti-inflammatory properties. A bilayer electrospun asymmetric membrane loaded with thymol designed for wound healing applications showed suitable porosity, wettability, mechanical properties, and also *in vitro* biocompatibility. Furthermore, the incorporation of thymol into the bottom layer of the membrane improved antibacterial capability against *S. aureus* and *P. aeruginosa* (Miguel et al., 2019). Eugenol has also been used for therapeutic applications. An electrospun polycaprolactone/polyvinyl alcohol/chitosan fiber mat loaded with eugenol was investigated as a wound dressing. The release of eugenol was rapid in the first 8 h, which enhanced progressively over 120 h. These electrospun fiber mats also possessed inhibition effects for *S. aureus* and *P. aeruginosa*, without cytotoxicity for human dermal fibroblasts (Mouro et al., 2019). These findings also suggest the potential to use plant-derived compounds for preventing and treating microbial wound infections.

Skin injuries are a challenge for the design of textile dressings. Currently, the production of electrospun fibers has been considered suitable for the advance of the new class of functional dressings because of their capability to deliver bioactive substances, the high surface-area-to-volume ratio, porosity and bio-inspired architecture that mimic the dermal extracellular matrix. (Croitoru et al., 2020). However, despite the hopeful results obtained to support the production of electrospun dressings, there are still several challenges until they can be applied in practical healthcare. Soon, more attention should be focused on *in vivo* studies and clinical trials to appraise the impact and importance of natural antimicrobial electrospun dressings to prevent skin infections and to enhance the healing process of the wound. During the progress and development of these therapeutic fibers, regulatory and economic aspects need to be taken into consideration to use these natural antimicrobial textile dressings in healthcare.

4.3. *Medical textile materials with drug-releasing properties* (Subsection Heading)

Drug-releasing medical textiles have recently gained great attention in different applications due to their cost-effectiveness and unique physical and chemical properties. With various fiber production and textile fabrication technologies, fibrous constructs with the required properties for the target drug delivery systems can be designed and fabricated.

Drug-releasing fibers obtained from various raw materials vary extensively in terms of their chemistry and, therefore, performance characteristics. By considering the difference in intrinsic functionality and physiochemical properties of various materials, selecting the right material or polymer plays a crucial role in designing and developing releasing drug textiles. Natural, synthetic polymers and inorganic compounds can be spun into fibers and form drug-releasing textile for versatile biomedical applications with varying properties, including macromolecule–drug interaction, drug loading efficiency, and release profiles (King et al., 2013). Moreover, various fabrication methods, such as melt- or wet-spinning, can be used both in the laboratory or industrial scales. The fabrication method depends on not only the raw material and the final application but also the dimension and shape of the fibers, biocompatibility of the solvent, and the processing parameters (King et al., 2013; Sharifi et al., 2016). Drug-releasing medical textiles can be divided into three leading categories of filament fibers, woven, and nonwoven fabrics. Such textiles can be degradable or nondegradable based on the nature of the base polymer from which they are made. Among these three categories, nanofibers nonwovens have attracted more attention in recent years and have been extensively developed for various biomedical applications using different polymers.

Additionally, individual fibers produced in the form of continuous filaments have been of great interest too. Such fibers may contain the active bio-agents inside or chemically bond to their surface. Braided surgical suture for wound closure is an example of mono and multifilament fibers. Such continuous filaments are usually manufactured using two main techniques of melt spinning and wet spinning based on whether the polymer is spun in melt or solution state (Ellis & Chaudhuri, 2007; Gerhardt et al., 2013; Natu et al., 2011; Tuzlakoglu & Reis, 2009).

Typically, natural fibers have diameters ranging from 10 to 100 µm, and manufactured fibers could reach a similar diameter range using melt or wet spinning. However, using the electrospinning method, the size of produced fibers could decrease to the nanometer scale (Ratner et al., 2004). Nevertheless, electrospinning is considered a textile manufacturing technique rather than a fiber production method since nonwoven mats are the output products and have no single fibers. Ultimately, multicomponent spinning is an approach to combine two or several polymers in the spinning head using the techniques mentioned above, which enables us to obtain fibers with a wide range of biological and mechanical properties (Zhou & Gong, 2008).

Drug-releasing systems provide sustained delivery of drugs and other bioactive agents over a period from hours to months. Drug-releasing fibers are recently used for delivering different kinds of drugs, such as antibiotics, anti-inflammatory drugs, growth factors, anticancer drugs, proteins, DNA, gens, and vaccines (Tiwari et al., 2012). Various loading mechanisms are used to produce drug-releasing fibers depending on the parameters such as the type of drug, fiber production method, and the expected drug release profile. Mathematical models proposed to describe, quantify, and predict drug release kinetics can help to portray a better picture of the drug release profiles.

Bioactive agents could also be loaded into fibers both in pre-and post-fabrication stages. However, loading methods should be selected based on the parameters such as bioactive agent chemistry, optimal release profile, the technical complexity of the spinning process, and the final application to avoid undesired results, including low drug efficiency, degradation of the bioactive agents, poor mechanical properties, drug burst effect, and toxicity (Qin, 2015). For instance, the drug can be incorporated at the pre-spinning stage by mixing with a polymer solution or after spinning using methods such as coating and supercritical loading (Bölgen et al., 2007; Champeau et al., 2015; T. G. Kim et al., 2007). Coating (Yao et al., 2014), encapsulation (Painuly et al., 2019), hollow fiber filling (Cheung et al., 2018), ion exchange (Yuan et al., 2015), inclusion complex (Haji et al., 2015), direct conjugation (Yoo et al., 2009), hot-melt extrusion (Van Laarhoven et al., 2002), and supercritical impregnation (Champeau et al., 2015) are some important methods that have been used to load fibers with drugs through physical adsorption, entrapment, and covalent attachment of the drugs to the fibers (Davies, 2018).

Several methods are used to characterise drug-releasing textiles; however, the most common methods are those that determine the chemical functionality, biological activity, surface morphology, mechanical properties, durability and degradation, and drug loading and release kinetics. Infrared (I.R.) spectroscopy is widely used in identifying the chemical functionalities of fiber surfaces. Most chemical functionalities absorb infrared frequencies that correspond to their molecular vibrational frequencies. I.R. can detect most of the mobilised compounds on the textile surfaces. In addition, any changes to the surface morphology of the textiles can be detected by scanning electron microscopy (SEM) (Tao & Collier, 1994). The surface analysis can also give an idea about the durability and surface degradation, which indirectly refers to the release behaviour of the drug-releasing textiles (Ueland et al., 2017). For the degradation studies, simulated body fluids at physiological temperatures are used. Enzymes can be added to the testing medium to accelerate the degradation of the base textiles (Zambrano et al., 2021). Determining the biological activities of the medical textiles, especially, antibacterial properties are essential when antibiotics are incorporated. AATCC 100 and 147 are widely used in the antimicrobial assessment of textile fabrics. In addition, evaluation of the physical and mechanical properties of the drug-releasing systems is essential in order to determine their suitability for different applications (Kumbar et al., 2008). Finally, understanding the release behaviour of the drugs is crucial to satisfy the requirement of the final application.

Woven and nonwoven structures from a broad range of natural to synthetic polymers or a combination of them have been used in various biomedical applications, such as wound care, tissue engineering, and regenerative medicine, due to features such as a high surface area to volume ratio, porous structure, and surface modification and functionalisation.

Recently, scientists have produced functional fibrous structures with the possibility of sensing the physiological data of the tissue and the ability to control drug delivery profiles (Mostafalu et al., 2017). Nanoscale sensors can be embedded into the medical textiles to enable a programmable responsive drug delivery system to tune the release profile of the bioactive agent (Van Langenhove, 2015). The drug release can be triggered by environmental stimuli, such as pH (Tamayol et al., 2016), temperature (Song et al., 2011), and chemical reactions or external stimuli, such as the magnetic field (Najafabadi et al., 2014), electric field (Tamayol et al., 2017), and light (Abdalkarim et al., 2019). For example, various metals, including gold, silver, magnesium, and zinc, can be patterned with low-temperature radiofrequency sputtering on the nanofibrous meshes to apply thermal stimulation to elute antibiotics when needed.

4.4. *Textiles for tissue replacement and regeneration* (Subsection Heading)

One of the main foundations of tissue engineering would be to design and manufacture scaffolding with tissue-like properties. Among the various scaffolding methods, textile technology has proven its unique advantages in mimicking the properties of human tissue, such as hierarchical, anisotropic and tension stiffness properties (Jiang et al., 2021; Jiao et al., 2020). The essential components of textile technology, textile patterns affect the porosity, architecture and mechanical properties of textile-based scaffolds (Jiang et al., 2021). However, the potential of various textile patterns is yet to be exploited when making textile-based scaffolds, and the effect of different textile patterns on scaffolding properties has not been fully investigated. There are first considerations about the nature of the fibers. Natural fibers have been used for medical applications for as long as mankind has existed. The use of silk for suturing open wounds, for instance, was already established in ancient Egypt, and sutures are still the most critical surgical textile structures. Compared to metals and ceramics, which are mainly used in osteosynthesis and dentistry, and apart from wound care materials (wound dressings, sutures), the number of implanted textile, medical devices is relatively low and focuses on very few applications, mainly for tendons and ligaments, heart valves, hernia and blood vessel repair. Table 1 gives an overview.

Table 1. Major applications for implantable textile, medical devices

Application	Implant
Abdominal wall, hernia	Meshes, patches
Blood vessel	Tubular prostheses (woven, knitted, nonwoven), stents, stent-graft coatings
Dura	Patches (nonwoven)
Heart	Patches, occluder, suturing ring of valves
Osteosynthesis	Fiber reinforced devices, cords for fixation
Tendon/ligament	Reinforcement
Trachea, oesophagus	Prostheses

Source: (Doser & Planck, 2011)

The use of textiles as implants was encouraged by the development and gross production of synthetic polymers in the middle of the last century. For a long time, surgeons and medical device companies used polymers and devices, which were easily available from other consumer products and technical applications like polyester (polyethylenterephthalate, PET) and nylon (polyamide, P.A.) used in garments or polypropylene (P.P.) used in technical applications. Recent developments have sought to modify or, mainly in the case of resorbable polymers, synthesise new polymers with properties adjusted to the medical application or with better biocompatibility. These adjustments concern cellular adhesion (or non-adhesion), degradation profiles, functionality, and overall biocompatibility (Doser & Planck, 2011).

The most frequently used textile implants worldwide are hernia meshes; more than a million are implanted every year. Historically, openings were closed by suturing, and this is still a standard treatment. The 'tension-free repair' with meshes is a relatively new therapy, allowing a faster recovery. Most of the meshes are warp knitted, allowing some elasticity and allowing the mesh to be cut to the desired size. Expanded polytetrafluoroethylene (ePTFE) as a porous membrane or polyvinylidene fluoride (PVDF, DynaMesh®) are also used as mesh material/patch because they reduce adhesion, one of the possible complications in hernia reinforcement (Cobb et al., 2006).

The second most important textile device for implantation is the artificial blood vessel. These devices are mainly inserted into an existing artery. Degenerative changes of the vessel wall are prevalent, mainly resulting in arteriosclerosis. This results in thickening, the loss of elasticity and, finally, stenosis or even occlusion of the vessel. The most frequent cause is the stenosis of coronary arteries. For their bypass, natural arteries (mainly veins from the leg) are still the first choice. It is known that small diameter coronary prostheses (with diameters ≤ 6 mm) are not effective: the body's reaction to the foreign material will cause occlusion of the device in a very short time. Several strategies have been developed to overcome this, such as specific textile constructions (Moghe & Gupta, 2008), coatings of the device with very hydrophobic surfaces or coagulation-inhibiting substances, but these were not very successful in the coronary area. All the same, prostheses of hydrophobic PTFE are used in the periphery, e.g. as femoral bypass (e.g. Goretex® Stretch vascular graft or VascuGraft® PTFE from B. Braun).

On the other side, regenerative medicine is one of the most promising research areas in medical sciences: while today the function of damaged tissues or organs is recovered with artificial devices, the aim is that these tissues will be repaired in the future by inducing and/or guiding regenerative processes to restore or establish normal function (Jiao et al., 2020). The primary idea of using resorbable filaments as carriers to grow cells outside the body and to re-transplant them into the body was developed at the Massachusetts Institute of Technology (Langer & Vacanti, 1993; Mikos et al., 1993; Vacanti et al., 1988) and was called 'tissue engineering'. Despite concerted efforts worldwide within the last 25 years, which have applied the technology to nearly every organ or tissue, the outcome has so far been disappointing. The complex regulation of living tissue is well understood, and thus a major problem remains the integration and connection of the 'engineered' tissue into the existing environment in the body. Therefore, the approach was broadened under the term 'regenerative medicine'. Most of today's procedures try to guide regeneration inside the body rather than build up the whole tissue in the laboratory. For this approach, cells are not necessarily needed (Coenen et al., 2018; Ghazanfari et al., 2019). Depending on the tissue to be regenerated, biomaterials, cells and/or signalling molecules (mediators) might be used in different combinations. It is therefore difficult to define which therapeutic approach can be called regenerative medicine. Tissue engineering involves the utilisation of a biodegradable matrix, a so-called scaffold, sometimes loaded with pharmaceutical agents and/or cells in order to assist the 3D tissue development. (Ghazanfari et al., 2015, 2016) (figure 3).

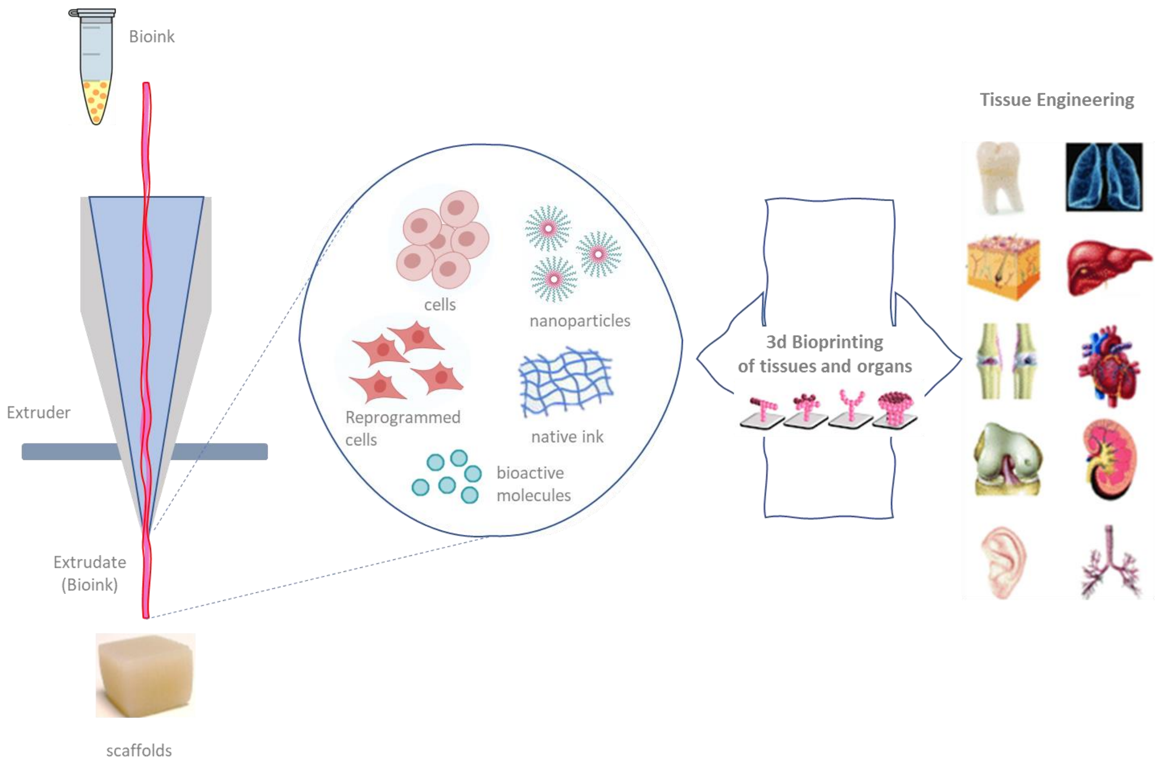

Figure 3. Modern 3D printed scaffold-based tissue engineering technique

The degradation time is ideally adjusted to the tissue/function: in cartilage repair, short times may be more appropriate, whereas in the bone, the biomaterials should last for more than six months, and in a liver support system, no degradation may be needed at all. Also of interest is the macro and microstructure of the material (Jiao et al., 2020). The porosity of the whole device can be crucial: in cartilage, a single cell in a pore can produce a matrix, whereas, in a bioartificial liver, the cells must have the ability to bind to one another strongly and to form clusters, which requires high porosity. Cells can be entrapped in large pores or on the surface of materials like membranes, fibers, or beads. Different technologies are available to form pores in scaffolds adjusted for tissue engineering (Mikos & Temenoff, 2000).

On the other hand, cells primarily recognise much smaller structures in the range of 1 µm or less. Furthermore, the physicochemical properties of the surfaces are also relevant. Most of the synthetic polymers used for fiber production are hydrophobic. In contrast, some cells may prefer hydrophilic surfaces because they do not bind directly to these materials but proteins adsorbed by the material (i.e. collagen on the material surface). These proteins might be modified or denatured by a strongly hydrophobic surface. Different strategies have been adopted to overcome these problems, e.g. by coating with hydrophilic components or even covalently binding signalling molecules of the matrix (Mikos & Temenoff, 2000).

It should be noted in this context that tissues are very dynamic. A hydrophilic surface allows a reversible attachment of matrices and cells, thus supporting normal tissue formation. Therefore, more natural materials are considered for tissue engineerings, such as protein-based (collagen, fibrin) or carbohydrate-based (alginate, chitosan, etc.) gels. The choice is mainly dependent on the intended tissue/organ. Therefore, for every application, a very specific material must be designed. In recent years special polymers have been developed, trying to meet the needs of the regenerating tissue.

Electrospun nonwovens have been well studied for regenerative medicine and tissue engineering applications since an ultrafine fibrous network with a high surface-to-volume ratio resembles the natural extracellular matrix. (Dias et al., 2020). Nonwoven fabrics with the capability to deliver bioactive components, such as antibiotics, growth factors, and chemotherapeutic agents, have proven to accelerate or inhibit certain activities during tissue regeneration and remodelling. Release of encapsulated bone morphogenetic proteins growth factor from electrospun composite scaffolds made of silk fibroin/ PEO or poly(d,l-lactide-co-glycolide)/hydroxyapatite (PLGA/HAp) accelerated osteogenesis and nerve regeneration processes. (Nie et al., 2008). Although electrospun constructs have been vastly used for tissue engineering applications, cell infiltration through the nanofiber is still the major limitation of this method due to their small pore sizes. Particle leaching and sacrificial nanofibers are the two proposed solutions to overcome this issue (Nam et al., 2007). Removing long molecular polymer chains of sacrificial fibers might be more difficult than the leaching particles, leading to better-interconnected pores between the fibers (Ifkovits et al., 2010).

Nonwoven wet-spun fibers from natural-based polymers, such as chitosan (Ucar et al., 2013; Yilgor et al., 2009), starch-based (Tuzlakoglu et al., 2010), and PLLA (Gao et al., 2007), have also been used for the fabrication of scaffolds. In a study, wet-spinning and electrospinning were used for preparing fibrous bioactive scaffolds to stimulate bone regeneration. The fibrous scaffold was made of a solution of biodegradable three-arm branched-star PCL, hydroxyapatite nanoparticles (HNPs), and clodronate (CDE), a bisphosphonate anti-inflammatory drug that has revealed effectiveness in the healing of different bone diseases, including osteoporosis and hyperparathyrosis. To introduce physical binding between CDE and HNP, CDE–HNP complex particles were developed to obtain better control over drug release and enhance osteoconductivity due to the presence of the inorganic phase. The collagen family of proteins plays important roles in forming tissues and organs and influences cell expression. (Gao et al., 2007) Strategies based on modulating crosslinking within the collagen matrices of worn-out or damaged tissues have received excellent results (McGann et al., 2015). Crosslinked collagen scaffolds (Camenzind et al., 2016; Suesca et al., 2017) have also been used in experimental regenerative medicine to promote regeneration/repair of diseased/damaged organs. In this sense and future advances, collagen can be a fiber structured in textile materials. However, evidence still does not prove its effectiveness or success.

Ribeiro et al. (2017) developed new three-dimensional (3D) bio textile architectures as a possible strategy for flat bone regeneration applications. The processing route showed to be fully automated, with the potential to be easily industrialised. Silk fibroin (S.F.) yarns were processed into weft knit fabrics spaced apart by a polyethene terephthalate (PET) monofilament. The structural adaptability of textile structures in synergy with the structural similarities of the 3D knitted spacer fabrics to craniofacial bone tissue, and the biological profile, turn these scaffolds into promising solutions for tissue engineering. In a different perspective, (Ribeiro, Almeida, et al., 2017) developed the knitting technology to produce fiber-based polybutylene succinate porous architectures is described. Different treatments were applied to functionalised the surface of the scaffolds developed: sodium hydroxide etching, ultraviolet radiation exposure in an ozone atmosphere and grafting (acrylic acid, vinyl phosphonic acid and vinyl sulphonic acid) after oxygen plasma activation to tailor cell adhesion. As a result, the hydroxide treatment altered most significantly the sodium surface properties, which in turn resulted in a high number of cells adherent to these surfaces and its potential for use in tissue applications. Almeida et al. (2013) described the use of two polymers, polybutylene succinate (PBS) proposed as a viable multifilament S.F., to produce fiber-based finely tuned porous architectures by weft knitting. In this case, PBS was proposed as a viable extruded fiber multifilament to be processed by a textile-based technology. The results showed that the developed systems could be attractive for the functional engineering of tissues, like skin, ligament, bone or cartilage. Magnan et al. (2020) produced a woven tissue-engineered vascular graft with burst pressure, suture retention strength and transmural permeability that surpassed clinical requirements. This novel strategy holds the promise of a new era of medical textiles, mechanically strong without foreign scaffolding and the ability to integrate into the body. These and other evidence proved potentially interesting nonwoven and woven structures (fabric, warp-knitted, braided, 3D-spaced, etc.). The relationship between the type of textile structure/porosity/final application is also very interesting and impacts the application of the final textile. Crucial issues are also related to modulating the type of fiber to influence cell adhesion: circular, hollow, trilobal, multilobal, pie, Island-in-the-sea fibers (Jiao et al., 2020; Magnan et al., 2020).

5. Emerging sustainable bio-based textiles industry (Section Heading)

Traditionally, the textile industry uses expensive and corrosive chemicals that pose a significant threat to environmental quality and public health. This is a resource-intensive sector that involves a very high dependence on fossil fuels, produces excessive greenhouse gas emissions, uses large amounts of water, and causes substantial water pollution and other burdens on the environment. This has generated serious concerns and has made it necessary to include sustainable, safer, and more environmentally friendly alternatives. Assessing the sustainability of a product should combine traditional concepts of a circular economy with a novel understanding of a circular economy going beyond waste treatment and enhanced recyclability to include holistic reuse and redesign of products. Consequently, biobased processing has created a new approach that uses biotechnological advances.

Lately, the textile industry has demanded a change in the sector as disruptive emerging start-ups are rapidly prototyping an increasing variety of textile replacement materials (Hildebrandt et al., 2021). Many of these materials are based on circular design strategies and bio-fabrication technologies and have been successfully introduced into consumer markets (Earley &

Goldsworthy, 2018; Wood, 2019). One of the main reasons for these substitution strategies and product innovation initiatives is the increasing political pressure on textile manufacturing to reduce impact. Some experimental start-ups, such as bio-inspired designers and eco-fashion companies, apply innovation processes. Thus, they offer a wide range of bio-based substitution options, circular strategies for sourcing secondary raw materials and agricultural residues, and novel manufacturing technologies. These can be introduced into the processing chain, not only for this type of more traditional approach but also for future biomedical applications. (Hildebrandt et al., 2021; Quijano, 2017; Wood, 2019)

An important component of the textile industry is fibers. As intermediate products, they are a common denominator for all subsequent products such as yarns, garments, and medical devices. In the fiber market, polyester fiber accounts for just over half of all annual global fiber production (Ivanović et al., 2021). In the textile industry, polyester conventionally refers to a fiber produced by melt-spinning amorphous polyethene terephthalate (PET) polymer, although polymer science groups many compounds, including PET, into polyesters. Therefore, it is a product of fossil origin, where all the structural carbon (C) comes from the raw material of fossil origin. Bio-sourcing is a solution, which supposedly influences all the environmental impacts. It is particularly relevant for polyester fiber due to the dominance of the fiber market. Bio-sourcing is based on the diversification of raw materials so that the so-called renewable or bio-based raw materials, such as crops (edible, first-generation) or lignocellulosic mass (inedible, second-generation), displace conventional inputs of fossil origin (Babu et al., 2013; Lambert & Wagner, 2017). In short, bio-sourcing is based on the idea that changing the origin of C in the molecular backbone results in a decrease in the environmental impacts of the product. The proportion of total carbon in the product that comes from the raw material of biological origin is expressed as % of the content of C of biological origin, which ranges from 0% of bioC (in the case of polyester of fossil origin) to 100% bioC (when polyester is produced entirely from the raw material of biological origin), with "partial biological basis" capturing everything in between. Due to the current lack of standardisation in the biobased field, both fully and partially biobased products are simply referred to as "bio-based". Furthermore, the European Commission (E.C.) particularly supports this strategy with its recent European Green Deal (European Commission, n.d.). Through these activities, the E.C. aims to stimulate the development of new markets for circular and climate-neutral products, especially in resource-intensive sectors such as textiles and plastics.

Following the aforementioned, polyester fibers could be largely replaced by three bio-based alternatives, taking into account the necessary functionalities of the fiber in different applications (Shen et al., 2010). Taking into account the technical substitution potential of total polyester put on the market, some references report that 65% of polyester can be substituted by bio-polyester, 20% by polytrimethylene terephthalate (PTT) fibers and 10% by polylactic acid (PLA) fibers (Shen et al., 2010). In the first case, an approach known as immediate replacement is applied (Ivanović et al., 2021). The substitute fiber is chemically identical to polyester, but the production chain has been redesigned to accommodate the bio-sourcing of the two underlying PET monomers. Second, PTT fiber is made from the homonymous polymer with favourable material properties replacing conventional polyester fiber. (Ivanović et al., 2021) The industry has known PTT fiber since 1941 as a fiber of fossil origin. However, it was only beginning to be considered when a biotech solution emerged to produce a bio-based version of this monomer because of its high original production cost. In its bio-based form, the PTT was reconsidered due to favourable economic factors, i.e., smart out-of-the-box. Finally, PLA fiber represents novel products, with a "dedicated" production path (Ivanović et al., 2021) and no fossil-based counterpart.

Besides, agricultural residues are another possible approach to promote the shift towards bio-sourcing for circular resource mobilisation strategies (Rana et al., 2014). An example of this includes pineapple leaf fibers from pineapple waste for fiber sourcing in the production of nonwovens. Another example is the use of lignocellulose residues, for example, straw and husks, for the cultivation of mycelium materials or the production of bio-based coating options based on lignocellulose-based polymers.

Now, it must not misunderstand the idea that bio-based products are immune to the use of fossil resources, as the approach refers only to the mass of the product without any other modification in the supply chain (e.g., energy production, transportation). Bio-sourcing is not without risk either. Competition between food supply and biomass production, overexploitation of natural resources, and biodiversity loss are just some of the possible unwanted effects of this strategy. (European Commission, n.d.) The main material and energy flow associated with bio-fabrication and textile manufacturing include the water footprint, the cumulative energy demand for drying, boiling, pressing, and confectioning the materials, and the upstream material and energy demands for supplementary materials. To reduce the need for these resources, progress has also been made in applying industrial biotechnology with enzymes as a more sustainable alternative. (Rahman et al., 2020) Enzymes offer a competitive advantage over chemicals with fewer resource requirements (energy and water), reduced emissions, and less waste. Due to their high specificity, enzymes produce minimal by-products. The implementation of enzymes in textile processing could offer environmental benefits and improve the public health and sustainability of traditional textiles and bio textiles.

As it was mentioned, different bio-based alternatives are being considered today. However, through life cycle assessment studies, it has been seen that current bio-based textiles are not competitive for the environment with conventional polyester (Ivanović et al., 2021). When European distance-to-target weights are applied, bio-based products are counterproductive in mitigating environmental impacts. From a strictly environmental perspective, moving to bio-based synthetics still requires further optimisation and improvements. If they remain predominantly "agricultural-based", their use as "green" substitutes for polyester and other traditional fibers lacks sustainability in some applications.

6. Future perspectives (Section Heading)

Multidisciplinary approaches are needed in the textiles industry to develop next-generation medical products cost-effectively and sustainably. Likewise, industry collaboration will become vital to advance this sector. Upon this, medical textiles have forwarded their usefulness over time as indispensable products for nurses and surgeons. All new technology applicable to textiles is crucial in contributing to the development of medical textiles. Moreover, the challenges are enormous. Combining classic technologies based on transformation polymers must be combined with cells and their living environments and, of course, with developments in electronics and textiles. Integrating all of them to meet regulatory requirements means a revolution in how human beings are monitored and treated. Soon, this will change the way how the health systems deliver their services since more preventive care will be based on data collected by wearables or implanted medical devices. In the meantime, major research efforts are needed and expected to fill the gaps.

7. Conclusion

Despite the numerous advantages offered by textile technology, there are still much to be explored to use this technology to its full potential in the medical field. The main obstacle to using bio textiles for tissue engineering and regenerative medicine is combining state-of-the-art textile machinery, new biomaterials and biological advances to create structurally advanced tissues, organs, and electronic textiles. There is an avenue of knowledge upon these promising products to be applied in the biomedical area.

8. Acknowledgements (Section Heading)

This work was supported by National Funds from Fundacão para a Ciência e a Tecnologia (FCT), through project UIDB/50016/2020. Sara Baptista-Silva gratefully acknowledges FCT for the grants (ref SFRH/BPD/116024/2016).

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