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A BRIEFREVIEW OF 3D PRINTING TECHNOLOGIES AND MATERIALS USED IN SMART TEXTILES

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ABSTRACT: The integration of 3D printing technology into smart textiles has witnessed a surge of interest from academia and industry over the past decade. 3D printing's inherent capability to fabricate intricate and customizable structures enhances functionality across key areas such as wearable electronics, medical textiles, and interactive fashion. Various 3D printing techniques, including Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Direct Ink Writing (DIW), and PolyJet printing, are currently employed in the fabrication of smart textiles. However, the wide range of applications for 3D printing in smart textiles often presents a challenge in synthesizing existing research accomplishments and identifying research gaps. To address this challenge, this review paper offers a comprehensive, application-oriented analysis of these specific 3D printing techniques and the materials utilized across various smart textile applications, including wearable technology, medical textiles, and smart fashion design. Our analysis draws upon a comprehensive review of peer-reviewed literature published between 2016 and 2024, identified through systematic searches of Google Scholar, PubMed, and Scopus. A central aim of this review is to emphasize the critical understanding of these 3D printing techniques for strategically selecting the most suitable method to incorporate advanced functionalities within smart textiles and interactive fashion. Despite significant progress in utilizing 3D printing for smart textile production, substantial challenges persist in the effective integration of diverse wearable sensors, necessitating interdisciplinary collaboration to develop innovative hybrid manufacturing strategies.

Keywords: 3D printing; Fabric surface; Fused deposition modeling; Smart textiles; Wearable sensors.

AKILLI TEKSTİLLERDE KULLANILAN 3D BASKI TEKNOLOJİLERİ VE MALZEMELERİNE İLİŞKİN KISA BİR DEĞERLENDİRME

ÖZET:3D baskı teknolojisinin akıllı tekstillere entegrasyonu, son on yılda akademi ve endüstriden büyük ilgi gördü. 3D baskının karmaşık ve özelleştirilebilir yapılar üretme konusundaki doğal yeteneği, giyilebilir elektronikler, tıbbi tekstiller ve etkileşimli moda gibi temel alanlarda işlevselliği artırır. Erimiş Biriktirme Modelleme (FDM), Seçici Lazer Sinterleme (SLS), Doğrudan Mürekkep Yazımı (DIW) ve PolyJet baskı dahil olmak üzere çeşitli 3D baskı teknikleri şu anda akıllı tekstillerin üretiminde kullanılmaktadır. Ancak, akıllı tekstillerde 3D baskının geniş uygulama yelpazesi, mevcut araştırma başarılarını sentezlemede ve araştırma boşluklarını belirlemede sıklıkla bir zorluk teşkil eder. Bunu ele almak için, bu inceleme makalesi bu belirli 3D baskı tekniklerinin ve giyilebilir teknoloji, tıbbi tekstiller ve akıllı moda tasarımı dahil olmak üzere çeşitli akıllı tekstil uygulamalarında kullanılan malzemelerin kapsamlı, uygulamaya yönelik bir analizini sunmaktadır. Bu analiz, Google Scholar, PubMed ve Scopus (2016-2024) tarafından kaynak gösterilen hakemli literatürün kapsamlı bir incelemesine dayanmaktadır. Bu incelemenin temel amacı, akıllı tekstiller ve etkileşimli moda içinde gelişmiş işlevleri birleştirmek için en uygun yöntemi stratejik olarak seçmek amacıyla bu 3D baskı tekniklerinin kritik anlaşılmasını vurgulamaktır. Akıllı tekstil üretimi için 3D baskının kullanımında önemli ilerleme kaydedilmesine rağmen, çeşitli giyilebilir sensörlerin etkili bir şekilde entegre edilmesinde önemli zorluklar devam etmekte olup, yenilikçi hibrit üretim stratejileri geliştirmek için disiplinler arası iş birliğini gerekli kılmaktadır.

Anahtar kelimeler: *3D baskı; Kumaş yüzeyi; Erimiş biriktirme modelleme; Akıllı tekstiller; Giyilebilir sensörler.*

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1.1 INTRODUCTION

1.1 Background

Over the past decade, 3D printing technology has been increasingly adopted in the field of smart textiles, driven by its ability to fabricate complex, customizable structures with enhanced functionality. This growing integration has attracted substantial attention from both academic researchers and industry professionals, who recognize its potential to revolutionize the design, performance, and manufacturing processes of wearable electronics, medical textiles, and interactive fashion. This review paper presents a comprehensive, application-focused overview of 3D printing technologies and materials employed in various smart textile domains, including wearable technology, medical textiles, and smart fashion design [1]. Nowadays, several 3D printing methods are leveraged in the production of customized smart textiles, including FDM, SLS, DIW, and PolyJet printing [2, 3]. The phrase "smart textile" covers a wide range of cutting-edge methods in textile manufacturing [4]. Smart textiles have advanced significantly, as their materials or structures inherently respond to external stimuli; for example, changes in the surrounding temperature lead to related adjustments in the internal composition of this smart material. Another aspect of smart textiles is the integration of sensors into garments to enhance functionality [4, 5]. 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 [6–9]. 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 [10].

One of the significant challenges in advancing the application of smart textiles is the complexity associated with integrating various technologies and components. Significant challenges remain in integrating multipurpose and multifunctional electronic structures, particularly in establishing reliable and efficient conductive pathways for sensors' communication [11].

Addressing these challenges requires seamless integration of solutions into the fabric manufacturing process. A further challenge involves future production and its automation, which requires the capability to develop miniature multilayer composites/sensors and incorporate them into textiles [12]. Furthermore, the integration of wearable energy generators, energy storage solutions, image fiber devices, and various multifunctional devices into everyday merchandise presents challenges, as traditional electronic components, wiring, and batteries do not seamlessly align with established fashion standards [13]. To tackle these challenges, 3D printing is widely regarded as a process that efficiently and seamlessly transforms virtual models into physical objects using a range of advanced technologies. Currently, 3D printing is actively being explored as a solution to these challenges, offering customization and flexibility in integrating electronics into textiles [14, 15]. This process can be executed on demand and accommodates a wide range of scales, from a few microns to several meters [16–18], making it particularly suitable for economic customization and beyond. The integration of 3D printing into the fashion industry began gaining significant momentum in 2011, marked by the debut of Iris van Herpen's 3D-printed dress at Paris Haute Couture Fashion Week. Recognized by Time magazine as one of the best inventions of the year, the dress customized using body-scanning technology captured widespread attention for its innovative design and personalized costume fit [19]. In 2014, the "Ice Dress," a transparent resin creation featuring intricate 3D-printed materials, was showcased exclusively on the catwalk [20]. From Karl Lagerfeld's SLS-printed mesh designs at Chanel's 2015 show to Claire Danes' illuminated Zac Posen gown at the 2016 Met Ball, fashion embraced tech-driven innovation. That same year, Paris debuted water-soluble clothing, while 2019 saw glow-in-the-dark fashion shine with Richard Nicoll's London show and Zendaya's standout fairy dress at the Met Gala [21]. 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 the development process of 3D-printed smart textiles embedded with integrated sensors. The process involves multiple steps, including the incorporation of functional fabric with 3D-printed sensors, the addition of protective and adhesive layers, and the final assembly into wearable smart textiles. These wearable smart textiles offer a sophisticated solution for the continuous monitoring of various health conditions in the human body [22].

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 [23]. 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 [24]. 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 [25]. Acrylonitrile butadiene styrene (ABS) is well-suited for durable

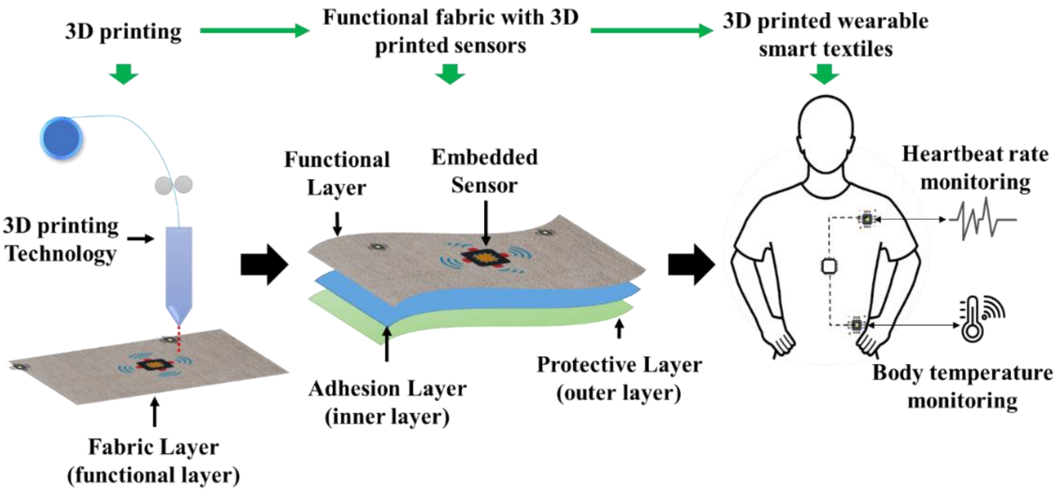

Figure 1. 3D-printed smart textiles with integrated sensors for monitoring human health conditions.

applications [26], while thermoplastic elastomers (TPE), TPU, and thermoplastic copolyester (TPC) are known for their high durability and flexibility [27]. Nylon is commonly used for applications that demand long-lasting parts, such as tools, functional prototypes, or mechanical components [28]. Smart materials like shape memory alloys (SMA), ferrofluid, magnetorheological fluids, electroactive polymers (EAPs), piezoelectric materials, and chromogenic materials are also integrated into 3D printing [29]. 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 [30]. Conductive threads, in particular, are valuable for creating circuits for sensors, actuators, heating elements, sound transmission, or LED contact points.

1.2 Market size and growth projections for smart textiles

The smart textile market is a rapidly evolving segment within the broader textile industry. Initially driven by the demand for fitness and sportswear, it has since expanded to encompass fashion, healthcare, and industrial applications. These innovative textiles can monitor health metrics, enhance athletic performance, provide environmental data, and contribute to sustainability efforts. According to the latest market analysis from the CMI Team, the global smart textiles market is expected to grow at a compound annual growth rate (CAGR) of 18.1% from 2023 to 2032. In 2023, the market size is projected to reach USD 1.7 billion, with a forecasted valuation of USD 7.4 billion by 2032, as illustrated in Figure 2[25].

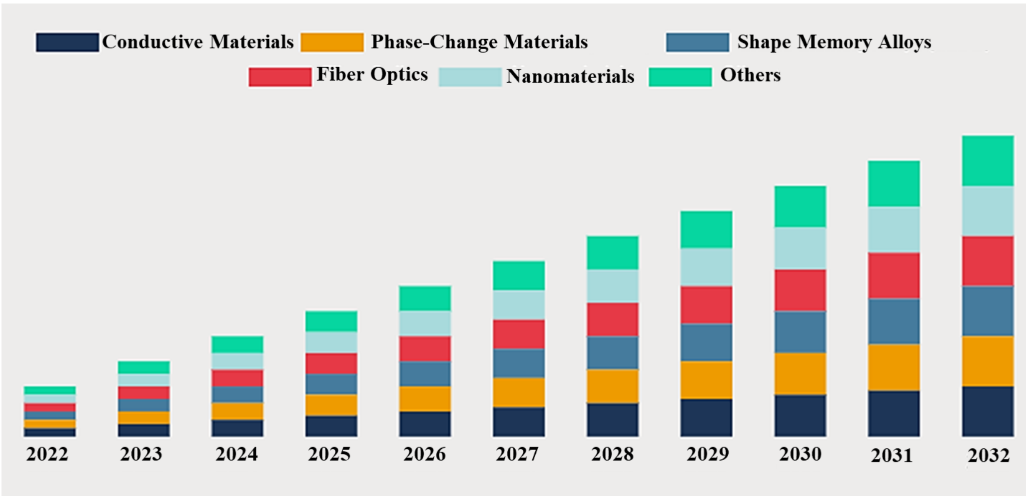

Figure 2. An overview of global smart textile market growth trends from 2022 to 2032

1.3 Review methodology

This review paper presents a comprehensive, application-focused overview of 3D printing technologies and materials employed in various smart textile domains, including wearable technology, medical textiles, and smart fashion design, based on an extensive literature review conducted in August 2024 using Google Scholar, PubMed, and Scopus to target peer-reviewed journal articles. The search focused on studies discussing the use of *3D printing in smart textiles*, emphasizing advancements in FDM, SLS, DIW, and PolyJet printing. Boolean operators and keyword combinations were applied to refine the search, such as ("3D printing" OR "additive manufacturing") AND ("smart textiles" OR "wearable textiles" OR "functional textiles") and ("FDM" OR "SLS" OR "DIW" OR "PolyJet") AND ("3D printed fabric" OR "conductive textiles"). All retrieved records were managed using Mendeley reference management software, where duplicate entries were automatically removed. The study selection process followed PRISMA's four-stage approach: identification, screening, eligibility, and inclusion. Initially, studies were screened based on titles and abstracts to ensure they specifically addressed 3D printing applications in smart textiles. During the eligibility phase, a full-text review was conducted, selecting articles that discussed technological advancements, material innovations, and practical applications of 3D printing methods without textile applications, theoretical modelling without experimental validation, or unrelated fields. After applying these criteria, 23 studies were included in the final review (from 2016 to 2024). The PRISMA flow diagram, as shown in Figure 3, visualizes the selection and exclusion processes. The review classifies the evolution of 3D printing technologies in smart textiles, highlighting significant advancements and innovations in materials. The technical overview of this paper is divided into two main sections:

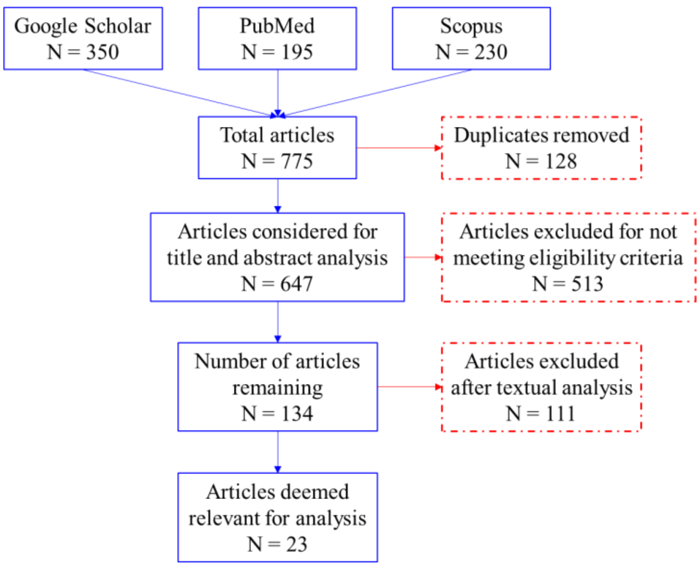

Figure 2. PRISMA flowchart for articles deemed relevant for analysis.

- First, this review examines 3D printing applications in smart textiles, focusing on materials used in wearable technology, medical textiles, and smart fashion.
- Second, this review provides a clear and concise summary of 3D printing materials used in smart textiles across various domains, offering readers a quick yet comprehensive understanding of the field.

The remainder of the paper is organized as follows: Section 2 reviews 3D printing technologies, applications in smart textiles, and related materials, with Section 2.5 summarizing key insights. Section 3 discusses technical challenges and concludes with future outlooks on materials and applications.

2. APPLICATION OF 3D PRINTING IN SMART TEXTILES

This study examines recent research at the intersection of smart textiles, wearable technology, and fashion design, highlighting how 3D printing enhances functionality, customization, and performance. Utilizing the PRISMA framework, this review systematically selected and analyzed relevant studies published from 2016 to 2024. The analysis specifically addresses additive manufacturing techniques, such as FDM, SLS, DIW, and PolyJet, with detailed descriptions provided in Sections 2.1–2.4. Section 2.5 summarizes these methods, emphasizing materials and their applications in smart textiles.

2.1 Fused Filament Fabrication (FFF)

Materials used in FDM for smart textiles. 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. The FDM process uses thermoplastic filaments, such as ABS, nylon, and PLA, to construct objects by melting and solidifying the material [31]. 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 [32]. The chronological use of the FDM method in smart textile applications is illustrated in the following sections, covering the period from 2016 to 2024. 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.

Sensors applications in smart textiles. Morehead et al.[33] 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 4 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.[34] proposed a CAD model for piezoelectric energy-harvesting fabric and developed an FDM-printed model of smart fabrics for energy harvesting. Grimmelsmann et al. [35]used FDM and Protopasta® Conductive PLA to create conductive pathways, integrating electronic components directly onto textile substrates, enhancing their functionality as smart textiles.

Thermal-responsive and shape-memory applications. Leist et al.[36] 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 (2017) 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 [37].

Adhesion, mechanical and electrical performance enhancement. Eutionnat-Diffo et al. [38] studied smart textiles using the FDM process, focusing on increasing PLA adhesion to polyethylene Terephthalate (PET) textiles. They printed plain and twill weave fabrics and found that larger pore size, increased roughness, and lower heat conductivity improve adhesion, while the construction platform has a quadratic impact. Their findings state that textile surface topography plays an important role in defining anchoring zones between the printed layer and fabric. However, adhesive strength decreases by 50% after washing, though coarser and more integrating FDM-printed elements into smart textiles. Similar to the previous work, Eutionnat-Diffo et al.[39] also investigated the stress, strain, and deformation performance of FDM-printed fabrics, further advancing the development of smart textiles. The results indicate that the deposition method influences the tensile characteristics of printed fabrics. The first 3D-printed PLA layer on top of the PET fabric combines the tensile strengths of both materials. However, the lack of flexibility and polymer dispersion makes the layer not stick well. There are big differences in how PLA on PET stretches and bends depending on the temperature of the printing platform and the fabric. Washing and conductive additives do not influence the tensile characteristics of extruded PLA. Despite this, 3D-printed PLA on PET textiles demonstrates worse elastic, total, and permanent deformation compared to untreated fabric, leading to enhanced dimensional stability, increased stiffness, and diminished flexibility.

Conductive materials for smart textiles for enhancing performance and wear resistance. 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. Nguyen and Kim studied polyurethane shape memory polymers (SMP) for wearable smart textile products [40]. 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

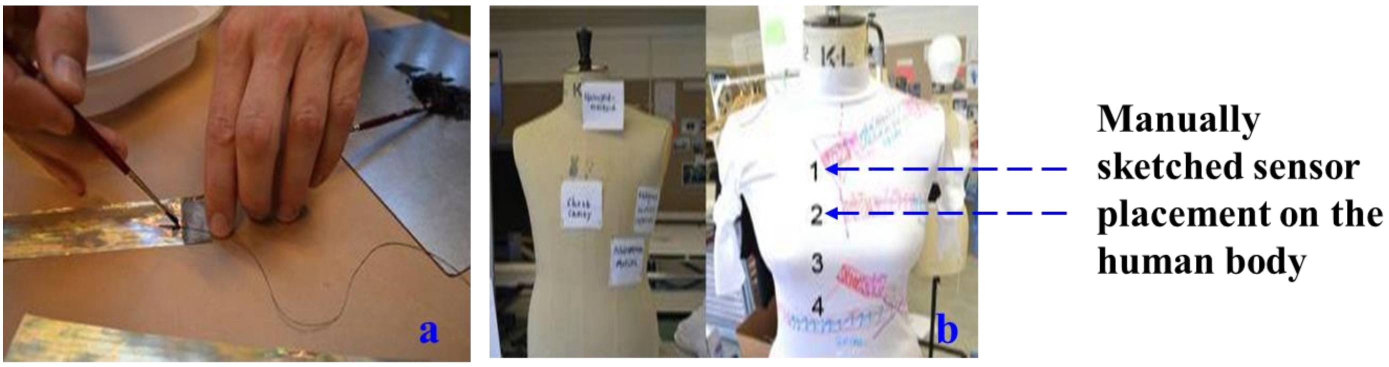

Figure 3. (a) Crafting custom sensors and (b) positioning them on the human body (re-produced with permission) [33].

samples for comparison. The study evaluates the materials, structures, procedures, and efficiency of each method to identify the best approach for wearable products [41]. Hofmann et al. [42] 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. Eutionnat-Diffo et al.[6] 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.

***Energy harvesting solar-powered smart textiles*.** Ertuna et al. [43] 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 photo-voltaic energy, thereby paving the way for the wearable smart textile industry. Figure 5 illustrates a vest embedded with 3D filaments designed to generate photovoltaic energy.

Figure 4. Vest with 3D filaments that can make photovoltaic energy (reproduced with permission) [43].

***Flexible phase-change nonwoven fabrics for smart textiles*.**

Yang et al. [44]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 nanotubes (SWNTs) embedded in hydrophobic filaments. This work offers key insights for producing multifunctional, stable wearable phase-change fabrics, advancing smart textiles.

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 [45]. 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 spread onto the build platform. The powder is then heated to just below its melting point [46]. 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 [47]. 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 [45]. Figure 6 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[48].

Figure 5. Kinematic Petal Dress produced by Nervous System Studio (reproduced with permission) [48].

Chainmail Patterns for wearable textiles. SLS has been used to create chainmail patterns for textile fabrics in apparel production, such as the Modeclix garment [49].

Flexible, geometrically complex textiles. Beecroft conducted experiments using SLS to print nylon powder for flexible textile production. The study demonstrated that this technology can produce complex geometric structures without requiring additional support elements during apparel manufacturing [50].

Performance innovations in footwear. NIKE has also adopted SLS in collaboration with HP to accelerate prototype development and enhance performance innovations in athletic footwear and gear [51].

NASA's foldable, multi-function metal materials. 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 [52].

Integrating energy harvesting into smart textiles. Szewczyk et al. [53] have 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 textile devices without batteries.

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 [54]. Three extrusion methods: pneumatic, piston, and screware commonly used [55]. Due to their conductivity and flexibility, silver nanowires are frequently employed, making them ideal for sensor integration into fabrics [56]. Hydrogels are also used to create adaptable smart textiles [57]. Palanisamy et al. [58]integrated conductive materials into filament fibers via DIW, enhancing smart textiles' functionality.

Core-sheath fiber designs for energy harvesting in smart textiles. Tay et al. [59] created core-sheath fiber-based designs on textiles for energy management in smart textiles, testing their efficacy as energy harvesters.

3D-printed stretchable smart fibers for self-powered e-skin and sensor-integrated textiles. Chen et al. [60]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.

Fabricated fiber-shaped strain sensor for wearable health monitoring. Zhang et al. [61] 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) [62]. 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.

Interactive textiles with eye-gaze responsive actuation. 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 can move in response to the wearer's gaze [63]. Figure 7 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) [63].

Stretchable fiber-based TENGs for self-powered smart textiles. Park et al. [64] employed PolyJet technology to incorporate stretchable, flexible tribo-electric 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 (TENGs) to turn human motion into electrical energy. However, contemporary TENGs need many fiber strands and have limited stretchability. This work offers extremely stretchable, flexible single-strand fiber-based TENGs (FW-TENGs), which produce around 34.4 μW/cm² through skin contact, demonstrating endurance and promise for electronic devices. Figure 8 shows self-powered smart textiles with a flexible fiber-based woven triboelectric nanogenerator.

Smart heating fabrics. Diatezo et al. [65] 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.

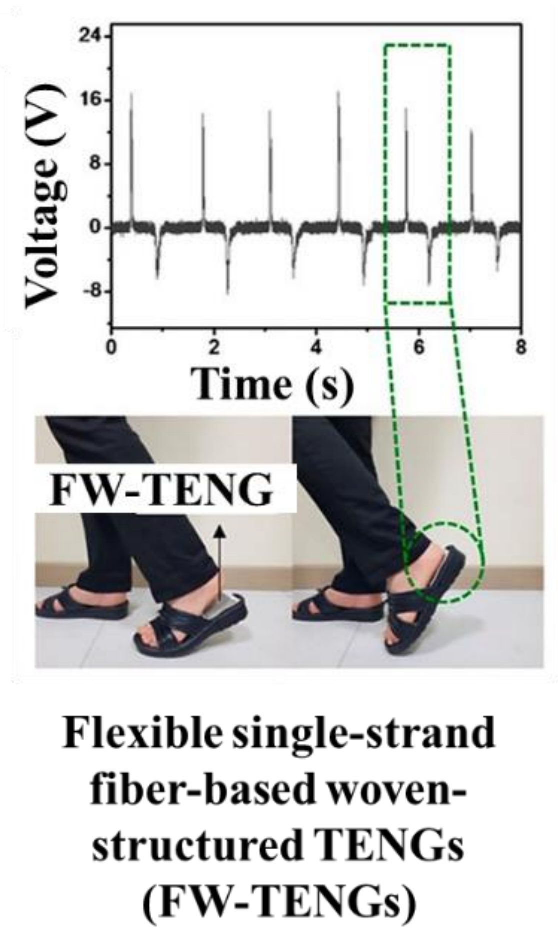

Figure 7. Self-powered smart textiles with flexible fiber-based woven triboelectric nanogenerator (reproduced with permission) [64].

2.5 Summary of 3D printing technologies and materials used in smart textiles

Various 3D printing techniques are comprehensively reviewed and summarized in Section 2.5. This review outlines their advantages and limitations, with a particular focus on the materials employed in fabricating smart textiles, thereby connecting to Sections 2.1 to 2.4. Section 2.5 highlights advanced 3D printing methods such as FDM, SLS, DIW, and PolyJet, and explores their applications in smart textiles, including sensors, energy harvesting, conductive and thermal-responsive elements, phase-change fabrics, flexible structures, multifunctional metals, stretchable e-skin fibers, and eye-gaze responsive textiles. Table 1 provides a summary of 3D-printed methods and materials in smart textiles, their advantages and limitations.

3. DISCUSSION, ADVANCES AND TECHNICAL LIMITATIONS

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 [69]. While significant advancements have been made in 3D printing technology for smart textiles 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. Developing energy-harvesting fabrics is also complex, as these materials must efficiently convert environmental energy into power for the embedded sensors [34]. Additionally, there is increasing interest in creating interactive textiles that respond to stimuli, such as eye gaze, to enhance user experience [63]. 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 [49]. 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.

Table 1. Comparison of 3D printing techniques in smart textiles with existing methods.

3D printing methods	Materials used	Applications for smart textiles	Advantages	Limitations
FDM	Dielectric Electroactive Polymer	Wearable smart sensor for monitoring deep breathing [33].	Lower cost and easier fabrication compared to traditional textile-based sensors, such as woven sensors [66].	Lower sensitivity and resolution than traditional MEMS-based sensors [66].
	Not specified materials	Energy-harvesting fabric [34].	Allows lightweight, complex structures compared to rigid solar cells or piezoelectric films.	Lower efficiency than silicon-based energy harvesting technologies.
	Nylon and conductive PLA	Smart textiles with thermal shape memory behavior [36]. Conductive PLA to create conductive wires [35].	Better incorporation into textiles than bulky shape-memory alloys or elastomer-based actuators [40, 67].	Slower response time and lower mechanical durability compared to shape-memory alloys (SMAs) [40, 67].
	Polyurethane-based SMP and LDPE	Thermal-responsive smart textiles [32]. Developed conductive and flexible monofilaments for integration into smart textiles [6].	Easier to manufacture and embed in textiles than phase-change materials embedded via lamination or coating [68].	Lower latent heat storage and durability than PCMs used in traditional thermoregulating fabrics [68].
	PLA and PET	Stress, Strain and deformation performance in FDM-printed fabrics [38, 39].	Offers real-time sensing capabilities that conventional woven strain sensors cannot provide [38, 39].	Worse elastic and permanent deformation compared to untreated fabric[38, 39].
	PLA monofilament and PET	Conductive smart textiles with wear resistance [40].	More robust than conductive coatings that degrade over time [40].	Higher electrical resistance than metal fiber-based conductive textiles [40].
	PEDOT	Energy-harvesting smart textiles [42].	More flexible than rigid, inorganic thermoelectric materials.	Lower power output compared to conventional.
	SWNT-embedded hydrophobic filaments	Phase-change nonwoven fabric for breathable, flexible smart textiles [44].	Better mechanical flexibility than phase-change microcapsules embedded in coatings [68].	Lower phase change efficiency and higher cost than conventional PCM-treated textiles [68].
SLS	Nylon powder	Convertible petal dress with complex geometric structures[48].	Allows for intricate designs that conventional sewing or knitting cannot achieve [48].	Less fabric comfort and drape compared to woven textiles.
	Nylon powder	Flexible textile production without support elements[50].	Eliminates the need for additional stabilizers [50].	Higher costs and powder-handling complexity [50].
	Nylon	Prototype development for athletic footwear and gear[51].	More customization potential than injection-molded shoe soles [51].	Slower production speed.
	Nylon	Chainmail patterns for apparel[49].	Enables fabrication of interlocking structures.	Rigid compared to flexible woven or knitted chainmail.
	Metal-woven material	Foldable material for space transportation[52].	Higher structural integrity than foldable fabric materials [52].	Heavier and more costly than ultra weight.
	Nylon-11	Triboelectric yarns for energy harvesting in smart textiles[53].	More effective charge generation.	Lower longevity compared to traditional piezoelectric fibers.
DIW	Conductive inks	Enhancing smart textiles' functionality with color-changing capabilities [58].	Better tunable compared to thermochromic dye-based textiles.	Slow response.
	Not specified materials	Energy harvesting in smart textiles [59].	Better adaptability than embedded batteries or energy storage units [59].	Energy density is low [59].
	PDMS, graphene, and PTFE	Stretchable smart fibers and textiles for self-powered electronic skin (e-skin) [60].	Skin-compatible and stretchable than metallic strain sensors [60].	Lower signal stability [60].
PolyJet	Photopolymer resins	Interactive textiles responding to eye-gaze.	Higher design complexity than thermally responsive textiles.	More expensive.
	Not specified	Self-powered textiles from mechanical movement [63].	Eliminates the need for external power sources [63].	Less energy efficient [63].
	Carbon composite	Smart heating fabrics for heated automobile seats [65].	Lightweight and flexible than other elements incorporated in seat cushions [65].	Lower heat output than conventional wire-based heating systems [65].

3.1 Advances in FDM 3D printing for smart textile applications and technical limitations

Amongst different 3D printing methods, FDM has emerged as the dominant technology due to its flexibility in design for smart textile applications. Kaergis et al. [70] studied how tuning printing parameters can enable pre-programmed shape transformations upon exposure to heat using FDM, enhancing the potential for smart textile applications. Beyond single-material applications, research has also focused on multi-material FDM techniques to create flexible, textile-like structures, with Georgopoulou and Clemens utilizing thermoplastic styrene-based elastomers to print elastic strips incorporating piezoresistive sensors, highlighting the potential for responsive and interactive smart textiles [71]. Material selection also plays a crucial role in FDM for smart textiles, directly affecting durability, mechanical properties, and integration with fabrics. While thermoplastic polymers like PLA are widely used for their environmental benefits, their mechanical limitations necessitate reinforcement materials [40, 72]. To improve flexibility and adhesion, Kroger et al. [73] examined thermoplastic elastomers, particularly styrene block copolymers and polyurethane, demonstrating their superior flexibility and strong adhesion to textile surfaces. Additionally, conductive materials such as graphene-based composites and carbon nanotubes (CNTs) have been investigated to enable sensing functionalities in printed textiles, though their integration poses challenges due to increased stiffness and viscosity [6, 74].

Despite these advancements, FDM for smart textiles faces several technical challenges, including insufficient mechanical properties, poor surface finish, and low dimensional accuracy, all of which hinder scalability [75]. Material limitations further complicate FDM applications, as the demand for flexible and durable materials remains an ongoing research focus [71]. Another critical challenge is ensuring strong adhesion between printed structures and textile substrates, where the surface topography and wettability of textiles play a crucial role. Kroger et al. explored form-locking connections, demonstrating how textile weave patterns, roughness, and post-processing treatments impact adhesion strength [76]. The viscoelastic behavior of printing materials further affects extrusion consistency and layer adhesion, necessitating precise control over material flow, as reviewed by Acierno et al. [77] in their study on rheological properties of thermoplastics in FDM extrusion processes. Additionally, fatigue behavior remains a concern, as FDM-printed polymeric materials often exhibit inferior durability compared to traditionally manufactured textiles, ultimately limiting their long-term performance [78].

3.2 Advances in SLS 3D printing for smart textile applications and technical limitations

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 [69, 79]. It can work with a wide range of photopolymers, including biobased and conductive materials, which are essential for smart textiles. For example, the incorporation of nanocellulose fillers has enhanced the mechanical and thermal properties of SLA-printed materials, making them suitable for advanced textile applications [80]. Studies have shown that SLA printing demonstrates better adhesion to textile substrates compared to other 3D printing techniques like FDM, which is attributed to the chemical bonding between the fabric and the photopolymer, ensuring a durable and strong interface [81, 82]. However, the main challenge of SLA is the limited availability of materials that combine flexibility, conductivity, and biocompatibility. Photopolymers used in SLA are often brittle and lack the flexibility required for textiles, leading to delamination, especially when subjected to repeated stretching and bending [83]. Additionally, post-printing curing is often required to achieve optimal mechanical properties, but this step can introduce additional cost and complexity. Moreover, the thermal stability of SLA-printed materials under environmental stimuli, such as temperature and light, requires further investigation [83, 84]. Moreover, SLS utilizes powdered materials, typically nylon or polyamide, which are fused together by a laser, making it ideal for aero-space 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 [79]. It supports a variety of materials, including polymers, composites, and even high-performance thermosets, making it suitable for different types of smart textiles [85, 86].

Unlike other 3D printing methods, SLS does not require support material, which simplifies the printing process and reduces post-processing steps [87, 88]. However, sanding or coating is often required to improve surface finish and functionality, adding time and cost to the production process [88]. The availability of SLS-compatible materials for smart textiles remains limited. For instance, materials such as polystyrene and carbon fiber-reinforced PEEK require specific process parameters to achieve optimal mechanical properties, and their printability can be challenging [85]. Additionally, SLS is highly sensitive to parameters such as laser power, scanning speed, and layer thickness, where incorrect settings can lead to insufficient sintering or material degradation [88–90].

3.3 Advances and technical limitations in DIW 3D printing for smart textile applications

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[59, 61]. One of the primary applications of DIW in smart textiles is the development of wearable strain sensors, which require inks with high mechanical strength and conductivity. The use of cellulose nanocrystal-regulated polyaniline composite inks has been shown to enhance the stretchability and sensitivity of these sensors, allowing for precise detection of human body movements [91]. However, preparing conducting polymer solutions remains challenging, particularly at high concentrations, which are crucial for achieving the desired mechanical and electrical properties [91]. Additionally, DIW struggles with fabricating complex structures, such as vascular scaffolds, due to limitations in ink formulation and extrusion precision [92]. The rheological properties of inks are critical to DIW's success, as they determine printability and the ability of printed objects to maintain their shape and support subsequent layers. Despite advancements, the relationship between ink rheology and printability is not yet fully understood, posing challenges in developing inks that meet the specific requirements of smart textiles [93].

4. CONCLUSION AND FUTURE OUTLOOK

Focusing on the period 2016-2024, this review offers a clear and concise analysis of the materials and additive manufacturing techniques FDM, SLS, DIW, and PolyJet printing used in the realm of 3D-printed smart textiles. This overview facilitates a swift, yet thorough understanding of the advancements achieved across diverse applications. FDM has emerged as a particularly significant technique, enabling the fabrication of wearable smart sensors for deep breathing monitoring, energy-harvesting fabrics, thermal shape memory textiles, thermally responsive materials, and fabrics exhibiting tailored mechanical properties (stress, strain, and deformation). The review further examines conductive smart textiles with enhanced wear resistance, solar energy-harvesting solutions, and phase-change nonwovens for breathable and flexible smart textile applications. SLS has also gained prominence, demonstrated in applications such as convertible petal dresses with intricate geometries, support-free flexible textiles, rapid prototyping for athletic gear, chainmail-inspired apparel, foldable structures for space applications, and triboelectric yarns for energy harvesting within smart textiles. DIW is crucial for integrating silver nanowires, leveraging their high conductivity and flexibility for sensor integration in fabrics, leading to functionalities like color-changing textiles, optimized energy management systems, and flexible health monitoring devices. PolyJet printing, akin to inkjet printing but utilizing UV-curable photopolymers, offers unique capabilities for multi-material and multi-color fabrication, exemplified by the interactive textiles in Iris van Herpen's "Ludi Nature" collection and Farahi's "Caress of the Gaze," which respond to eye movement. Despite these advancements, challenges including production complexity, high costs, and environmental implications persist. The escalating disposal rates of smart textiles highlight their negative environmental footprint. Technological, market, and business model barriers further complicate production, and the integration of electronics into textiles raises significant sustainability concerns. Embedded electronics impede end-of-life management due to the presence of hazardous materials, and the short lifespan of these products drives increased consumption, contributing to the growing problems of electronic and textile waste.

To advance sustainability in smart textiles, future efforts must focus on eco-friendly material selection, sustainable production processes, and robust end-of-life management guided by the 4R principles: repair, reuse, recycle, and reduce. Repair can involve techniques such as resewing, reweaving, reknitting, recoating, or reprinting, while effective recycling requires differentiated approaches for base textiles and integrated electronics. Realizing the full capabilities of 3D printing for smart textiles hinges on future research dedicated to creating multifunctional, scalable, and durable materials suitable for various additive manufacturing methods. DIW promises health monitoring sensors and wearable electronics, but challenges remain in achieving high ink solid loading and intricate geometries, necessitating further investigation into ink rheology and printability. Likewise, FDM requires the development of new material formulations with superior mechanical performance, and PolyJet printing needs enhancements in flexibility and durability for wearable applications. Overcoming these technological hurdles will require interdisciplinary collaborations to explore and implement hybrid manufacturing strategies. Moreover, future research should prioritize the optimization of critical material properties, including washability and long-term wear resistance.

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REFERENCES

1. Xiao Y-Q, Kan C-W (2022) Review on Development and Application of 3D-Printing Technology in Textile and Fashion Design. Coatings 12:267. https://doi.org/10.3390/coatings12020267
2. Tan WS, Suwarno SR, An J, et al (2017) Comparison of solid, liquid and powder forms of 3D printing techniques in membrane spacer fabrication. J Memb Sci 537:283–296. https://doi.org/10.1016/j.memsci.2017.05.037
3. Muthuram N, Sriram Madhav P, Keerthi Vasan D, et al (2022) A review of recent literatures in poly jet printing process. Mater Today Proc 68:1906–1920. https://doi.org/10.1016/j.matpr.2022.08.090
4. Júnior HLO, Neves RM, Monticeli FM, Dall Agnol L (2022) Smart Fabric Textiles: Recent Advances and Challenges. Textiles 2:582–605. https://doi.org/10.3390/textiles2040034
5. Ruckdashel RR, Khadse N, Park JH (2022) Smart E-Textiles: Overview of Components and Outlook. Sensors 22:. https://doi.org/10.3390/s22166055
6. Eutionnat-Diffo PA, Cayla A, Chen Y, et al (2020) Development of Flexible and Conductive Immiscible Thermoplastic/Elastomer Monofilament for Smart Textiles Applications Using 3D Printing. Polymers (Basel) 12:2300. https://doi.org/10.3390/polym12102300
7. Stoppa M, Chiolerio A (2014) Wearable Electronics and Smart Textiles: A Critical Review. Sensors 14:11957–11992. https://doi.org/10.3390/s140711957
8. Xu D, Ouyang Z, Dong Y, et al (2023) Robust, Breathable and Flexible Smart Textiles as Multifunctional Sensor and Heater for Personal Health Management. Adv Fiber Mater 5:282–295. https://doi.org/10.1007/s42765-022-00221-z
9. Bunea A-C, Dediu V, Laszlo EA, et al (2021) E-Skin: The Dawn of a New Era of On-Body Monitoring Systems. Micromachines 12:1091. https://doi.org/10.3390/mi12091091
10. Takagi T (1999) Present State and Future of the Intelligent Materials and Systems in Japan. J Intell Mater Syst Struct 10:575–581. https://doi.org/10.1106/33UC-FBCW-342W-P2WW
11. Rotari E, Negara C (2017) Possibilities and applications of smart textiles. MATEC Web Conf 112:1–6. https://doi.org/10.1051/matecconf/201711204025

12. Razzaq MY, Gonzalez-Gutierrez J, Mertz G, et al (2022) 4D Printing of Multicomponent Shape-Memory Polymer Formulations. Appl Sci 12:. https://doi.org/10.3390/app12157880
13. Younes B (2023) Smart E-textiles: A review of their aspects and applications. J Ind Text 53:1–23. https://doi.org/10.1177/15280837231215493
14. Valentine AD, Busbee TA, Boley JW, et al (2017) Hybrid 3D Printing of Soft Electronics. Adv Mater 29:1703817. https://doi.org/https://doi.org/10.1002/adma.201703817
15. Yang H, Leow WR, Chen X (2018) 3D Printing of Flexible Electronic Devices. Small Methods 2:1–7. https://doi.org/10.1002/smtd.201700259
16. Tumbleston JR, Shirvanyants D, Ermoshkin N, et al (2015) Continuous liquid interface production of 3D objects. Science (80-) 347:1349–1352. https://doi.org/10.1126/science.aaa2397
17. Kelly BE, Bhattacharya I, Heidari H, et al (2019) Volumetric additive manufacturing via tomographic reconstruction. Science (80-) 363:1075–1079. https://doi.org/10.1126/science.aau7114
18. Lim S, Buswell RA, Le TT, et al (2012) Developments in construction-scale additive manufacturing processes. Autom Constr 21:262–268. https://doi.org/10.1016/j.autcon.2011.06.010
19. Vanderploeg A, Lee S-E, Mamp M (2017) The application of 3D printing technology in the fashion industry. Int J Fash Des Technol Educ 10:170–179. https://doi.org/10.1080/17543266.2016.1223355
20. Pasricha A, Greeninger R (2018) Exploration of 3D printing to create zero-waste sustainable fashion notions and jewelry. Fash Text 5:30. https://doi.org/10.1186/s40691-018-0152-2
21. Manaia JP, Cerejo F, Duarte J (2023) Revolutionising textile manufacturing: a comprehensive review on 3D and 4D printing technologies. Fash Text 10:20. https://doi.org/10.1186/s40691-023-00339-7
22. Komolafe A, Zaghari B, Torah R, et al (2021) E-Textile Technology Review–From Materials to Application. IEEE Access 9:97152–97179. https://doi.org/10.1109/ACCESS.2021.3094303
23. de Albuquerque TL, Marques Júnior JE, de Queiroz LP, et al (2021) Polylactic acid production from biotechnological routes: A review. Int J Biol Macromol 186:933–951. https://doi.org/10.1016/j.ijbiomac. 2021.07.074
24. Franco Urquiza EA (2024) Advances in Additive Manufacturing of Polymer-Fused Deposition Modeling on Textiles: From 3D Printing to Innovative 4D Printing—A Review. Polymers (Basel) 16:700. https://doi.org/10.3390/polym16050700
25. Goncu-Berk G (2023) 3D Printing of Conductive Flexible Filaments for E-Textile Applications. IOP Conf Ser Mater Sci Eng 1266:012001. https://doi.org/10.1088/1757-899X/1266/1/012001
26. Hart KR, Wetzel ED (2017) Fracture behavior of additively manufactured acrylonitrile butadiene styrene (ABS) materials. Eng Fract Mech 177:1–13. https://doi.org/10.1016/j.engfracmech. 2017.03.028
27. Awasthi P, Banerjee SS (2021) Fused deposition modeling of thermoplastic elastomeric materials: Challenges and opportunities. Addit Manuf 46:102177. https://doi.org/10.1016/j.addma. 2021.102177
28. Arioli M, Puiggalí J, Franco L (2024) Nylons with Applications in Energy Generators, 3D Printing and Biomedicine. Molecules 29:2443. https://doi.org/10.3390/molecules29112443
29. Iftekar SF, Aabid A, Amir A, Baig M (2023) Advancements and Limitations in 3D Printing Materials and Technologies: A Critical Review. Polymers (Basel) 15:2519. https://doi.org/10.3390/polym15112519
30. Wilson S, Laing R (2019) Fabrics and Garments as Sensors: A Research Update. Sensors 19:3570. https://doi.org/10.3390/ s19163570
31. Calignano F, Manfredi D, Ambrosio EP, et al (2017) Overview on additive manufacturing technologies. Proc IEEE 105:593–612. https://doi.org/10.1109/JPROC.2016.2625098
32. Mogan J, Harun WSW, Kadirgama K, et al (2022) Fused Deposition Modelling of Polymer Composite: A Progress. Polymers (Basel) 15:28. https://doi.org/10.3390/polym15010028
33. Morehead S, Oliver R, O'Connor N, et al (2016) The Power of 'Soft.' MRS Adv 1:69–80. https://doi.org/10.1557/adv.2016.96
34. Gowthaman S, Chidambaram GS, Rao DBG, et al (2018) A Review on Energy Harvesting Using 3D Printed Fabrics for Wearable Electronics. J Inst Eng Ser C 99:435–447. https://doi.org/10.1007/s40032-016-0267-4
35. Grimmelsmann N, Martens Y, Schäl P, et al (2016) Mechanical and Electrical Contacting of Electronic Components on Textiles by 3D Printing. Procedia Technol 26:66–71. https://doi.org/10.1016/j.protcy.2016.08.010
36. Leist SK, Gao D, Chiou R, Zhou J (2017) Investigating the shape memory properties of 4D printed polylactic acid (PLA) and the concept of 4D printing onto nylon fabrics for the creation of smart textiles. Virtual Phys Prototyp 12:290–300. https://doi.org/10.1080/17452759.2017.1341815
37. Ly ST, Kim JY (2017) 4D printing – fused deposition modeling printing with thermal-responsive shape memory polymers. Int J Precis Eng Manuf Technol 4:267–272. https://doi.org/10.1007/s40684-017-0032-z
38. Eutionnat-Diffo PA, Chen Y, Guan J, et al (2019) Optimization of adhesion of poly lactic acid 3D printed onto polyethylene terephthalate woven fabrics through modelling using textile properties. Rapid Prototyp J 26:390–401. https://doi.org/10.1108/RPJ-05-2019-0138
39. Eutionnat-Diffo PA, Chen Y, Guan J, et al (2019) Stress, strain and deformation of poly-lactic acid filament deposited onto polyethylene terephthalate woven fabric through 3D printing process. Sci Rep 9:14333. https://doi.org/10.1038/s41598-019-50832-7
40. Eutionnat-Diffo PA, Chen Y, Guan J, et al (2020) Study of the Wear Resistance of Conductive Poly Lactic Acid Monofilament 3D Printed onto Polyethylene Terephthalate Woven Materials. Materials (Basel) 13:2334. https://doi.org/10.3390/ma13102334
41. Nguyen TT, Kim J (2020) 4D-Printing — Fused Deposition Modeling Printing and PolyJet Printing with Shape Memory Polymers Composite. Fibers Polym 21:2364–2372. https://doi.org/10.1007/s12221-020-9882-z
42. Hofmann AI, Östergren I, Kim Y, et al (2020) All-Polymer Conducting Fibers and 3D Prints via Melt Processing and Templated Polymerization. ACS Appl Mater Interfaces 12:8713–8721. https://doi.org/10.1021/acsami.9b20615
43. Ertuna I, Güngör Y, Karaoğlu F, et al (2021) Design and Production of Smart Wearable Textile Products Using Layered Manufacturing Technology with Photovoltaic Energy. South Florida J Dev 2:1636–1644. https://doi.org/10.46932/sfjdv2n2-040
44. Yang Z, Ma Y, Jia S, et al (2022) 3D-Printed Flexible Phase-Change Nonwoven Fabrics toward Multifunctional Clothing. ACS Appl Mater Interfaces 14:7283–7291. https://doi.org/10.1021/ acsami.1c21778

45. Kruth JP, Wang X, Laoui T, Froyen L (2003) Lasers and materials in selective laser sintering. Assem Autom 23:357–371. https://doi.org/10.1108/01445150310698652

46. Kim S, Seong H, Her Y, Chun J (2019) A study of the development and improvement of fashion products using a FDM type 3D printer. Fash Text 6:9. https://doi.org/10.1186/s40691-018-0162-0

47. Kruth J, Mercelis P, Van Vaerenbergh J, et al (2005) Binding mechanisms in selective laser sintering and selective laser melting. Rapid Prototyp J 11:26–36. https://doi.org/10.1108/13552540510573365

48. Rosenkrantz J, Louis-Rosenberg J (2017) Dress/Code Democratising Design Through Computation and Digital Fabrication. Archit Des 87:48–57. https://doi.org/10.1002/ad.2237

49. Bloomfield M, Borstrock S (2018) Modeclix. The additively manufactured adaptable textile. Mater Today Commun 16:212–216. https://doi.org/10.1016/j.mtcomm.2018.04.002

50. Beecroft M (2019) Digital interlooping: 3D printing of weft-knitted textile-based tubular structures using selective laser sintering of nylon powder. Int J Fash Des Technol Educ 12:218–224. https://doi.org/10.1080/17543266.2019.1573269

51. Ukobitz D, Faullant R (2021) Leveraging 3D Printing Technologies: The Case of Mexico's Footwear Industry. Res Manag 64:20–30. https://doi.org/10.1080/08956308.2021.1864919

52. Paek SW, Balasubramanian S, Stupples D (2022) Composites Additive Manufacturing for Space Applications: A Review. Materials (Basel) 15:4709. https://doi.org/10.3390/ma15134709

53. Szewczyk PK, Busolo T, Kar-Narayan S, Stachewicz U (2023) Wear-Resistant Smart Textiles Using Nylon-11 Triboelectric Yarns. ACS Appl Mater Interfaces 15:56575–56586. https://doi.org/10.1021/acsami.3c14156

54. Sharma V, Roozbahani H, Alizadeh M, Handroos H (2021) 3D Printing of Plant-Derived Compounds and a Proposed Nozzle Design for the More Effective 3D FDM Printing. IEEE Access 9:57107–57119. https://doi.org/10.1109/ACCESS.2021.3071459

55. Nocheseda CJC, Fazley Elahee GM, Santos MFA, et al (2023) On the 3D printability of one-part moisture-curable polyurethanes via direct ink writing (DIW). MRS Commun 13:647–656. https://doi.org/10.1557/s43579-023-00407-5

56. Hou Z, Lu H, Li Y, et al (2021) Direct Ink Writing of Materials for Electronics-Related Applications: A Mini Review. Front Mater 8:1–8. https://doi.org/10.3389/fmats.2021.647229

57. Wan X, Luo L, Liu Y, Leng J (2020) Direct Ink Writing Based 4D Printing of Materials and Their Applications. Adv Sci 7:1–29. https://doi.org/10.1002/advs.202001000

58. Palanisamy S, Tunakova V, Militky J (2018) Fiber-based structures for electromagnetic shielding – comparison of different materials and textile structures. Text Res J 88:1992–2012. https://doi.org/10.1177/0040517517715085

59. Tay RY, Song Y, Yao DR, Gao W (2023) Direct-ink-writing 3D-printed bioelectronics. Mater Today 71:135–151. https://doi.org/10.1016/j.mattod.2023.09.006

60. Chen Y, Deng Z, Ouyang R, et al (2021) 3D printed stretchable smart fibers and textiles for self-powered e-skin. Nano Energy 84:105866. https://doi.org/10.1016/j.nanoen.2021.105866

61. Zhang C, Ouyang W, Zhang L, Li D (2023) A dual-mode fiber-shaped flexible capacitive strain sensor fabricated by direct ink writing technology for wearable and implantable health monitoring applications. Microsystems Nanoeng 9:. https://doi.org/10.1038/s41378-023-00634-9

62. Badar F, Vandi L-J, Carluccio D, et al (2024) Preliminary colour characterisation of a Stratasys J750 digital anatomy printer with different fillings and face orientations. Prog Addit Manuf 9:1277–1287. https://doi.org/10.1007/s40964-023-00519-3

63. Farahi B (2016) Caress of the gaze: A gaze actuated 3D printed body architecture. ACADIA 2016 Posthuman Front Data, Des Cogn Mach - Proc 36th Annu Conf Assoc Comput Aided Des Archit 352–361. https://doi.org/10.52842/conf.acadia.2016.352

64. Park J, Kim D, Choi AY, Kim YT (2018) Flexible single-strand fiber-based woven-structured triboelectric nanogenerator for self-powered electronics. APL Mater 6:. https://doi.org/10.1063/1.5048553

65. Diatezo L, Le MQ, Tonellato C, et al (2023) Development and Optimization of 3D-Printed Flexible Electronic Coatings: A New Generation of Smart Heating Fabrics for Automobile Applications. Micromachines 14:. https://doi.org/10.3390/mi14040762

66. Sapkota A, Ghimire SK, Adanur S (2024) A review on fused deposition modeling (FDM)-based additive manufacturing (AM) methods, materials and applications for flexible fabric structures. J Ind Text 54:1–51. https://doi.org/10.1177/15280837241282110

67. Bi H, Xu M, Ye G, et al (2018) Mechanical, thermal, and shape memory properties of three-dimensional printing biomass composites. Polymers (Basel) 10:. https://doi.org/10.3390/polym10111234

68. Kalaoglu-Altan OI, Kayaoglu BK, Trabzon L (2022) Improving thermal conductivities of textile materials by nanohybrid approaches. iScience 25:103825. https://doi.org/10.1016/j.isci.2022.103825

69. Kočevar TN (2023) 3D Printing on Textiles – Overview of Research on Adhesion to Woven Fabrics. Tekstilec 66:164–177. https://doi.org/10.14502/tekstilec.66.2023055

70. Kačergis L, Mitkus R, Sinapius M (2019) Influence of fused deposition modeling process parameters on the transformation of 4D printed morphing structures. Smart Mater Struct 28:. https://doi.org/10.1088/1361-665X/ab3d18

71. Uysal R, Stubbs JB (2019) A New Method of Printing Multi-Material Textiles by Fused Deposition Modelling (FDM). TEKSTILEC 62:248–257. https://doi.org/ 10.14502/Tekstilec2019. 62.248-257

72. Çevik Ü, Kam M (2020) A Review Study on Mechanical Properties of Obtained Products by FDM Method and Metal/Polymer Composite Filament Production. J Nanomater 2020:. https://doi.org/10.1155/2020/6187149

73. Korger Michael, Glogowsky Alexandra, Sanduloff Silke, et al (2020) Testing thermoplastic elastomers selected as flexible three-dimensional printing materials for functional garment and technical textile applications. J Eng Fiber Fabr 15:1558925020924599. https://doi.org/10.1177/1558925020924599

74. Gnanasekaran K, De With G, Friedrich H (2014) On packing, connectivity, and conductivity in mesoscale networks of polydisperse multiwalled carbon nanotubes. J Phys Chem C 118:29796–29803. https://doi.org/10.1021/jp5081669

75. Diak V, Diak A (2024) Features and Limitations of Fused Deposition Modelling (FDM) in Obtaining Textile-like Structures. Tekstilec 67:397–411. https://doi.org/10.14502/tekstilec.67.2024106

76. Unger L, Scheideler M, Meyer P, et al (2018) Increasing adhesion of 3D printing on textile fabrics by polymer coating. Tekstilec 61:265–271. https://doi.org/10.14502/Tekstilec2018.61.265-271

77. Acierno D, Patti A (2023) Fused Deposition Modelling (FDM) of Thermoplastic-Based Filaments: Process and Rheological Properties—An Overview. Materials (Basel) 16:. https://doi.org/10.3390/ma16247664

78. Shanmugam V, Das O, Babu K, et al (2021) Fatigue behaviour of FDM-3D printed polymers, polymeric composites and architected cellular materials. Int J Fatigue 143:106007. https://doi.org/10.1016/j.ijfatigue.2020.106007
79. Kafle A, Luis E, Silwal R, et al (2021) 3D/4D Printing of Polymers: Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), and Stereolithography (SLA). Polymers (Basel) 13:3101. https://doi.org/10.3390/polym13183101
80. Barkane A, Jurinovs M, Briede S, et al (2023) Biobased Resin for Sustainable Stereolithography: 3D Printed Vegetable Oil Acrylate Reinforced with Ultra-Low Content of Nanocellulose for Fossil Resin Substitution. 3D Print Addit Manuf 10:1272–1286. https://doi.org/10.1089/3dp.2021.0294
81. Tuvshinbayar K, Mpofu NS, Berger T, et al (2024) Comparison of FDM and SLA printing on woven fabrics. 169–177. https://doi.org/10.25367/cdatp.2024.5.p169-177
82. Popescu D, Amza CG (2024) 3D Printing onto Textiles: A Systematic Analysis of the Adhesion Studies. 3D Print Addit Manuf 11:E586–E606. https://doi.org/10.1089/3dp.2022.0100
83. Kornfellner E, Königshofer M, Unger E, Moscato F (2023) Elastic and dimensional properties of newly combined 3D-printed multimaterials fabricated by DLP stereolithography. Front Mater 10:1–8. https://doi.org/10.3389/fmats.2023.1272147
84. Becker P, Ciesielska-Wróbel I (2024) Performance of Fabrics with 3D-Printed Photosensitive Acrylic Resin on the Surface. Polymers (Basel) 16:. https://doi.org/10.3390/polym16040486
85. Liu L, Zhu S, Zhang Y, et al (2024) Process Study of Selective Laser Sintering of PS/GF/HGM Composites. Materials (Basel) 17:. https://doi.org/10.3390/ma17051066
86. Hassan MS, Billah KMM, Hall SE, et al (2022) Selective laser sintering of high temperature thermoset. 12044:9. https://doi.org/10.1117/12.2614779
87. Beecroft M (2016) 3D printing of weft knitted textile based structures by selective laser sintering of nylon powder. IOP Conf Ser Mater Sci Eng 137:0–7. https://doi.org/10.1088/1757-899X/137/1/012017
88. Khazaee S, Kiani A, Badrossamay M, Foroozmehr E (2021) Selective Laser Sintering of Polystyrene: Preserving Mechanical Properties without Post-processing. J Mater Eng Perform 30:3068–3078. https://doi.org/10.1007/s11665-021-05606-6
89. Rahman MM, Ahmed KA, Karim M, et al (2023) Optimization of Selective Laser Sintering Three-Dimensional Printing of Thermoplastic Polyurethane Elastomer: A Statistical Approach. J Manuf Mater Process 7:. https://doi.org/10.3390/jmmp7040144
90. Choudhury D, Ponneganti S, Radhakrishnanand P, et al (2023) Selective laser sintering additive manufacturing of solid oral dosage form: Effect of laser power and hatch spacing on the physico-technical behaviour of sintered printlets. Appl Mater Today 35:101943. https://doi.org/10.1016/j.apmt.2023.101943
91. Bao X, Meng J, Tan Z, et al (2024) Direct-ink-write 3D printing of highly-stretchable polyaniline gel with hierarchical conducting network for customized wearable strain sensors. Chem Eng J 491:151918. https://doi.org/10.1016/j.cej.2024.151918
92. Deshpande AA, Pan Y (2023) Direct Ink Writing on a Rotating Mandrel—Additive Lathe Micro-Manufacturing. J Micro- Nano-Manufacturing 11:. https://doi.org/10.1115/1.4065506
93. Wei P, Cipriani C, Hsieh CM, et al (2023) Go with the flow: Rheological requirements for direct ink write printability. J Appl Phys 134:. https://doi.org/10.1063/5.0155896

Nomenclature

- ABS: Acrylonitrile Butadiene Styrene
- CAGR: Compound Annual Growth Rate
- CNT: Carbon Nanotube
- DEAP: Dielectric Electroactive Polymer
- DIW: Direct Ink Writing
- EAP: Electroactive Polymers
- FDM: Fused Deposition Modelling
- FFF: Fused Filament Fabrication
- KB: Ketjenblack
- OECT: Organic Electrochemical Transistor
- LDPE: Low-density Polyethylene
- PBE: Propylene-based Elastomer
- PCNF: Phase-change Nonwoven Fabric
- PDMS: Polydimethylsiloxane
- PETG: Polyethylene Terephthalate Glycol
- PLA: Polylactic Acid
- PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
- PTFE: Polytetrafluoroethylene
- SLS: Selective Laser Sintering
- SMA: Shape Memory Alloys
- SMP: Shape Memory Polymer
- SWCNT: Single-walled Carbon Nanotubes
- SWNT: Single Wall Nano Tube
- TENG: Triboelectric Nanogenerator
- TPC: Thermoplastic Copolyester
- TPE: Thermoplastic Elastomers
- TPU: Thermoplastic Polyurethane