Journal of Textiles, Coloration and Polymer Science
https://jtcps.journals.ekb.eg/

Egyptian Society for Textile Science and Technology
الجمعية المصرية لعلوم وتكنولوجيا النسيج

Navigating Challenges and Seizing Opportunities on smart textile - A Review

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Abstract

The textile industry is undergoing a transformation focused on sustainability and efficiency. Innovations such as biodegradable fibers made from renewable sources like wood pulp and mycelium are promoting circularity by recycling materials and reducing waste. Textile-to-textile recycling is converting waste into new fibers, fostering a more sustainable fashion industry. Smart textiles equipped with sensors can monitor temperature and movement, enabling wearable technologies that provide real-time data. 3D knitting technology minimizes waste by producing seamless garments tailored to body contours. Advanced dyeing methods, such as CO_2-based techniques, are reducing water usage and harmful chemicals.
Incorporating antimicrobial agents enhances hygiene, while phase changes materials help regulate temperature for comfort. Self-healing textiles extend the lifespan of garments, making them ideal for workwear and outdoor apparel. These innovations are reshaping the textile industry and supporting global sustainability goals. This review explores the latest trends in textiles and the challenges they encounter in industrial and application sectors.

Keywords: Sustainability, Smart Textiles, Recycling.

Introduction

Textiles are set to play a crucial role in shaping the future of fashion, sustainability, and functionality as technology advances and consumer demands evolve.[1] The future of textiles is rooted in the integration of functionality, comfort, responsiveness, and sustainability. Recent innovations in smart fabrics are changing traditional materials into adaptive systems that not only respond to environmental stimuli but also improve the user experience while minimizing their ecological impact.[2] We are on the brink of a transformative era in textile science, driven by ten pioneering innovations that are reshaping the industry. These advancements include sustainable biomaterials, intelligent textiles, and regenerative manufacturing processes, all working together to create a more resilient and eco-friendly textile ecosystem.[3]

The textile industry is undergoing significant changes, propelled by innovations that prioritize sustainability, functionality, and efficiency. Advances in biotechnology have led to the creation of fibers made from renewable sources, such as wood pulp, agricultural waste, and mycelium. These fibers are biodegradable and can be integrated into circular textile systems.[4]

The industry is also embracing circularity by recycling and upcycling materials to produce new products, which minimizes waste and reduces resource consumption. Innovations in textile-to-textile recycling are allowing us to transform textile waste into new fibers, contributing to a more sustainable fashion industry.[5]

Smart textiles that incorporate conductive fibers and sensors can monitor various parameters such as temperature, humidity, and movement. These fabrics enable the development of wearable technologies that collect real-time data and interact with electronic devices. Advancements in electronic textiles (e-textiles) are paving the way for garments that can adapt to environmental changes and offer health monitoring capabilities.[6]

3D knitting technology allows for the creation of garments directly from digital designs, which reduces material waste and enhances production efficiency. This approach enables the manufacturing of seamless

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Received date: 16 June 2025, **Revise Date**: 30 June 2025, **Accept Date**: 01 July 2025
DOI: 10.21608/jtcps.2025.394991.1454

garments that fit precisely to body contours, improving comfort and reducing the need for additional finishing processes.[7]

The integration of antimicrobial agents, such as copper nanoparticles, into textiles enhances hygiene and durability. These fabrics inhibit the growth of bacteria and fungi, reducing odors and the need for frequent washing, which is especially beneficial in healthcare and activewear sectors. [8]

Phase change materials embedded in fabrics can absorb, store, and release heat, allowing garments to adapt to temperature fluctuations. This technology enhances wearer comfort by maintaining an optimal microclimate, making it ideal for activewear and outdoor apparel.[9]

Self-healing textiles incorporate materials that can repair themselves after damage, extending the lifespan of garments and reducing waste. These fabrics are particularly valuable in applications where durability is crucial, such as workwear and outerwear.[10 - 11]

In recent years, nanotechnology has become a promising approach for creating eco-friendly synthetic dyes , as innovative dyeing techniques address the environmental issues associated with traditional dyeing processes [12]. Traditional methods consume large amounts of water and release harmful chemicals into waterways. In contrast, new techniques like CO_2-based dyeing and air-dyeing methods aim to reduce these environmental impacts by eliminating the need for water and lowering energy consumption [13]. For example, CO_2 dyeing uses supercritical carbon dioxide as a solvent to transfer dyes into textile fibers, significantly decreasing water usage and chemical waste.[14]

These innovations are revolutionizing the textile industry while also supporting global sustainability goals. As these technologies advance, they have the power to reshape the future of fashion and textile manufacturing.

Research methodology: A review

1-Sustainable Bio- Based Textiles

Sustainable bio-based textiles are transforming the fabric industry by providing eco-friendly alternatives to traditional materials, derived from renewable resources such as plants, algae, and even fungi. These materials aren't only biodegradable but also reduce the carbon footprint associated with fabric production. For instance, organic cotton, hemp, and bamboo are becoming popular due to their minimal environmental impact during cultivation and processing.[15-16]

Bio-based textiles can originate from natural, semi-synthetic, and synthetic fibers[17] . They play a crucial role in reducing the reliance on virgin fossil-based synthetic materials, enhancing textile-to-textile recycling, and curbing overproduction. However, this presents challenges, as the production of synthetic textile fibers derived from fossil resources has surged in recent years, accounting for 67% of the global market in 2023.[18-19]

Globally, cotton ranks as the second most produced fiber. Other natural fibers, such as flax, hemp, and wool, are also significant, but their value chains tend to be fragmented, resulting in smaller production volumes and limited market presence. For flax and hemp, there are various opportunities for enhancement in areas like retting/degumming, spinning, fiber modification, and yarn treatment. To boost wool production and usage , it is vital to revitalize the collection and processing infrastructure.[20]

Semi-synthetic man-made cellulosic fibers are produced through the chemical transformation of cellulose and, after cotton, are the most prevalent type of bio-based fiber. Besides wood pulp , agricultural residues and wood cellulose also serve as key resources for the textile sector, as they can be sourced from both paper products and end-of-life textiles.[21]

Polylactic acid (PLA) is currently the sole synthetic bio-based polyester fiber on the textile market. While it is biodegradable, PLA tends to underperform compared to fossil-based polyesters, and its use often incurs higher costs. Other fully bio-based synthetic fibers are still in the early development stages. Creating bio-based synthetics necessitates dependable and sustainable sources of bio-based monomers, in addition to adequate and efficient production infrastructure and logistics. Addressing current knowledge gaps regarding the sustainability of bio-based synthetics is essential.[22-23]

Using bio-based textiles is supporting a cycle that prioritizes ecological balance. These fabrics often require less water and fewer pesticides compared to conventional counterparts, contributing to a healthier planet.[24]

2-Smart Fabrics with Sensors

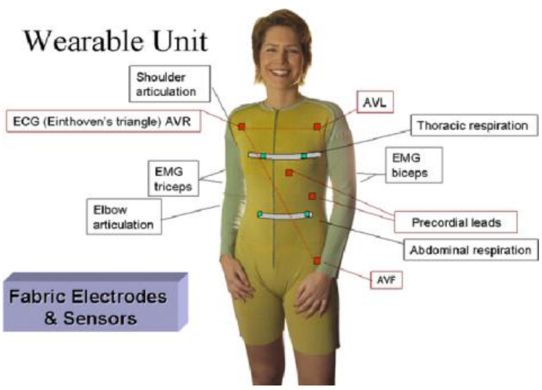
These fabrics are spearheading the movement for greater interactivity and responsive future. These innovative textiles integrate electronic components, allowing fabrics to sense and react to environmental stimuli.[25]

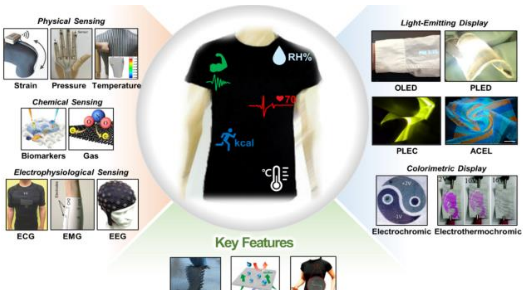
In numerous domains like healthcare and athletics, the collection of real-time data is essential. Take smart shirts, for instance; they come with sensors that monitor heart rate and other important health indicators, providing instant feedback to the user.[26]

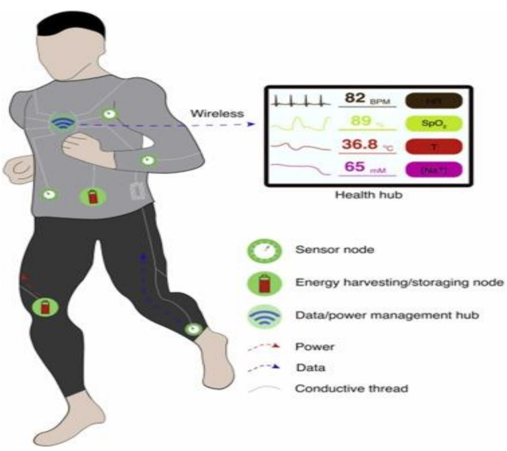
Smart textiles incorporate sensors directly into the fabric, allowing garments to monitor changes in temperature, pressure, and movement. These sensors are typically undetectable by touch, ensuring that the garment remains comfortable and flexible. This integration enables real-time tracking of physiological parameters, enhancing functionality without sacrificing wearability. Ongoing advancements in textile engineering are continually improving these technologies, making them more durable, washable, and better suited for everyday use.[27]

Sensors

Sensors play a crucial role in smart textiles by converting different stimuli into measurable signals that monitor physiological parameters. Advances in textile-based sensor technologies have led to the creation of garments that can track vital signs such as heart rate, respiration, movement, and moisture levels.[28]







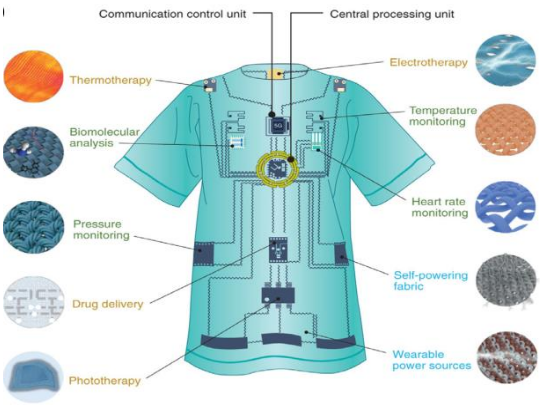


Figure (1) Smart Fabrics with Sensors

Table (1) : sensors and their applications

sensors	**Application**
Sound sensors	These sensors convert sound into electrical signals using piezoelectric materials.[29]
Chemical sensors	These sensors are designed to detect chemicals.
Light sensors	Devices that transform light energy into a voltage signal are known as photoresistors.
sensors of Temperature	A thermal sensor like a thermistor changes its resistance based on temperature shifts, enabling it to track thermal variations.
humidity Sensors	They assess absolute or relative humidity, which affects the dielectric properties of fabric when it is exposed to moisture.
Sensors of pressure	They convert pressure into an electrical signal by either opening or closing an electric circuit.
Strain sensors	They convert mechanical strain into an electrical signal. These sensors can be activated by semiconductor materials, strain sensing devices, or piezoelectric phenomena.
Biosensor	This sensor responds to changes in a patient's case, such as blood glucose level changes.[30]
Data processing	Data processing in SMART textiles is essential for active information analysis, requiring an effective processor to evaluate sensor data.

	While textile sensors gather extensive information, challenges for data processors include signal fluctuations, energy consumption, and the need for flexible, waterproof components in wearables.[31-32-33]

Essential Elements of Smart Textiles

Sensors: These devices measure changes in environmental conditions or physiological indicators, such as temperature and heart rate.[34]
Actuators: These components react to sensor inputs, which may include light-emitting diodes (LEDs) or heating elements.[35]
Data Processing Unit: This unit processes the information gathered by the sensors and manages the operation of the actuators.[36]
Interconnections: Conductive threads or fabrics serve to connect all the components together.
Communication Devices: These transmit data wirelessly to outside systems for further analysis.
Energy Components: These elements supply power to the system, often using batteries or methods for energy harvesting.

Challenges and Insights for Smart Textiles[37]

- Battery Size and Power Harvesting

Lithium polymer (Li-Po) batteries, commonly used in wearable electronics, are often criticized for their size, which can limit the design flexibility of garments. Their limited capacity and need for frequent recharging further hinder their practicality in continuous-use applications. To address these limitations, researchers are exploring power harvesting techniques, such as energy scavenging from body movements, thermal gradients, and ambient light, to supplement or replace traditional battery power sources. [38]

Washability and Non-Toxicity

Ensuring the durability and safety of wearable electronics is crucial. For instance, integrating electrical threads into garments requires protective coatings to withstand multiple wash cycles. Thermoplastic polyurethane (TPU) coatings have been shown to protect conductive threads for up to 50 washes, maintaining their functionality and safety . Additionally, the use of non-toxic materials is essential to prevent adverse skin reactions and ensure the long-term safety of users.[39-40]

Fiber Brittleness and Electrical Reliability

The integration of conductive fibers into textiles can lead to challenges such as brittleness and electrical reliability issues. The electric fields generated by these fibers can cause them to become fragile, increasing the risk of breakage. Furthermore, the narrow widths of these fibers, typically ranging from 100 to 250 micrometers, can exacerbate these issues, potentially compromising the overall performance of the smart textile.[41]

Component Encapsulation and E-Textile Lifespan

The longevity and functionality of e-textiles depend on effective encapsulation of electronic components. Techniques such as plastic threaded chip carriers (PTCC) allow for the integration of microelectronic components into fabrics, providing protection against environmental factors and mechanical stress. These encapsulated components, including microcontrollers, sensors, and capacitors, contribute to the overall durability and lifespan of the smart textile.[42]

Challenges with Fabric Sensor Capacitors

Fabric-based capacitive sensors face several challenges that can affect their performance. Issues such as creep, poor resilience, signal drift, and hysteresis can lead to inaccuracies in measurements. To mitigate these challenges, researchers are developing advanced insulating materials and compensation techniques to enhance the reliability and accuracy of fabric sensor capacitors. [41-43]

3- Waterless Dyeing Techniques

The textile sector is one of the largest consumers of water, using it extensively throughout all stages of chemical wet processing. The wastewater, which contains dyes, dispersing agents, and various chemicals, is typically treated before being released into water bodies[44]. A significant investment is required for the treatment of textile effluents prior to disposal. Water scarcity and environmental awareness are significant global issues, leading to higher costs for water intake and disposal. New legislation may threaten the stability of the textile industry. The chemical wet processing of textiles is increasing as older methods are replaced by innovative technologies. Although there have been efforts to reduce water consumption through recycling and reusing wastewater, water usage in the textile industry remains high.[45]

supercritical carbon dioxide

A significant advancement in sustainable textile processing is the adoption of waterless dyeing technologies, particularly those that utilize supercritical carbon dioxide ($scCO_2$). Traditional dyeing methods are known for their high water consumption and the production of toxic effluents, which create considerable environmental challenges. In contrast, $scCO_2$ dyeing provides a cleaner and more efficient alternative by eliminating the need for water and reducing the use of harmful chemicals.[46]

The first dyeing process using supercritical carbon dioxide was developed in Germany in 1994. However, creating the dyeing machine system proved to be too costly. Eventually, the developed dyeing machine became revolutionary.

Fundamentals of Supercritical Fluid Carbon Dioxide

Carbon dioxide (CO_2) and water serve as key eco-friendly solvents, although CO_2's solvent properties are not as well understood. In response to water shortages, methods utilizing supercritical carbon dioxide ($scCO_2$) for dyeing synthetic and certain natural fibers have been developed. $ScCO_2$ is non-flammable, environmentally sustainable, and offers a cost-effective alternative to traditional organic solvents, making it advantageous for textile dyeing processes.[47-48]

CO_2 is the most extensively researched gas in supercritical fluid dyeing. It is a chemically inert, affordable, and readily available resource. A liquid transitions into a supercritical fluid when subjected to increased temperature and pressure, Under these conditions, the distinction between liquid and gas phases fades, leading to a supercritical state.[49]

Table 2: Comparison of Old Dyeing and $ScCO_2$ Dyeing system

CONVENTIONAL DYEING	scCO2 DYEING SYSTEM
Huge amount of water is required for wet processing technology of textile material during processing	No water is required for wet processing technology of textile material during processing
High volumes of waste water with the residual dye and chemicals	No waste water at all. The dye remains as powder
High energy requirements	Only 20% energy requirement
Dyeing/washing, drying times is 3- 4	hours Only 15 -60 minutes are required for dyeing/washing

advantages of this $scCO_2$ system

- Contaminated wastewater streams are eliminated.
- No effluents are produced.
- Energy consumption for heating the dyeing liquor is low.
- Energy is preserved because drying processes are no longer required.
- There is no air pollution, as the carbon dioxide used is recycled and remains uncontaminated by the processes.
- Dyeing times are significantly shorter.
- The penetration of fibers occurs rapidly due to the absence of surface tension and the miscibility of air with carbon dioxide under pressure.
- Environmentally friendly formulations of dyestuff are used; no dispersants or adulterants are necessary.
- Chemicals such as leveling agents and pH regulators are not required.
- There is no need for auxiliary agents, disposal agents, or adulterants.
- For synthetic fabrics, a reduction clearing treatment is not necessary.
- The dyeing time is greatly reduced.
- Higher diffusion coefficients result in increased extraction or reaction rates.[50]

The most common issue with $scCO_2$ dyeing systems in commercial applications is the requirement for high pressures to dissolve dyes, coupled with the limited data available on dye solubility in $scCO_2$.

Finally, Supercritical dyeing using CO_2 is currently limited to synthetic fibers due to difficulties encountered with natural fibers, as $scCO_2$ has trouble breaking hydrogen bonds. The dyes suitable for natural fibers—such as reactive, direct, and acid dyes—are not soluble in $scCO_2$. There is a need for research focused on modifying fibers or creating new fixation techniques. One significant advantage of $scCO_2$ is its ability to conserve considerable amounts of water and energy, which is particularly important in water-scarce regions like China and India. However, to achieve commercial viability, issues related to equipment costs, maintenance, and dyeing of natural fibers must be resolved.[51]

Digital Printing Technique

Digital textile printing has emerged as a transformative force in the textile industry, providing sustainable alternatives to traditional printing methods. Unlike conventional techniques like screen printing, which are water-intensive and generate significant chemical waste, digital printing enables the direct application of designs onto fabrics from digital files. This approach significantly reduces water usage and chemical waste, contributing to a more eco-friendly production process.[52-53]

Over the last two decades, digital printing technology has reshaped the textile industry by offering sustainable solutions. It allows manufacturers to print directly from digital files onto fabrics, greatly minimizing water consumption and chemical waste. Key advancements, such as water-based and UV inks, along with high-definition print heads, have improved both print quality and versatility.[54-55]

One of the most significant advantages of digital printing is its water savings and production flexibility. However, challenges remain, including high initial costs and the need for specialized expertise, which can hinder widespread adoption. As consumer demand for eco-friendly and personalized products continue to grow, digital printing is expected to further promote sustainability and customization in the textile sector. Additionally, emerging technologies like 3D printing and artificial intelligence are poised to revolutionize the industry even further. Ultimately, this paper discusses how digital printing makes textiles more sustainable, flexible, and focused on consumer needs.[56]

Benefits of Digital Textile Printing

a- Environmental Friendliness: Digital textile printing is a more environmentally responsible option compared to traditional techniques. It consumes less water and produces less waste, and the use of water-based, non-toxic inks enhances its eco-conscious appeal.

b- Personalization: This method enables the straightforward creation of unique, tailored designs, which is particularly advantageous in the dynamic fashion sector. Designers can swiftly adjust to changing trends and produce limited-edition pieces that align with consumer desires.

c- Speed and Productivity: Digital printing greatly accelerates production timelines, reducing setup times from days or weeks to just a few hours. This increased efficiency allows manufacturers to quickly meet market demands while also lowering costs, especially for smaller production runs.[57-58]

Obstacles in digital textile printing

a-Significant Upfront Costs and Ongoing Expenses

Digital textile printing involves considerable initial investments, which include the cost of equipment, necessary infrastructure, and specialized software. This can pose a considerable challenge for smaller manufacturers when compared to traditional methods like screen printing. Additionally, recurring costs related to ink, maintenance, and technical support can intensify financial strain. Consequently, manufacturers must focus on optimizing production processes and reducing waste to stay economically viable.[52-53]

b- Need for Specialized Skills and Training

This process demands skilled operators who have a deep understanding of printing technology, materials, and ink properties. Proper calibration of machines is crucial to avoid issues such as color discrepancies. Ongoing training is essential to keep pace with technological advancements. Moreover, choosing appropriate inks is vital to prevent complications like color fading or inconsistent saturation, which complicates the process further.[59]

c-Environmental Effects and Ink Quality

It is generally less harmful to the circumference than old methods but has its own challenges. Solvent-based digital inks pose dangers during production and elimination, and the energy needed for high-resolution printing gives to a larger carbon footprint. While it uses less water and fewer risks chemicals, reliance on non-renewable energy sources can still harm the environment.[60]

d- Speed of Production and Volume Constraints

This printing provides customization but is slower than old mass-production ways. Any design is printed separately; it is less economical for large works, leading manufacturers to favor old printing for high-volume projects. [61]

4- 3D Knitting Technology

Textile fabrics created through diverse technologies incorporate innovative ideas for new products that can be applied in various fields. These fabrics are classified based on their dimensions:

One-dimensional materials, like filaments and synthetic fibers, have minimal length compared to other dimensions, while three-dimensional fabrics involve relationships along the x, y, and z axes.[62]

3D textiles, produced using different technologies outlined in Table 1, frequently employ knitting as a versatile method for fabric formation. Knitted fabrics are recognized for their ability to drape and stretch, making them suitable for form-fitting uses. They are produced by interlocking yarn loops in weft and warp directions, leading to examples such as multi-axial fabrics and those featuring 3D surface textures.[63]

3D Pattern Creation

The 3D surface effect is a method of transforming a flat textile surface into a textured one. This transformation occurs during the knitting process through various techniques, including the combination of raw materials, adjustments to process variables, modifications in the knitting cycle, and finishing techniques. Knitted fabrics with a 3D effect generally have a greater thickness compared to standard single yarn knitting. [64-65]

All types of flat knitting machines can be utilized to create 3D shapes; however, the range of patterns is limited in hand-operated knitting machines and significantly expanded in computerized flat knitting machines. These computerized machines facilitate rapid and straightforward pattern creation using a variety of techniques, Additionally, self-folding knitted fabrics can be produced through a transforming mechanism that employs knit and purl stitches, resulting in a distinct 3D effect on the fabric's surface.[66-67]

D Knitting brings notable time efficiency, which is a key benefit. By optimizing the production workflow and removing several steps, garments can be finished more rapidly, allowing brands to quickly respond to market needs. Moreover, labor costs are lowered due to the reduction of manual tasks involved.

Consequently, brands can offer high-quality, customized garments at competitive prices.

Integrating D Knitting technology into your manufacturing process also improves flexibility, enabling prompt adaptations to evolving trends. This versatility, combined with a smaller environmental footprint, establishes D Knitting as a game-changer in the textile industry.[68]

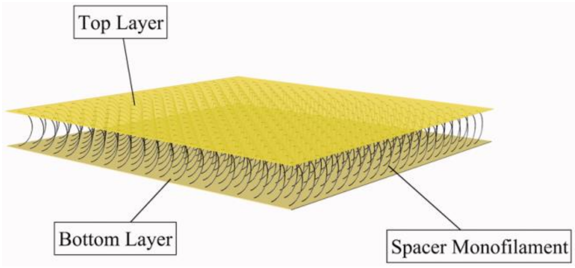


Figure (2): 3D knitting textiles

5-Recycled and Upcycled Fibers (waste minimization)

The demand for essential living commodities is rapidly increasing, leading to a focus on overproduction and resource utilization. The rising need for textiles and clothing is fueled by population growth and changing fashion habits, presenting a challenge for optimizing raw material use.[69 -70]

Textile production waste, an unavoidable by product, falls into three categories:

- Trashy waste: Requires cleaning before reprocessing (e.g., blow room waste, carding waste).
- Clean waste: Does not need further cleaning (e.g., comber waste, card waste).
- Hard waste : Requires special machines for processing (e.g., twisted roving, yarns, rags).

Historically, waste from spinning, weaving, and knitting was sold to waste spinners at low prices. To improve the quality of waste yarns and reduce breakage, blending with good materials was often necessary.[71]

Types of waste according to consuming

Pre-consumer Waste: this refer to materials that are thrown away before they are used by the consumers, often arising from manufacturing processes in the textile sector. This category includes mill remnants, scraps, and damaged products. These materials can be recycled or sold to third parties to be used in various sectors, including furniture and automotive manufacturing.

Postconsumer Waste: this waste includes items that consumers discard and after they have been used, such as towels , bed linens, and worn clothing. Recoverable postconsumer textiles encompass clothing, curtains, rags, and various household items.[72 -73]

production wastes

a) Spinning and Yarn Waste

Textile manufacturing generates various types of waste during the spinning process, each with distinct characteristics and potential for recycling:[74-75]

Opening Waste

Carding Waste

Sliver Waste

Roving Waste

Combed Noil

Bonda Soft Waste

Pneumafil Waste

Bonda Hard Waste

Ring Spinning Waste

Winding and Doubling Waste.[76]

b) Clothing Waste

Clothing waste encompasses various types of textile materials discarded during garment production and usage:

Knitting Waste: Includes fiber and yarn remnants from knitting processes, often due to machine faults or material issues.

Woven Waste: Fiber and yarn waste generated during weaving, such as broken threads or loom stoppages.

Cutting Waste: Excess fabric and trimmings discarded during the garment cutting process.[77-78-79]

c) Nonwovens waste

Thermally and chemically bonded, lightweight webs, needled webs, coated and uncoated .[80]

d) Carpet mill waste

Needle felt, tufted carpet, cut waste ,coated, and un coated.[79]

e) Used textiles

Old clothes

Advantages of Waste Recycling

Recycling waste provides numerous benefits for both companies and the environment, such as:

1- Lowering material procurement costs.

2- Enhancing profitability.

3- Reducing disposal and treatment expenses.

4- Lessening environmental impacts by decreasing the demand for new raw materials and facilitating the creation of products from recycled materials.

5- Textile recycling consumes less energy compared to other recycling methods.

6- Textile recycling does not generate new hazardous waste or harmful by-products.[81-82]

Operations for Converting Old Clothes into Fibers:

1. Remove dust.

2. Sort carefully.

3. Oil for softness and pliability.

4. Cut into specified strip dimensions.

5. Distribute strips on the feed lattice; high-speed spiked beater tears strips into fibers. Collected fibers go into a container, while unprocessed strips are sent for re-processing.[79]

Fiber Recycling Technologies

Various products can be created from reprocessed fiber. A significant portion of this fiber is spun again into new yarns or transformed into woven, knitted, or non-woven fabrics. These products encompass upholstery materials, composite biomaterials, garment linings, household goods, furniture upholstery, insulation materials, automobile soundproofing, vehicle carpeting, and even toys.[83-84]

Yarns from Recycled Fibres

Textile mill waste significantly impacts operating costs and profits. Recovered fibers can be blended with virgin fibers to produce yarns using various spinning methods. Quality standards limit the amount of recovered fibers; studies indicate that up to 20% can be blended with primary materials without compromising quality. Specifically, mixtures of 15% and 25% waste fibers in cotton maintain tenacity, irregularity, and elongation. These recovered fibers are clean enough for blending, allowing them to be woven or knitted, but they cannot fully replace virgin fibers. Researchers suggest particular formulations based on waste types and desired yarn characteristics. For instance, yarn made from 100% cotton waste (including various waste types) can produce a woven bed sheeting. Additionally, Dref yarns from recycled fibers show promise, but the resulting fabrics are economical, suitable for cleaning, wrapping, and covering cloths.[85-86-87]

Nonwovens from Recycled Fibres

Reclaimed fibres are often used in technical textiles, particularly nonwovens for mobility, agro-textiles, and geo-textiles. While they are chosen for cost-effectiveness or basic coverage, they can also incorporate high-value functional components. Examples include:

- High-quality woolen hair in nonwovens for vehicle seats.
- Aramid fibres for protection against cutting or impact.
- Microfiber materials for insulation or cleaning.

Geo-textiles are especially suitable for reclaiming fibres, necessitating careful selection of textile waste and precise tuning of processing parameters.[88-89]

Shoe insoles

Insulation Materials

Stuffed toys

Figure (3) : Method of Using recycled Fibers

Challenges of Recycling

Focusing on waste reduction purely for environmental benefits may not be enough, as the costs associated with collection and disposal aren't necessarily tied to the amount of waste produced or how well it's sorted.

- There are no strong financial incentives for waste producers to reduce their waste output.

- Factors such as low material value, expensive transportation, and weak market demand for recycled materials can hinder recycling initiatives.

- The prevalence of small and medium-sized recycling companies limits investment in advanced waste recovery technologies.[90]

<u>6- Self-Healing Fabrics</u>

Self-regenerating polymer compounds are effective in treating chronic skin wounds and have applications beyond textiles, including water-repellent coatings. Various materials like metals, plastics, and ceramics utilize self-healing mechanisms, such as the release of healing agents or reversible crosslinking. Techniques such as electrohydrodynamics and shape memory effects also play a role in self-healing strategies. Textiles with self-healing capabilities, whether woven or nonwoven, extend the life cycle of products and support sustainability efforts. This review examines the mechanisms behind self-healing and emphasizes its applications in textiles, while also exploring potential uses in non-textile fields like aerospace and protective clothing.[91-92]

classification of self healing fabrics

Self-healing materials can be classified into two types: intrinsic and extrinsic, along with autonomous and non-autonomous methods.[93]

a) Extrinsic self-healing materials are designed with a healing agent encapsulated within a polymer matrix. When damage occurs, this encapsulated healing agent is released, initiating the self-healing process.

b) Intrinsic self-healing materials, on the other hand, contain specific reversible chemical bonds that enable multiple healing processes to occur at the same location after damage. These bonds can include mechanisms such as the Diels-Alder reaction, radical-based systems, supramolecular interactions, ionic interactions, and metal-ligand interactions, among others.[94-95]

Table (3) : classification of self healing mechanism

Self healing	
Extrinsic	Intrinsic
Autonomous	Non - Autonomous
Hallow tube - microcapsule	Mimicry: chemical, mechanical, electrical ,light, heat and pressure

Applications of self-healing materials

Building on the operational principles outlined earlier, this section discusses the existing applications of self-healing textiles found in the market and ongoing research. These applications are categorized into industrial uses, with aerospace serving as a key example, and applications related to clothing manufacturing.[91]

clothing manufacturing

The clothing industry encompasses a variety of application areas. In addition to conventional fashion apparel, there are also specialized sectors such as protective clothing and workwear, which have already begun incorporating innovative solutions like self-healing textiles.[96-97]

protective clothing

The adoption of self-healing polymeric materials for protective clothing, such as armor for police, firefighters, and factory workers, is gaining popularity due to their durability. Incorporating self-healing elements like microcapsules in polymers can enhance textile longevity. For example, poly(ethylene-co-methacrylic acid) copolymers can repair immediately after ballistic impacts, while multifunctional superamphiphobic fabrics offer chemical resistance and self-cleaning features.[98]

workwear

Working in settings with chemical exposure, particularly in agriculture, presents significant health risks, particularly due to the handling of pesticides. It's crucial that protective clothing is both durable and resistant to hazards such as fabric tears. Researchers are exploring the use of self-healing composites for these protective garments, incorporating squid ring teeth protein and polyelectrolyte multilayer (PEM) films. This innovative combination provides elasticity, self-repair capabilities, and resistance to bacterial growth, which enhances protection against viruses and allows for self-regeneration.[99]

The self-healing process is triggered by water, enabling the material to regenerate as it dries. This technology can be applied to a variety of fabrics, ensuring worker safety in challenging conditions. Furthermore, high-performance gloves made from methylvinyl silicone rubber and hybrid molecules are being developed as part of ongoing research aimed at enhancing the healing properties of fabrics used in protective work clothing.[100]

The self-healing mechanism is activated by water, allowing regeneration when the material dries. This technology is adaptable to various fabrics, ensuring worker safety in harsh conditions. Additionally, high-performance gloves made from methylvinyl silicone rubber and hybrid molecules are being developed as part of ongoing research into improving fabric healing properties for protective work garments.[100-101-102]

fashion clothing

The fashion industry is a significant contributor to pollution, producing approximately 92 million tons of waste each year, largely driven by fast fashion practices that encourage the rapid disposal of clothing, often after just one season. Common reasons for throwing away clothes include holes and tears. To advance sustainable fashion, methods like Zero Waste focus on minimizing environmental impact and extending the lifespan of garments. One innovative solution is self-healing fabrics, such as the windbreaker introduced in 2017, which incorporates Nano Cure Tech (NCT). This lightweight, water-resistant nylon features a ripstop design, enabling it to resist tearing and self-repair when damaged. Simply rubbing the affected area restores the fabric, making it a practical choice for outdoor clothing and attractive to both consumers and apparel manufacturers.[103]

7- Antimicrobial fabrics

Antimicrobial textile solutions are designed to promote cleanliness and hygiene. These advanced fabrics are treated or created with substances that prevent the growth of bacteria, fungi, and other microorganisms. [104-105]

They are especially advantageous in settings where minimizing the risk of infection is crucial, such as in healthcare facilities. By inhibiting the accumulation of harmful microbes, these textiles enhance safety and comfort for users.[106-2]

Antimicrobial Finishing operation

The antimicrobial finishing process allows textile materials to prevent the growth or reproduction of specific microorganisms or to eliminate them [107]. A successful antimicrobial finish functions by disrupting microbial cell walls, changing membrane permeability, obstructing protein synthesis, or inhibiting the production of vital enzymes. Frequently used antimicrobial agents include silver, quaternary ammonium compounds (QAC), N-Halamines, triclosan, and polyhexamethylenebiguanide.[108-109]

Types of Antimicrobial Finishing

Antimicrobial finishes can be applied to textiles through either physical or chemical methods, which involve integrating functional agents into the fabric fibers. These finishes can be categorized into two main types: temporary and durable.[110]

Temporary finishes may wash out or diminish easily due to their weak bonding with the fibers. In contrast, durable finishes involve embedding the antimicrobial agent directly into the fibers during wet processing. This approach typically employs a controlled release mechanism, creating stronger bonds that effectively neutralize bacteria.[111]

Organic antimicrobial agents

Organic antimicrobial agents, including quaternary ammonium compounds (QACs), N-Halamines, Polyhexamethylene Biguanide (PHMB), and Triclosan, are used for antimicrobial treatments on textiles. QACs demonstrate strong antimicrobial activity on various fabrics, with minimum inhibitory concentration (MIC) values ranging between 10-100 mg/l. They work by altering cell membrane permeability and inhibiting protein synthesis in microbes. [112]

N-Halamines enhance the antimicrobial properties of cotton fabrics through a pad-dry-cure process that incorporates chlorine bleach, making them effective against both gram-positive and gram-negative pathogens. Triclosan is effective on polyester, nylon, and acrylic fibers, with an MIC value below 10 ppm; it inhibits lipid biosynthesis.

PHMB is widely accepted in healthcare and food industries due to its effectiveness against bacteria, yeasts, and fungi. It maintains good washing durability and has low toxicity. At concentrations of 1-10 mg/l, PHMB exhibits bacteriostatic properties, while higher concentrations demonstrate bactericidal activity.[113]

Inorganic antimicrobial agents

Such as metal oxides including silver, zinc, titanium, copper, magnesium, and gold, are used to enhance the antimicrobial properties of textiles. These agents demonstrate good durability across various materials, with a minimum inhibitory concentration (MIC) ranging from 0.05 to 0.1 mg/l against E. coli. Silver, in particular, is a well-known inorganic agent that kills microorganisms by disrupting intracellular proteins. However, it can be slightly toxic and may diminish over time when applied to fabric.[114]

Chabazite-type zeolites modified with combinations of silver, copper, and zinc ions have shown superior antimicrobial activity, especially against foodborne bacteria and fungi within a green polyethylene matrix. These materials have proven effective in controlling harmful pathogens in food processing and storage environments, making them promising candidates for hygiene applications.[115-116]

New trends in antimicrobial fabric healing

One of this trens is using plants extracts. The use of plant extracts for antimicrobial textiles is gaining attention, such as the Meliaceae family. Neem is noted for its effective antimicrobial properties, with both seed and bark extracts applied to cotton and cotton/polyester fabrics, as well as neem leaf extract nanoparticles. [117]

Aloe vera also shows antibacterial and antifungal potential for medical textiles, though research on Aloe vera-treated cotton fabrics is limited.[118]

Ginkgo biloba plant is recognized for its antimicrobial potential in healthcare textiles. Its standardized extract contains more than 5% ginkgolides and bilobalide, but cyto-toxicity concerns require careful formulation.

Also Nanotechnology has the potential to create coatings that fight infectious pathogens by working with materials at the nanoscale [119-120]. Research indicates that silver nanoparticles possess strong antimicrobial properties. For example, metals such as zinc, copper, and silver were added to a polymer approved by the FDA (polycaprolactone – PCL) to produce filaments through a hot melt extrusion process. Various wound dressing shapes were fabricated using filaments with differing metal concentrations. The antibacterial effectiveness of these dressings was assessed, showing significant results, especially with silver.[121-122]

8- Phase change material (PCMs)

Phase-change materials (PCMs) are transforming the textile industry with their advanced temperature regulation. They absorb, store, and release heat during the transition between solid and liquid states, helping to maintain a comfortable temperature based on the body's needs.[123-124]

Especially beneficial for outdoor clothing, PCMs reduce the need for multiple layers and enhance comfort. They also improve sleep quality in bedding by maintaining an ideal environment and support athletes in managing body temperature for optimal performance.[125]

Furthermore, PCMs contribute to energy efficiency by minimizing the reliance on artificial heating or cooling, making them a sustainable choice in textiles. Overall, PCMs drive innovation toward smarter and more responsive products in the textile industry.[124]

8-1- classification of (PCMs)

There are more than 500 recognized synthetic and natural phase change materials (PCMs) that vary in their heat storage abilities and melting points. Paraffin stands out as the most widely used PCM because it can be easily microencapsulated for use in textiles through either coating or incorporation into fibers. In the following sections, we will examine PCMs with phase transition temperatures that are near human skin temperature.[126]

Inorganic PCMs

Sodium sulfate, commonly known as Glauber's salt, is an effective inorganic phase change material (PCM) because of its advantageous chemical and physical properties. It has a melting temperature of 32.4 °C and a heat storage capacity of 254 J/g, making it suitable for textile applications. Additionally, it features high thermal conductivity, a significant volumetric storage capacity, and a lower cost.[127]

Organic PCMs

Table (4) kinds of phase change materials

Organic paraffin	Paraffin waxes, consisting of n-alkanes ($CH_3–(CH_2)_n–CH_3$), are (PCMs) contiaing carbon .These have energy storage due to their high latent heat storage capacity of 200 to 250 kJ/kg and thermal stability up to 250 °C. Noncorrosive, chemically inert, inexpensive, nontoxic, and ecologically safe, paraffin waxes are ideal for commercial heat storage applications.[128]
Polyethylene glycols	Composed of linear oxyethylene units (–O–CH_2–CH_2–) with hydroxyl (–OH) end groups. - Melting point increases with molecular weight. - Phase change temperatures determined by differential scanning calorimetry (DSC). - Soluble in water and organic solvents. - Key properties: suitable melting ranges, high heat of fusion, low vapor pressure, stability, biodegradability, nonflammability, noncorrosiveness, nontoxicity, affordability. - Suitable for thermal storage applications.[129]
Plant &animals based fatty acids	Fatty acids, derived from the hydrolysis of plant and animal fats and oils, are renewable resources that exhibit characteristics similar to synthetic paraffin waxes, which make them suitable for use as phase

	change materials (PCMs). They can endure numerous freezing and melting cycles without deteriorating and are non-toxic, chemically stable, and have favorable melting temperature ranges. Their outstanding thermal properties make them well-suited for energy-storing composites in building envelopes and solar energy systems. Furthermore, researchers are working on eutectic mixtures of fatty acids to improve phase transition temperatures and mitigate problems such as odor and corrosivity by esterifying them with alcohols, producing fatty acid esters.[130]
Polyalcohol	PCMs derived from alcohols and their derivatives are efficient for thermal regulation, transitioning through solid–solid phase changes from low-temperature monoclinic structures to high-temperature FCC crystals. They demonstrate minimal changes in volume, low erosion, no leakage, an extended lifespan, and prevent phase separation problems.**[**129**]**

PCMs Microencapsulation

During the melting and crystallization processes, phase change materials (PCMs) undergo transitions between liquid and solid states. To incorporate PCMs into textiles, it's essential to microencapsulate or nanoencapsulate them to prevent leakage and improve durability. Microencapsulation involves encasing the core material, with nanoencapsulated materials measuring less than 1 mm and microcapsules ranging from 1 to 1000 mm. There are several techniques available, such as complex coacervation, in-situ polymerization, interfacial polymerization, and spray drying. In-situ polymerization is particularly preferred for rapidly producing robust capsules. Microencapsulation techniques commonly include mechanical, physico-chemical, and chemical methods, all of which are based on the principle of enclosing and solidifying the core material.[131]

Researchers have investigated various materials for encapsulating shells to improve the thermal and shear stability of capsules and to protect the core phase change materials (PCMs). Polyurea shells are formed through interfacial polymerization, while shells made of styrene and PMMA (polymethyl methacrylate) can be produced using suspension or emulsion polymerization techniques. Microcapsule walls based on melamine derivatives are synthesized through in-situ polymerization. Recently, the Sol-Gel method has become popular for creating silica shells. Some of these chemical encapsulations are:

-Phase coacervation technique

-In-situ polymerization

-emulsion and solvent evaporation technique[132]

Conclusion

The future of textiles looks promising, as it is set to merge technology, sustainability, and functionality. By ushering in a future characterized by innovation, sustainability, and enhanced utility, smart fabrics are expected to revolutionize the textile industry. This review work studys most methods, challenges, and opportunities that define the textile industry's path toward a bright future. There are many possibilities, including smart textiles that effortlessly integrate technology into everyday life and fabrics infused with nanotechnology for improved quality.

Groundbreaking innovations expected in the coming years—such as smart textiles, sustainable materials, nanotechnology, 3D printing, advanced dyeing techniques, shape-memory fabrics, and biodegradable electronics—are set to influence the textile sector significantly.

However, this impressive advancement comes with its own set of challenges. A considerable investment in research and development is essential to pursue next-generation textiles, requiring a careful balance between cutting-edge technology and cost efficiency. Additionally, it's crucial to minimize the environmental impact of manufacturing processes while ensuring user safety regarding health and privacy. Despite these challenges, many opportunities lie within them. It holds the potential to transform various sectors, including fashion, healthcare, energy harvesting, and beyond. These fabrics promise enhanced performance, customized interactions, and sustainable solutions.

Conflict of Interest

There is no conflict of interest in the publication of this article.

Acknowledgment

The author thanks the Faculty of Applied Arts, Tant University.

Funds

There is no funding

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التغلب على التحديات واغتنام الفرص في مجال المنسوجات الذكية – مراجعة

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الخلاصة

تشهد صناعة النسيج تحولاً يركز على الاستدامة والكفاءة. تعمل الابتكارات مثل الألياف القابلة للتحلل المصنوعة من مصادر متجددة مثل لب الخشب والأفطورة على تعزيز التدوير من خلال إعادة تدوير المواد وتقليل النفايات. تعمل إعادة التدوير من نسيج إلى نسيج على تحويل النفايات إلى ألياف جديدة، مما يعزز صناعة أزياء أكثر استدامة.

يمكن للمنسوجات الذكية المجهزة بأجهزة استشعار مراقبة درجة الحرارة والحركة، مما يتيح تقنيات يمكن ارتداؤها توفر بيانات في الوقت الفعلي. تعمل تقنية الحياكة ثلاثية الأبعاد على تقليل النفايات من خلال إنتاج ملابس سلسة مصممة خصيصًا لتناسب محيط الجسم. تعمل طرق الصباغة المتقدمة، مثل التقنيات المعتمدة على ثاني أكسيد الكربون، على تقليل استخدام المياه والمواد الكيميائية الضارة.

يعمل دمج العوامل المضادة للميكروبات على تعزيز النظافة، بينما تساعد المواد المتغيرة الطور على تنظيم درجة الحرارة لتوفير الراحة. تعمل المنسوجات ذاتية الإصلاح على إطالة عمر الملابس، مما يجعلها مثالية لملابس العمل والملابس الخارجية. تعمل هذه الابتكارات على إعادة تشكيل صناعة النسيج ودعم أهداف الاستدامة العالمية.

الكلمات المفتاحية: الاستدامة، المنسوجات الذكية ، اعادة التدوير.