

Review

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A Brief Review of 3D Printing Technologies and Materials Used in Smart Textiles

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Review

A Brief Review of 3D Printing Technologies and Materials Used in Smart Textiles

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Abstract: 3D printing technology has made significant strides in smart textiles—fabrics embedded with electronics like conductive fibers and sensors—now widely applied in areas such as health condition monitoring, wearable energy-harvesting devices, and interactive textiles that respond to environmental conditions and color changes. Different 3D printing methods, such as Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Direct Ink Writing (DIW), and PolyJet printing, are used in the fabrication of smart textiles. This study provides a detailed, application-specific overview of 3D printing technologies—such as FDM, SLS, DIW, and PolyJet printing—and their use in smart textiles across various sectors, including wearable technology, medical textiles, and smart fashion design. We gathered articles and reports from Scopus and Google Scholar, providing a concise assessment of 3D printing materials for smart textiles to give readers a quick understanding of the field. The timeline of 3D printing's use in smart textiles, from 2016 to 2023, highlights significant advancements in various additive manufacturing techniques applied to smart textiles. The review emphasizes the importance of understanding 3D printing techniques such as FDM, SLS, DIW, and PolyJet, as their applicability for selecting the best approach to incorporating advanced functionalities into smart textiles.

Keywords: 3D printing; fabric surface; fused deposition modeling; smart textiles; wearable sensors

1. Introduction

1.1. Background

The rapidly developing area of additive manufacturing, usually known as 3D printing, encompasses a wide range of applications, including aerospace, automotive, biomedical, construction, and textiles [1,2]. The evolution of 3D-printed fashion shows is well-known among designers as the future of fashion, a trend that gained significant momentum in 2011 when Iris van Herpen's 3D-printed dress debuted at Paris Haute Couture Fashion Week and was later recognized by Time magazine as one of the best inventions [3]. This dress, created by scanning the wearer's body for individualized customization, attracted considerable attention for its unique characteristics. In 2014, the "Ice Dress," a transparent resin creation featuring intricate 3D-printed materials, was showcased exclusively on the catwalk [4]. For the 2015 Chanel Haute Couture Show, Karl Lagerfeld utilized SLS printing to develop innovative mesh designs on fabric. At the 2016 Met Ball, Claire Danes' Zac Posen gown created a stunning visual effect in the dark through the use of cutting-edge lighting. In the same year, Paris introduced water-soluble clothing that disintegrated to reveal new styles. In 2019, glow-in-the-dark fashion technologies made a splash with Richard Nicoll's dress at his London show and Zendaya's fairy dress at the Met Gala, both of which stood out as leading innovations due to their unique formability and artistic expression. From the past decade, 3D printing

has expanded large acceptance in the realm of smart textiles, inspiring increased interest among academics and industry professionals in recent years [5]. Takagi introduced the concept of smart materials in 1990 as those that respond to environmental changes optimally. Smart materials began in Japan in 1989 with shape memory silk yarn, and by the early 2000s, the first textile electronic components were produced [6]. Smart textiles, or intelligent textiles, are fabrics embedded with electronics like conductive fibers and sensors that detect and respond to stimuli from the human body, such as thermal, chemical, and biological changes, creating wearable clothing that monitors temperature, tracks health condition monitoring, and enhances interaction with the environment [7–10]. In healthcare, fashion, entertainment, and defense, smart textiles hold significant potential to enhance conventional materials, with comfort being crucial for consumer adoption [11].

3D printing technology merges traditional textile techniques with innovative production methods, enhancing the industry's versatility and enabling precise, customizable designs through computer-aided design (CAD), while also offering complex designs at a lower cost, often unattainable with conventional production processes. Smart textile devices necessitate a multidisciplinary approach to circuit design in the development of intelligent textiles integrating knowledge of intelligent materials, microelectronics, and chemistry with a profound understanding of textile manufacturing to get optimal outcomes. Figure 1 illustrates how 3D-printed smart textiles, embedded with integrated sensors, provide a sophisticated solution for the continuous monitoring of various health conditions in the human body. They fulfill various roles in technical textiles—such as thermal insulation, safety, and energy storage—as well as in security applications like identification and monitoring, and aesthetic features such as color changes and light emission [12]. Nowadays, several 3D printing methods are leveraged in the production of customized smart textiles, including FDM, SLS, DIW, and PolyJet printing [13,14]. Different materials used in 3D printing for smart textiles require specific attributes depending on the application of the final product. Various polymers are employed in 3D printing, each with distinct characteristics and purposes. Polylactic acid (PLA) is a popular choice due to its wide range of colors, designs, and biodegradability [15]. PLA composites produced through FDM-based 3D printing are versatile, with applications in bioprinting, sensor development, four-dimensional (4D) printing, smart textiles, and luminescence technologies [16]. TPU-based flexible conductive filaments enable direct 3D printing onto textiles for electronic textile applications, offering flexibility that allows the printed material to bend and flex with the fabric [17]. Acrylonitrile butadiene styrene (ABS) is well-suited for durable applications [18], while thermoplastic elastomers (TPE), TPU, and thermoplastic copolyester (TPC) are known for their high durability and flexibility [19]. Nylon is commonly used for applications that demand long-lasting parts, such as tools, functional prototypes, or mechanical components [20]. Smart materials like shape memory alloys (SMA), ferrofluid, magnetorheological fluids, electroactive polymers (EAPs), piezoelectric materials, and chromogenic materials are also integrated into 3D printing [21]. Resins, colloids, filament/paste, powder, and solid sheets are the primary materials for 3D printing. The technical requirements of the embroidery machine influence the choice of cord and ground fabric. Materials such as conductivity threads that are active metal wires, layered polymers, and carbon fibers are often employed [22]. Conductive threads, in particular, are valuable for creating circuits for sensors, actuators, heating elements, sound transmission, or LED contact points.

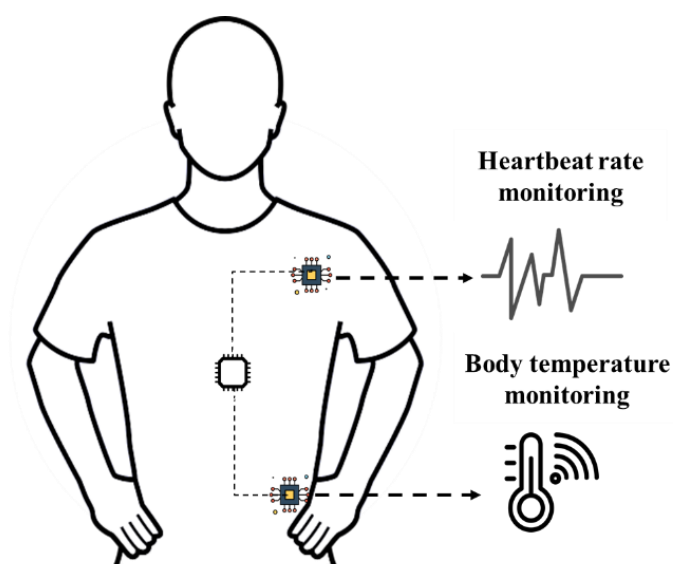


Figure 1. 3D- printed smart textiles with integrated sensors for monitoring human health conditions.

1.2. Method

In recent years, 3D-printed smart textiles have attracted substantial research attention, as reflected in the growing number of publications on the topic. We conducted an extensive literature review, collecting relevant articles and reports from reputable databases like Scopus and Google Scholar. This study provides a well-organized and concise assessment of the materials used in 3D printing for smart textiles, ranging from polymers to conductive and flexible materials. By analyzing the latest developments and trends, we offer readers a comprehensive yet accessible understanding of the key materials driving innovation in wearable technology, medical textiles, and smart fashion design, helping to bridge the gap between emerging research and practical applications in the field. **Figure 2** illustrates the number of scientific papers published between 2016 and 2023 on 3D-printed smart textiles utilizing FDM, SLS, DIW, and PolyJet printing technologies. Although 3D printing has gained significant popularity in advanced manufacturing, its applications in smart textiles remain relatively underdeveloped. Amongst different 3D printing methods, FDM has emerged as the dominant technology due to its flexibility in design for smart textile applications. The technical overview of this paper is divided into two main sections:

- First, this review study examines the diverse applications of 3D printing in smart textiles, providing a detailed analysis of the materials used across various sectors, including wearable technology, medical textiles, and smart fashion design.
- Second, this review paper presents a summary that consolidates this information, offering readers a clear and concise overview of the materials used in 3D printing for smart textiles across these domains, facilitating a quick yet comprehensive understanding of the field.

The technical innovation of smart textiles from specialized wearable technology and fashion design has sparked a surge in research on 3D-printed smart textiles. As technology advances, integrating 3D printing with smart textiles is being explored to enhance functionality, customization, and performance, driving innovation in the field. The rest of the paper is managed as follows: Section 2 provides a thorough literature review, exploring various 3D printing technologies, their applications in smart textiles, and the materials involved. Section 2.5 summarizes the key insights from Sections 2.1 to 2.4 and section 3 discusses the technical challenges associated with adopting 3D printing in smart textiles. Finally, Section 3 concludes the paper, offering potential outlooks on materials and applications in the context of environmental sustainability.

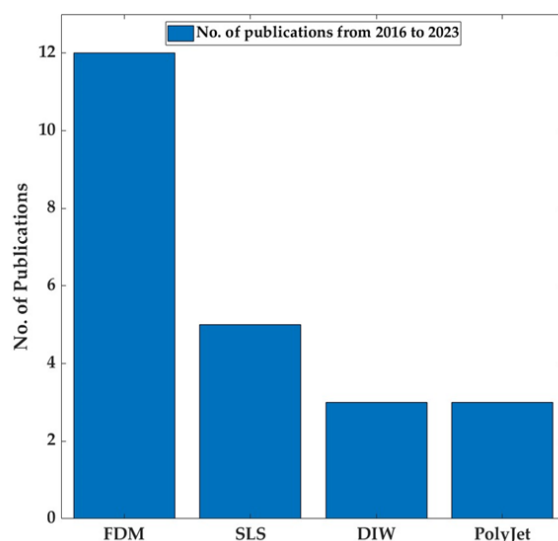


Figure 2. Application specific publications on 3D-printed smart textiles have explored various printing techniques, including FDM, SLS, DIW, and PolyJet printing.

2. Application of 3D Printing in Smart Textiles

This section discusses the significant technical innovations emerging from the intersection of smart textiles, wearable technology, and fashion design. These innovations have catalyzed a wave of research focused on the expansion of 3D-printed smart textiles. As advancements in technology continue, the incorporation of 3D printing into smart textile manufacturing is gaining momentum. Researchers are investigating how this combination can elevate functionality, offer greater customization, and improve performance across various applications, making it a key area for future breakthroughs in textile and wearable technologies. The timeline of 3D printing's involvement in smart textiles extends from 2016 to 2023, showcasing significant advancements in the application of various additive manufacturing techniques. These techniques include FDM, SLS, DIW, and PolyJet printing, discussed in detail in Sections 2.1, 2.2, 2.3, and 2.4, respectively. Section 2.5 offers a comprehensive summary of these methods, focusing on the materials used and their specific applications in smart textiles.

2.1. Fused Filament Fabrication

Fused Filament Fabrication (FFF), also known as FDM, is a widely used 3D printing method that creates objects by depositing molten thermoplastic filaments layer by layer, based on a CAD design, and has many applications in textiles [23,24]. The FDM process uses thermoplastic filaments, such as ABS, nylon, and PLA, to construct objects by melting and solidifying the material [25]. For smart textiles, TPU is the most commonly used material, while ABS is known for its durability, PLA for its biodegradability, polyethylene terephthalate glycol (PETG) for its strength and flexibility, and carbon fiber-reinforced polyamide for its strength and thermal stability [23,26,27]. The chronological use of the FDM method in smart textile applications is illustrated in the following sections, covering the period from 2016 to 2023. This overview highlights key advancements in FDM technology within the smart textile industry, showcasing its evolving applications in areas such as wearable electronics, medical textiles, and fashion.

2016: Morehead et al. [28] utilized a handcrafted, soft-stretchable wearable smart sensor made from dielectric electroactive polymer (DEAP) material, embedded in fabric, for monitoring deep breathing in humans. They concluded that FDM is effective for flexible design and highlighted the increasing importance of biomimetic approaches in developing products that are both aesthetically pleasing and functional. [Figure 3](#) illustrates two key processes: (a) the meticulous crafting of custom sensors, showcasing the intricate design and construction techniques employed to tailor the sensors to specific applications, and (b) the precise positioning of these sensors on the human body,

demonstrating their strategic placement for optimal performance and data collection. Gowthaman et al. [29] proposed a CAD model for piezoelectric energy-harvesting fabric and developed an FDM-printed model of smart fabrics for energy harvesting. Grimmelsmann et al. [30] used FDM and Protopasta® Conductive PLA to create conductive pathways, integrating electronic components directly onto textile substrates, enhancing their functionality as smart textiles.

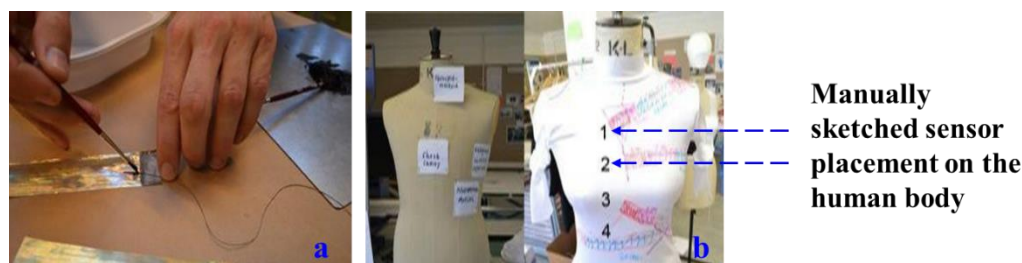


Figure 3. (a) Crafting custom sensors and (b) positioning them on the human body. (reproduced with permission) [28].

2017: Leist et al. [31] investigated the FDM process with PLA material and explored combining PLA with nylon fabric to make smart textiles. PLA displays thermal shape memory behavior, which is preserved when merged with nylon fabric, allowing it to be trained into temporary shapes that revert to their original forms when heated. This research accelerates the development of 3D-printed materials for smart textiles. Ly and Kim demonstrated the FDM printing process and examined how different printing parameters affect the performance of polyurethane-based thermal-responsive shape memory polymers (SMPs). The printed samples exhibited the expected SMP recovery characteristics, and the simple filament production process provides a practical and adaptable method for FDM printing. This process supports broader SMP applications and global interest and can be scaled for low-cost, mass production with advancements in FDM printing [32].

2019: Eutonnat-Diffo et al. [33] studied smart textiles using the FDM process, presenting models for improving adhesion of FDM-printed PLA layers on polyethylene terephthalate (PET) textiles. They printed both plain and twill weave fabric patterns, and their findings highlight the significant potential of FDM printing for smart textiles, with optimizable adhesion properties based on textile characteristics. Similar to the previous work, Eutonnat-Diffo et al. [34] also investigated the stress, strain, and deformation performance of FDM-printed fabrics, further advancing the development of smart textiles.

2020: Wear resistance of conductive PLA monofilament FDM printed onto PET plain and twill weave fabrics is crucial for developing smart textiles that maintain their mechanical and electrical properties, particularly the electrical conductivity of 3D printed conductive polymers on textiles [35]. Nguyen and Kim studied polyurethane shape memory polymers (SMP) for wearable smart textile products. One method involved mixing conductive single-walled carbon nanotubes (SWCNTs) into the SMP, while the other simultaneously printed SMP and a conductive material, with heating via electric current. SMP pellets were processed for both methods to fabricate SMP and SMP/m-SWCNT arrays using an extrusion system, which were then used in FDM to produce samples for comparison. The study evaluates the materials, structures, procedures, and efficiency of each method to identify the best approach for wearable products [36]. Hofmann et al. [37] used melt processing and Fused Filament Fabrication (FFF) to integrate PEDOT (3,4-ethylenedioxythiophene) by integrating Nafion fibers into organic electrochemical transistors (OECTs). These fibers maintained high conductivity under strain, while FFF enabled the precise creation of complex structures, showcasing potential applications in energy harvesting and smart textiles. Eutonnat-Diffo et al. [7] developed conductive, flexible monofilaments for smart textiles using FDM technology. They employed a biphasic blend of low-density polyethylene (LDPE) and propylene-based elastomer (PBE), incorporating carbon nanotubes (CNT) and Ketjenblack (KB) to improve stress, strain, rupture strength, and flexibility.

2021: Ertuna et al. [38] conducted studies on integrating solar panels into textile materials by embedding them within 3D-printed structures created using the FDM method, utilizing materials

from vests and bags to facilitate the charging of electronic devices with photovoltaic energy, thereby paving the way for the wearable smart textile industry. Figure 4 illustrates a vest embedded with 3D filaments designed to generate photovoltaic energy.

2022: Yang et al. [39] introduced a scalable FDM printing method for creating flexible, durable phase-change nonwoven fabric (PCNF). The fabric has breathable pores and a uniform structure, with single wall nano tubes (SWNTs) embedded in hydrophobic filaments. This work offers key insights for producing multifunctional, stable wearable phase-change fabrics, advancing smart textiles.



Figure 4. Vest with 3D filaments that can make photovoltaic energy (reproduced with permission) [38].

2.2. Selective Laser Sintering (SLS)

SLS is an additive manufacturing method that fuses tiny particles of powdered polymer into solid 3D objects using one or more lasers [40]. The typical components of an SLS printing system include a sintering platform, powder supply platform, roller, scanning system, and laser. The process begins with a thin layer of powder being spread onto the build platform. The powder is then heated to just below its melting point [41]. Various binding mechanisms, such as chemically induced binding, full melting, solid-state sintering, and phase sintering, can be used to fuse the powder particles together [42]. The laser selectively fuses the particles by scanning across the bed according to the cross-section of the item being produced. After each layer is scanned, the build surface is lowered, and another layer of powder is applied. This layering process continues until the final product is complete [40]. Figure 5 showcases a petal dress created by the Nervous System studio using SLS technology, featuring over 1,600 unique components connected by more than 2,600 hinges. This dress was engineered to fit the exact shape of the wearer's body using a 3D scan and could be worn as a dress, skirt, or top, making it convertible [43].

2018: SLS has been used to create chainmail patterns for textile fabrics in apparel production, such as the Modeclix garment [44].

2019: Beecroft conducted experiments using SLS to print nylon powder for flexible textile production. The study demonstrated that this technology able to produce complex geometric structures without requiring additional support elements during apparel manufacturing [45].

2021: NIKE has also adopted SLS in collaboration with HP to accelerate prototype development and enhance performance innovations in athletic footwear and gear [46].

2022: SLS holds significant potential for space-related projects, as demonstrated by NASA's Jet Propulsion Laboratory, which developed a foldable, metal-woven material with three integrated functions to improve space transportation efficiency [47].

2023: Szewczyk et al. [48] has developed Nylon-11 triboelectric yarns using SLS to integrate energy harvesting capabilities into smart textiles. These yarns can transfer mechanical energy into electric energy, powering wearable smart textiles devices without batteries.



Figure 5. Kinematic Petal Dress produced by Nervous system studio (reproduced with permission) [43].

2.3. Direct Ink Writing (DIW)

The DIW process begins with the preparation of ink that possesses specific rheological properties to ensure optimal adhesion and flow during printing. The ink is formulated from materials such as ceramics, composites, or polymers, selected based on the thermal and mechanical properties required for the final product. Hydrogels or slurries are commonly used as 3D printing inks. Once prepared, the ink is loaded into a nozzle connected to a computer-controlled system. As the printer moves according to a pre-designed model, the ink is layered onto a substrate and solidified during the printing process. It is crucial that the ink's rheology strikes a balance between viscosity and shear-thinning behavior, allowing it to flow through the nozzle under pressure while retaining its shape post-extrusion. To meet printability criteria, the ink must have suitable physical and chemical properties [49]. Three extrusion methods—pneumatic, piston, and screw—are commonly used [50]. Due to their conductivity and flexibility, silver nanowires are frequently employed, making them ideal for sensor integration into fabrics [51]. Hydrogels are also used to create adaptable smart textiles [52]. Palanisamy et al. [53] integrated conductive materials into filament fibers via DIW, enhancing smart textiles' functionality.

2019: Tay et al. [54] created core-sheath fiber-based designs on textiles for energy management in smart textiles, testing their efficacy as energy harvesters.

2021: Chen et al. [55] developed stretchable smart fibers and textiles for self-powered electronic skin (e-skin) using DIW and FDM technologies. Initially, they employed DIW printing to fabricate polydimethylsiloxane (PDMS)-based coaxial stretchable fibers with a core-sheath structure, designed for self-powered tactile sensing. Later, they integrated FDM technology, incorporating graphene and polytetrafluoroethylene (PTFE) as fillers in the PDMS matrix, each serving distinct functions. This approach enabled the efficient production of continuous stretchable smart fibers. The final outcome was the fabrication of e-skin fibers, leading to sensor-integrated smart textiles.

2023: Zhang et al. [56] developed a dual-mode, fiber-shaped flexible capacitive strain sensor using DIW technology, designed specifically for wearable health monitoring applications. The study demonstrated the potential of DIW in fabricating flexible sensors capable of accurately measuring strain, making them ideal for integration into smart textiles for health monitoring.

2.4. PolyJet: Material Jetting

PolyJet is a 3D printing technology akin to inkjet printing, except rather than ink, it uses UV light to cure layers of liquid photopolymers on a build platform. Multiple print heads spray layers of liquid photopolymer according to a CAD model, with each layer rapidly cured by UV light, hardening

nearly instantly. The Stratasys J750 PolyJet printer is capable of producing full-color parts with various finishes (matte or glossy) and material colors (CMYK) [57]. This technology stands out for its ability to print multiple colors and materials in a single build. Notable examples include Iris van Herpen's "Ludi Nature" collection, Karim Rashid's "Reflection" collection, and Ganit Goldstein's innovative patterns, which add shimmer and vibrant color to sustainable fabrics, enhancing garment movement.

2016: Farahi utilized PolyJet technology to create interactive textiles incorporating eye-gaze tracking. By integrating cameras and SMA actuators into the 3D-printed garment, the clothing is able to move in response to the wearer's gaze [58]. Figure 6 illustrates the concept of "Caress of the Gaze," an interactive wearable technology that detects and responds to the viewer's gaze



Figure 6. Caress of the Gaze produced by Farahi (reproduced with permission) [58].

2018: Park et al. [59] employed PolyJet technology to incorporate stretchable, flexible triboelectric nanogenerator fibers into fabrics. These fibers create electricity from mechanical movements, transforming the textiles into smart, self-powered devices. Wearable and portable devices use woven-structured triboelectric nanogenerators (TEGs) to turn human motion into electrical energy. However, contemporary TEGs need many fiber strands and have limited stretchability. This work offers extremely stretchable, flexible single-strand fiber-based TEGs (FW-TEGs), which produce around $34.4 \mu\text{W}/\text{cm}^2$ through skin contact, demonstrating endurance and promise for electronic devices. Figure 7 shows self-powered smart textiles with flexible fiber-based woven triboelectric nanogenerator.

2023: Diatezo et al. [60] developed PolyJet-based Joule heaters for flexible electronic coatings, creating smart heating fabrics ideal for heated automobile seats. The electrically conductive carbon composite coatings on fabric substrates allow for customizable shapes and provide greater comfort compared to traditional rigid heating elements.

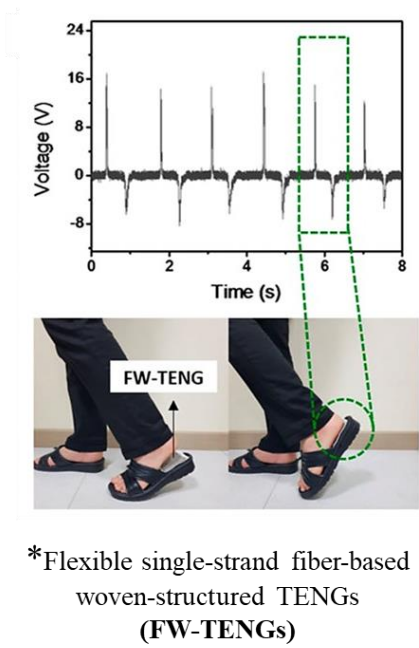


Figure 7. Self-powered smart textiles with flexible fiber-based woven triboelectric nanogenerator (reproduced with permission) [59].

2.5. Summary of 3D-Printed Methods and Materials in Smart Textiles

Section 2.5 presents an overview of various methods, with a focus on the materials used in the development of smart textiles through advanced 3D printing techniques such as FDM, SLS, DIW, and PolyJet. It delves into the diverse applications of 3D printing in smart textiles, providing a detailed analysis of how these materials are selected and tailored for specific functionalities within the field. Table 1 provides summary of 3D-printed methods and materials in smart textiles.

Table 1. Overview of 3D printing methods focused on materials used in developing smart textiles.

3D printing Methods	Materials	Applications in smart textiles
FDM	Dielectric Electroactive Polymer	Wearable smart sensor for monitoring deep breathing [28].
	Not specified	Energy-harvesting fabric [29].
	PLA, Nylon, conductive PLA	Smart textiles with thermal shape memory behavior [31]. Conductive PLA to create conductive wires [30].
	Polyurethane-based SMP, LDPE	Thermal-responsive smart textiles [26]. Developed conductive and flexible monofilaments for integration into smart textiles [7].
	PLA, PET	Stress, Strain and deformation performance in FDM-printed fabrics [33,34].
	PLA monofilament, PET	Conductive smart textiles with wear resistance [35].
	PEDOT	Energy-harvesting smart textiles [37].

	SWNT-embedded hydrophobic filaments	Phase-change nonwoven fabric for breathable, flexible smart textiles [39].
SLS	Nylon powder	Convertible petal dress with complex geometric structures [43].
	Nylon powder	Flexible textile production without support elements [45].
	Nylon	Prototype development for athletic footwear and gear [46].
	Nylon	Chainmail patterns for apparel [44].
	Metal-woven material	Foldable material for space transportation [47].
DIW	Nylon-11	Triboelectric yarns for energy harvesting in smart textiles [48].
	Conductive inks	Enhancing smart textiles' functionality with color changing capabilities [53].
	Not specified	Energy management in smart textiles [54].
PolyJet	PDMS, graphene, and PTFE	stretchable smart fibers and textiles for self-powered electronic skin (e-skin) [55].
	Photopolymer resins	Interactive textiles responding to eye-gaze [58]
	Not specified	Self-powered textiles from mechanical movement [59].
	Carbon composite	Smart heating fabrics for heated automobile seats [60].

3. Discussion and Technical Challenges

A range of 3D printing techniques, each with distinct applications and classifications, has revolutionized the textile industry. One widely used method, FDM, extrudes thermoplastic materials to create flexible and durable components for wearable textiles, particularly in fashion. Its versatility is evident in real-world applications, such as custom-fit sports textiles that enhance both performance and comfort [61]. Photopolymer resins used in SLA harden when exposed to light, allowing the production of high-resolution components suitable for fashion design and medical textiles. For instance, SLA is effectively utilized in the creation of custom prosthetics, demonstrating its capability to deliver precise and tailored medical solutions [61,62]. Moreover, SLS utilizes powdered materials, typically nylon or polyamide, which are fused together by a laser, making it ideal for aerospace textiles where lightweight yet strong components are essential. This technique enhances the functionality of aircraft parts by allowing the fabrication of intricate geometries that are impossible to achieve with conventional manufacturing methods [62]. DIW has been employed to fabricate health monitoring sensors and wearable electronics, such as core-sheath fibers and fiber-shaped capacitive strain sensors, expanding its applications in medical and wearable technologies. This technique allows for the integration of conductive patterns into textiles, enhancing both their mechanical stability and functionality [54,56]. PolyJet, a versatile 3D printing method, uses materials such as photopolymer resins, carbon composite inks, and shape memory alloys to produce interactive, self-sustaining fabrics, expanding the potential of smart textiles in functional wearables and fashion. Each material offers unique benefits, showcasing how 3D printing is revolutionizing the textile industry by advancing energy harvesting, functionality, and wearable technology [58,59].

While significant advancements have been made in 3D printing technology for garment production, challenges remain in integrating various wearable sensors. These sensors are crucial for real-time health monitoring, providing essential insights into a wearer's physiological status

[2,11,63]. Developing energy-harvesting fabrics is also complex, as these materials must efficiently convert environmental energy into power for the embedded sensors [29]. Additionally, there is increasing interest in creating interactive textiles that respond to stimuli, such as eye gaze, to enhance user experience [58]. Initially, some designers and scientists devised chainmail structures to create flexible fabrics; however, comfort continues to be a significant barrier, and only a few fashion companies have adopted 3D printing technology for garment production [44]. The limited availability of essential materials hinders the ability to produce pore structures and air permeability comparable to traditional fabrics. As a result, there is a growing demand for innovative raw materials that can replicate the properties of natural fibers or soft fabric structures. Furthermore, most 3D-printed wearable clothes are presently constrained to artistic creations or haute couture, featuring complicated geometric patterns and vibrant effects that require extensive production times. Developing affordable clothing for everyday use is crucial. Additionally, limited performance tests on 3D-printed textiles, such as drape, breathability, and tensile strength, coupled with the lack of standardized testing procedures, hinder comparisons of different 3DP textiles. Thus, prioritizing a consensus on testing methodologies for 3D-printed textile structures is essential.

4. Conclusion and Future Outlook

The review emphasizes the importance of understanding 3D printing techniques such as FDM, SLS, DIW, and PolyJet, as their applicability for selecting the best approach to incorporating advanced functionalities into smart textiles. It provides readers with a clear and concise examination of the materials utilized in 3D printing for smart textiles across these domains, facilitating a quick yet thorough understanding of the field. The timeline of 3D printing's utilization in smart textiles, spanning from 2016 to 2023, highlights significant advancements in the application of various additive manufacturing techniques. This technical overview includes FDM, SLS, DIW, and PolyJet printing and among these technologies, FDM has been particularly prominent, with applications ranging from wearable smart sensors for monitoring deep breathing to energy-harvesting fabrics, thermal shape memory textiles, thermal responsive smart materials, and FDM-printed fabrics that demonstrate performance in stress, strain, and deformation. Additionally, conductive smart textiles with wear resistance, solar energy-harvesting fabrics, and phase-change nonwoven materials for breathable, flexible smart textiles are also explored. SLS-based 3D printing technology has also gained popularity in smart textile applications, with notable uses including convertible petal dresses featuring complex geometric structures, flexible textile production without the need for support elements, prototype development for athletic footwear and gear, chainmail patterns for apparel, foldable materials for space transportation, and triboelectric yarns for energy harvesting in smart textiles. DIW is utilized in smart textile applications, particularly for integrating silver nanowires, which are valued for their conductivity and flexibility. These characteristics make them especially suitable for sensor integration into fabrics. Notable applications of DIW in smart textiles include enhancing functionality with color-changing capabilities, optimizing energy management, and developing flexible sensors for health monitoring. PolyJet is a 3D printing process akin to inkjet printing; however, it utilizes UV light to cure layers of liquid photopolymers on a build platform instead of ink. This technology is distinguished by its capability to print multiple colors and materials in a single build. Notable examples include Iris van Herpen's "Ludi Nature" collection and "Caress of the Gaze" by Farahi, which features interactive textiles that respond to eye movement.

According to GlobeNewswire, the smart textiles market is undergoing fast growth, with an envisioned compound annual growth rate of 31.30%, anticipated to reach \$24.84 billion by 2030. However, challenges such as production complexity, high costs, and environmental concerns persist. The rising disposal of smart textiles highlights their negative environmental impact. Production is further complicated by technological, market, and business model barriers, and integrating textiles with electronics and ICT raises sustainability issues. Embedded electronics complicate end-of-life management, as these textiles often contain heavy metals, nanoparticles, and toxic chemicals. Their short lifespan increases consumption, exacerbating e-waste and textile waste problems. To promote sustainability, it is crucial to use eco-friendly materials, adopt sustainable production methods, and

implement effective end-of-life strategies based on the 4Rs: repair, recycle, replace, and reduce. Repair can involve resewing, reweaving, reknitting, recoating, or reprinting, while recycling should differentiate between base textiles and electronics.

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