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Review of Recent Advancements in 3D Printing Technologies for Textile Applications

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Review

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ABSTRACT

3D printing (3DP) ranks as one of the more advanced methods in the manufacturing sector. All of the industrial sectors, including automobiles, medical services, aviation, athletics, fabrics, apparel, and fashion industries, have noticed an increase in the use of this approach for prototyping. In the past decade, 3DP technology has been applied in several industries by academics, textile technologists, designers of apparel, manufacturers, and suppliers. Textiles perform numerous purposes in addition to meeting the basic human need to protect the body. The textile industry has expanded its horizons with the incorporation of 3DP technology. This paper's goal is to present an integrated overview of the recent state of research to identify the most advanced 3DP techniques, materials, and applications currently used in the clothing and textile sectors. Fundamentals of basic textile substrates, numerous textile-related 3DP technologies, printing methods, materials for print inks, direct printing of 3D elements on different textile surfaces, and the impacts, benefits and limitations of 3D printed textile structure fabrication techniques are all addressed. It also emphasizes the ways 3DP technology will be used in the textile sector moving forward. Overall, the purpose of this issue of Textile Progress is to identify the potential of 3DP, which, despite certain limits, may improve the products of the fashion and textile sectors and encourage future scientists and designers to continue additional research.

KEYWORDS

3D printing, textiles, fashion, fabrics, polymer, software

INTRODUCTION

3D printing (also known as additive manufacturing (AM) or rapid prototyping (RP)) was invented in the early 1980s by Charles Hull, who is regarded as the father of 3D printing [1].

Hideo Kodama of the Nagoya Municipal Industrial Research Institute invented 3DP as a fast prototyping device employing a photopolymer under UV light in 1980 [2]. Since then, 3DP has begun to contribute to the Third Industrial Revolution, particularly in 1984 [3] . It has lately made its way into the textile sector, promising to change the supply chain [4]. AM can enhance the geometric complexity and usefulness of traditional fibre-based textiles, creating new solutions for both traditional and high-performance applications [4,5]. The idea of combining 3D printing technology with textiles began to emerge in the early 2000s. Researchers and designers began experimenting with the notion of employing 3D PRINTING technology to produce three-dimensional structures directly on cloth. In the twenty-first century, clothes designers and textile manufacturers are embracing more inexpensive and advanced 3D-printing technology to reduce the environmental effect of fast fashion while also promoting sustainability via reusing existing materials and minimizing manufacturing and resource waste. In recent years, 3D printing has emerged as a game-changing technology with the potential to change a variety of sectors. In the textile industry, 3D printing is driving a new wave of innovation, transforming how materials and clothing are designed, made, and consumed.

Compared to conventional methods, this strategy enhances design production, rapid prototype development, sustainability, and price reduction.

3DP includes methods that build three-dimensional models by layering materials together instead of removing the [6,7]. By providing quality and performance testing of parts and products before large-scale manufacturing, this approach saves money, time, and resources.

As a result, it received a lot of interest from a variety of sectors, including the automotive, healthcare, construction, fashion, and jewellery industries. 3DP applications have been extended to printed shoes, clothing, and fashion items by recent technical advancements.

To match customers' different body measurements and fulfil their comfort requirements, textile clothing and fashion accessories must be incredibly robust, flexible, soft, and durable [8]. As it comes to customization, 3D-printed clothing gives customers an enormous benefit over traditional techniques.

The 3D printing process starts with designing the thing with CAD software. This can include Rhino-based software [9,10] as well as traditional CAD packages such as Solid works, PTC Creo [10], Blender, Autodesk, Netfabb [4], and so on. Each design software has its features, for example, traditional CAD for machine design, such as Solidworks or Autodesk Inventor, is a hybrid solid and surface modeller in which the geometry is created using some basic 3D bodies with regular forms, their combinations, cutting holes, and some algorithms for sweeping cross sections along or around axes. Rhino 3D's surface modelling feature, non-uniform rational B-spline (NURBS), facilitates the creation of complicated curved surfaces. Rhino 3D's surface modelling feature, non-uniform rational B-spline (NURBS), facilitates the creation of complicated curved surfaces. In such software, the 3D surface may be instantly adjusted by moving just one control point on the NURBS surface. Similar abilities have also been added in recent years to the CAD program Autodesk Fusion 360 product.

Another method for creating a 3D model is to use parametric models and a scripting language within 3D CAD software to construct complicated forms. Changing one or more criteria produces different shapes, resulting in unique personalized design and mass customisation [11]. Emerging 3D body scanning technology is another method used to create flawlessly fitted clothing by capturing the body size and shape. The designer may design accessories directly on the simulated body shape using CAD software [10,12].

The textile industry can benefit immensely from the development of integrated 3D CAD systems, in which body models play a critical role. While significant advancements have been made in computer technologies and approaches that improve 3D modelling, research continues in the development of more realistic and mechanically accurate models. Completed models may be integrated with 3D garment design and visualization and 3D fabric modelling systems to create a truly interactive 3D product development and marketing tool.

Three-dimensional body, garment, and fabric modelling have significant implications not only for the way designers design products and businesses communicate product designs, but also for how consumers buy apparel products. Realistic 3D body models can be used to improve the online shopping experience for consumers as part of a virtual try-on environment. In this application, consumers create personalized virtual body models (using either adjustable generic models or individualized 3D body scan data) who can try on products in a virtual dressing room. While many consumers are excited about virtual try-on environments, body models, fabric models, and garment styles and fit must be accurately portrayed in 3D for them to provide the most beneficial experience [13]. 3D printing technologies allow for the customization of clothes to match each individual's body type, while body scanning allows for the creation of customized clothing. Wearable smart fabrics and fashion clothes with lightweight, tiny, and sensitive trackers have attracted the attention of researchers, who have tried using 3D printing to develop and manufacture electronic fabrics. Wearable clothes with sensors and trackers allow patients to monitor their health while engaging in physical activity or hospital stays by providing a visual and quantitative display of the gathered data. E-textiles assist athletes in monitoring their health and performance by tracking body temperature, perspiration, and body motion during sports activities [14]. The integration of 3DP technology into sportswear and electronic textiles has enormous potential for enhancing the connection between physical condition monitoring and apparel [15]. Current sustainability trends in textiles and clothing demonstrate the need for reducing unwanted production and ensuring the continued viability of 3DP technology in the textile and fashion sectors by reducing energy and transportation expenses [16]. Additionally, researchers have produced jewellery with minimal waste by utilizing polylactic acid (PLA) filament. Nowadays, jewellery makers develop jewellery designs digitally using computer-aided design (CAD). Some use 3D technology throughout the manufacturing process, beginning with 3D scanning and progressing to 3D printing for prototypes. When choosing a jewellery 3D printer, the first consideration is the technology used. Resolution, printing speed, material compatibility, cost, and volume are all important factors to consider. These will ensure the best results in their jewellery design and manufacturing operations [1].

3D Printing Jewelry producers have employed 3D printing methods such as fused depositing modeling (FDM), selective laser sintering (SLS), and digital light processing (DLP) to build prototypes. Unlike traditional jewelry production processes, 3D printing creates jewellery from digital 3D data. Designers and manufacturers may make adjustments to 3D files without investing additional time and effort.

They have achieved this without the use of support. Their study demonstrated the potential of this technology to create unique, affordable, and eco-friendly fashion designs [10,16].

The research demonstrates the latest developments in 3DP knowledge and application in the textile and fashion sectors. It also makes predictions about the technology's sustainability, inventiveness, and intricacy in fashion-related disciplines. As shown in Figure 1, the primary industrial uses of 3DP are in the following fields: aerospace [17,18], automotive [19], textiles and fashion [9,20], food [21,22], health [23,24], architecture and construction [25], and electrical and electronic engineering [26,27].

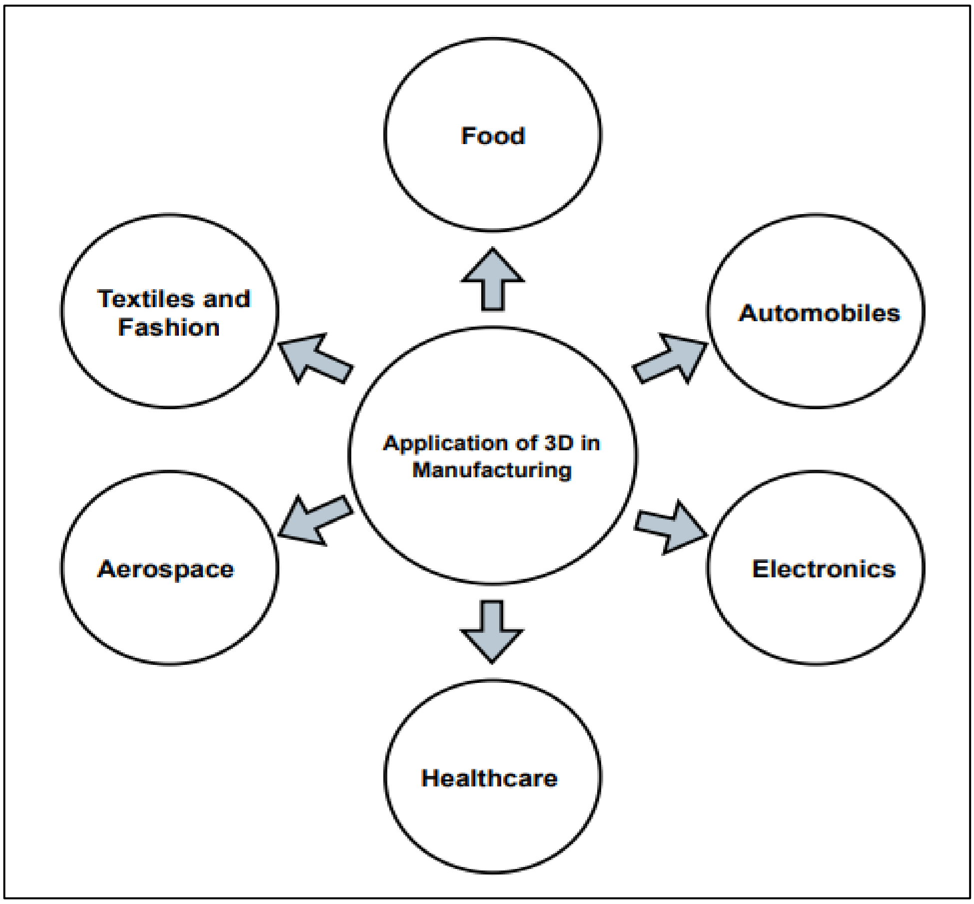


Figure 1. Applications of 3DP in Industry

In the past few years, 3DP for textiles and fashion has seen a surge in interest and commercial activity [28]. Integrating 3DP with conventional textiles, including knitted fabrics [29], and modifying and customizing textiles using 3DP can create new application areas [30]. It is feasible to create unique smart textiles by 3D printing functional pieces onto textiles [31,32] and the concept of printing and linking conductors, actuators, antennae, and sensors on the textile substrate may be critical for effective textile applications [32,33].

Three-Dimensional Printers for Textile Surface Manufacturing

The first stage in designing and producing three-dimensional printers is to determine the purpose of textile and modelling research. The second step includes using the proper CAD software to create three-dimensional drawings of textile patterns. After that, the designs are transformed into STL files. "An unsorted triangle surface list that represents the outer surface of the design" is the definition of the STL file format [34].

This file information undergoes pre-processing, including error checking, building instructions, and, if required, the creation of support structures [35]. Ultimately, the printing machine receives the sliced geometric data deemed fit for manufacturing (Figure 2). Compared to traditional technologies, textiles made using a 3DP could be dimensionally inaccurate, requiring critical object surfaces to be cleaned, cured and brought to the final size.

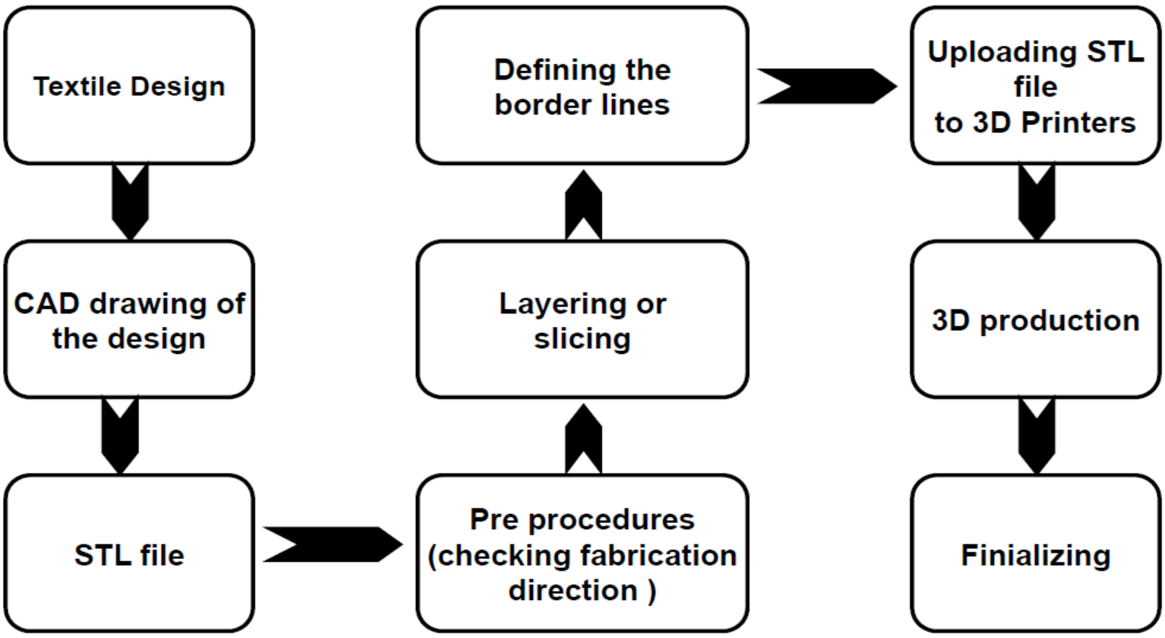


Figure 2. 3DP textile manufacturing phases [36]

Classification of 3DP in Textiles

3DP textiles may be categorized according to the surface, material, process, and other structural features [36]. Single-piece or multi-piece (modular) production is possible, and they may be used to print brand logos or create patterns on traditional fabrics. 3D-printed textile surfaces are still being researched and developed to expand their use across a range of industries. The purpose of this issue of Textile Progress is to compile information on the most recent advancements in 3DP technology across a range of textile and fashion-related industries. Fundamental textile substrates are addressed in this overview, followed by the most recent cutting-edge 3DP processes used in textiles.

It also discusses recent advancements and research endeavours in 3DP in traditional textile substrates and 3DP printed textile structures (i.e. yarns, fabrics, and clothing), as well as software and printed materials for textiles. Through the use of 3DP technologies, the paper highlights current developments in the fabrication of smart textiles, which combine textiles with innovative and useful components like wearable electronics.

The benefits and drawbacks of 3DP methods for textile applications are also covered, and the effects of different process parameters are investigated. The review highlights important aspects of 3DP's potential impact on the textile sector [37].

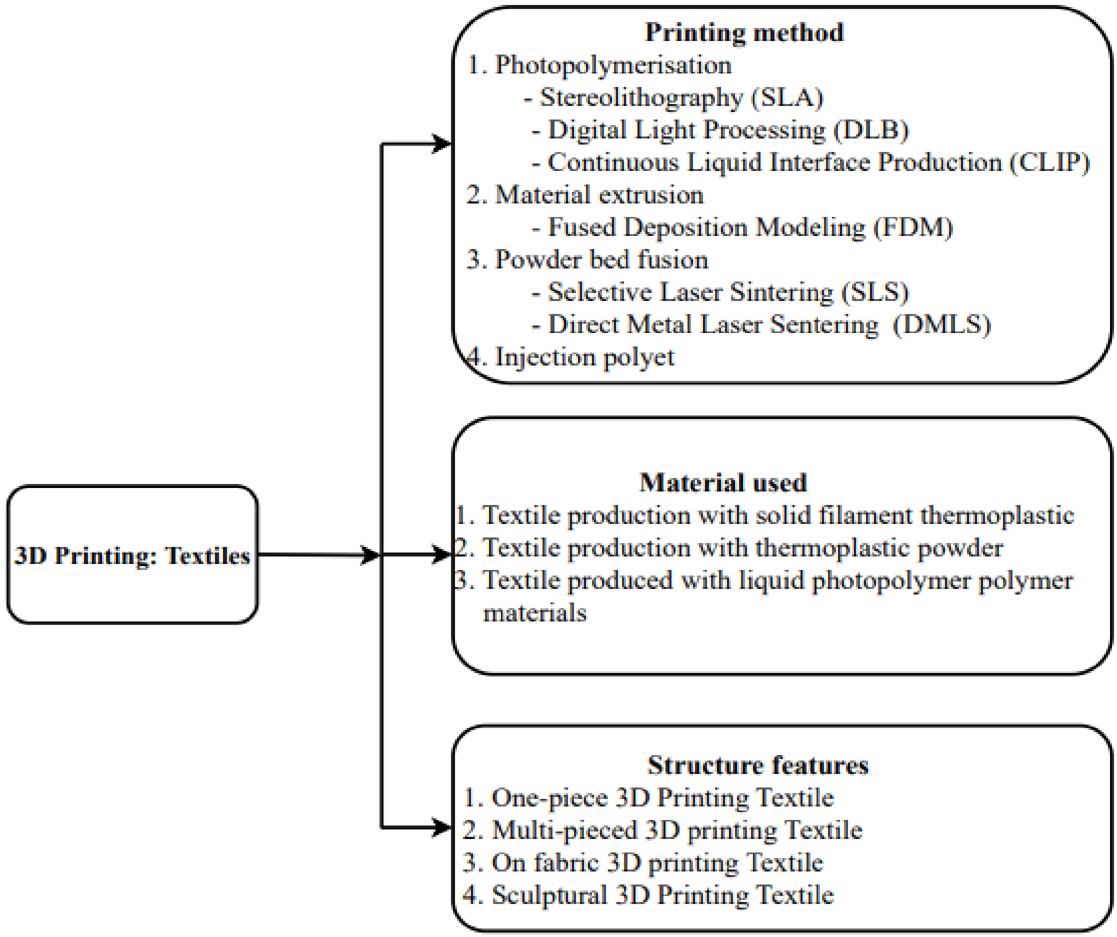


Figure 3. Classification of 3D textiles [38]

MATERIALS USED IN TEXTILE 3D PRINTING TECHNOLOGY

The materials or ingredients used in 3DP inks originate from various polymeric sources, either natural or manufactured, or both [38]. Combining different can enhance the distinct qualities of every constituent, often resulting in special features that a single element powder, or liquid [37]. The following section discusses the three different types of materials utilized in 3DP: natural, synthetic, and composites, along with their varied forms.

Natural printing polymers

Biopolymers, also known as natural printing polymers, are made from plants or other living things[39] Prototypes were also examined for a design-driven approach, and textiles were functionalized using rigid cellulose acetate and its derivatives [30]. Composites based on cellulose derivatives are popular in a variety of disciplines, including smart textiles, due to their enhanced characteristics [40]. Cellulose nanocrystals improve the mechanical and surface characteristics of 3D-printed bio-polymers and offer them the required toughness [41]. It is claimed that 3DP, which uses cellulosic materials for surface tailoring of cellulosic textiles, will allow the new processes that use less material because it can improve mechanical durability, eliminate labour-intensive processing, and give textiles refractive and thermoresponsive properties [30].

Synthetic materials

In 3DP, synthetic filaments are often and widely utilized. Good tensile strength, a quick melt-flow rate, and an excessive load to break are necessary for successful 3DP [42,43]. To improve these qualities and effectively create a superior synthetic polymer for filament production, various filaments were studied. While less common components are infrequently used [44,45], synthetic polymers, particularly PLA, offer intriguing potential [44-47]. Materials including PLA, ABS, and nylon 6,6 have been emphasized for FDM since they are included in certain current 3DP techniques.

Textile-based structures can be recreated using soft PLA mixed with less flexible materials like Bend Lay, a product created by Kai Parthy [46]. Tami Care, a Manchester, UK-based Company, has developed a Cosy flex 3DP technology that can directly form fabric from liquid polymers such as latex, polyamide, silicone, Teflon, and polyurethane [10], and Materialise introduced a lightweight material TPU-92A-1 that demonstrated improved elasticity and a softer hand feel for printing textile products [48].

Despite being in the theoretical stage, 3DP technology recycling polyester yarn is an example of sustainable production [49]. Research indicates that using the right settings for FDM 3DP produces items with unsatisfactory qualities, but additional effort is still needed to make synthetic filaments more suitable for 3DP technology applications [50]. The exploration and application of the different synthetic polymer 3DP inks are shown in Table 1.

Table 1. Different forms of ingredient inks are used in 3D printing [2]

Typical Polymer material	3DP technique used	State of the ingredients
ABS	FDM	Powder
PLA	Extruder-heating system	Solid
PLA	FDM	Solid
ABS	FDM	Solid
SEBS	Material Extrusion	Powder
ABS	Melt Extruder	Solid
HDPE, ABS	Single screw extruder	Solid
CNF	3D Bio-printing	Liquid
Boron nitride powder	3D inkjet printing	Powder

Composite materials

Composites of metals, natural polymers, and synthetic polymers are the most often used filaments for 3DPs; the synthetic polymers are mostly utilized as reinforcement and the others as matrixes. These composites exhibit enhanced heat conductivity when filled with metal particles like copper, iron, etc., with ABS as the matrix material. Because of their shown ability to enhance characteristics, composites based on cellulose derivatives are widely used in a variety of industries, including smart textiles [38,40]. In these kinds of 3DP bio-polymers, cellulose nanocrystals enhance mechanical and surface characteristics and give the required toughness [41]. Enhancing mechanical properties, lowering labour-intensive procedures, and adding new functions to cellulosic textiles by surface modification might open the possibilities for new technologies that use less material [30].

Recent studies have concentrated on conductive nanocomposite polymers based on graphene (G) and non-conventional polymer nanocomposites (CNT) for functional 3D-modelled composition. High functionality was achieved by experimental work using PBT as the matrix polymer, resulting in structures that were durable and mechanically strong.

The 3DP construction's properties such as morphology, conductivity, printability, crystallinity, and viscoelastic behaviour were also evaluated. At the higher level of organization, 3D-printed polymers have also been directly mixed with textile fibres, yarns, and textiles to generate composites, which can improve their mechanical characteristics [51,52].

Reinforcement materials

High-performance multifilament fibres like carbon and glass fibres significantly impact the characteristics of composites, such as inter-laminar shear strength and damage tolerance while also reducing the cost of manufacturing [49]. The significant potential application of 3DP textile-reinforced composites makes them popular for the rapid manufacturing of structures having novel functionalities [50].

Glass is a typical reinforcing material. Buildings, cars, and aeroplanes are just a few of the high-performance applications that will likely adopt nylon-coated, glass-filament reinforced composites because of their exceptional load-bearing capacity [53]. Glass with epoxy resin Good mechanical and damage-tolerance qualities were possessed by 3D stitched preform composites [54]. When compared to commercial aluminium and 3DP neat nylon honeycomb structures, glass fibre-reinforced 3DP honeycomb sandwich composites exhibit much higher mechanical performance and flexural, and compressive qualities.

As reinforcing materials, continuous carbon fibre filaments show promise in enhancing the stiffness, strength, and design ability of 3DP polymer components [55]. Continuous pre-processed carbon fibre-reinforced PLA composites are appropriate for high-performance applications because they have shown superior flexural qualities (16%), higher tensile strength (91 MPa), higher storage modulus, and better fibre matrix bonding than PLA alone [56].

When compared to the non-reinforced specimen, the carbon-fibre-reinforced specimen may increase tensile strength by up to 70% and flexural strength by up to 18.7% [57]. To fabricate PLA nanocomposite 3DP filament with conductive characteristics and achieve the required functional features and efficient manufacture, multiwall carbon nanotube (2%) and highly-structured carbon (5%) have been introduced[58]. When compared to thermoplastic materials without reinforcement, components constructed from reinforced composites have better mechanical and physical characteristics. The inter-laminar shear strength of reinforced composites is superior to that of unreinforced ones, and carbon-fibre-reinforced composites often beat glass-fibre-reinforced composites. However, increasing inter-laminar shear strength is essential for laminar composites' wide range of applications.

3D PRINTING TECHNOLOGIES USED IN THE TEXTILE INDUSTRY

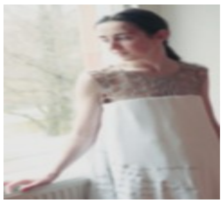
As per ASTM standard F2792, 3DP processes may be divided into seven main categories: vat photopolymerization, binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, and sheet lamination [59]. However, three primary categories of 3DP technologies utilized in the fashion and textile industries are:

Powder bed fusion: Stereolithography (SLA),

Binding process: Selective laser sintering (SLS), Inkjet printing, Binder jetting, and Polyjet [59,60].

Deposition process: Fused deposition modelling (FDM) and 3D microfiber extrusion [61,62].

Table 2. 3DP technology utilized in the textile industry

3Dprinting techniques	Methods	Materials	Examples
SLA	SLA is a widely used additive manufacturing method that uses a UV light source to rapidly polymerize and crosslink photo reactive polymers, such polyester, epoxy, and polyacrylates, to create three-dimensional (3D) objects layer by layer [54].	Liquid resin was exposed on the printer to create thin, sheer pieces of different patterns[55].	 This stereolithographic dress was created for Paris Fashion Week AW-2012/13 .The Anemone Dress and Parametric Sculptured Dress by Lady Gaga [63].
SLS	Using computer controlled laser technology and slicer software, SLS creates objects layer by layer. Then, using a scanning laser beam, the object is created by selectively fusing powders of the selected material that are deposited in layers [64].	Some nylon-based flexible textiles were used[8] . TPU white powder was used[60,65].	 Dress named ‘Voltage’, Collection[2].
FDM	In the FDM technique, a molten printing substance typically a thermoplastic polymer is horizontally deposited via a nozzle head to create 3D objects layer by layer on a platform or base material [66].	Commonly used thermoplastics include (PLA) and (ABS).	 FDM 3D-printed dress with a top portion[63]
Binderjetting	Using a specific bonding agent sprayed to fuse powder materials, 3D powder binder jetting is a 3D manufacturing technique.	Printing inks that are often used for 3DP construction with metallic and ceramic powder particles, as well as film-forming polymers and polymeric powder (such as PVA, starch, and cellulose derivatives).	 The shoe sole and insole are produced using 3D printing [67].

3Dprinting techniques	Methods	Materials	Examples
CIJ	A piezoelectric element separates the printing material into droplets from a pressurized liquid stream that is created by a nozzle head in CIJ[68]	Triethylene glycol dimethacrylate or tetrahydrofurfuryl methacrylate are used as reactive diluents when mixed with an inert urethane wax.	 Iris van Herpen and Professor Neri Oxman collaborated to create a 3D-printed cape and skirt [2]

SOFTWARE USED IN THE 3DP OF TEXTILE

In the computer-aided technique of 3D printing [3], printed objects are created layer by layer using slicer software and virtual design. As to Gershenfeld[69], 3DP is a social transformation that transforms information into tangible objects and vice versa. 3DP frequently starts with a 3D graphic tool for visual rendering, modelling, and animating the product in the textile and apparel industries [69]. An acquired picture or scanned structural data of the thing to be printed is usually used to create a product through virtual modelling [70]. Research showed that to attain the highest level of form compatibility, 3D scan data is crucial [71]. Since traditional 2D-based pattern design makes around 4% to 6% of the entire cost of a garment, virtual modelling is crucial [13]. Software that uses real-world measurements and references to generate virtual prototypes includes Rhinoceros [72] and Autodesk's 3DS Max, formerly known as 3D Studio Max (Autodesk, San Rafael, CA USA) [3,64]. Before moving on to the next phase, 3DP methods use many kinds of 3D modelling and visualization software programs to customize and validate the printed object.

3DS Max by Autodesk [73], a slicer program that uses the surface tessellation language (.stl) format is then used to import such 3D designs. Other well-known formats in addition to STL are object (.obj), film box (.fbx), standard for product data exchange (.step), drawing (.dwg), and others. To print the structure at a certain orientation layer by layer at a specific orientation [74] slicer software divides the printing portion into many 2D layers, which are then sent to the 3D printer [46,72].

Popular slicer software includes Ultimaker Cura, open source LGPLv3 software developed by David Braams and maintained by Ultimaker, a 3D printer manufacturer (Ultimaker Utrecht, Netherlands) [75], Simplify3D (Simplify3D, Cincinnati, OH, USA) [76], and Slic3r, an open source 3D printing toolbox [76]. These slicer programs automatically rendered G-Code, the numerically controlled programming language used for printing [77]. Table 2 lists some of the most-used software packages for 3DP along with their functions [2].

Table 3. List of some software compatible with 3DP technology [2]

3DP stage	Function description	Example of software	Associated 3DP technique
	Creating 3D CAD data	Autodesk Fusion 360	FDM, SLA
	The design's visual effects, animation, and 3D modelling are created using tools for 3D modelling, animation, and rendering.	Autodesk 3DS Max Autodesk Maya	FDM, SLA FDM, SLA
3D design and modelling software	To create auxetic forms for printing models of various textiles and textile-based structures.	AutoCAD Inventor Blender	FDM, SLA FDM SLS
	To make a virtual design by assembling elements using code and designing components with various shapes.	Autodesk Tinker cad	FDM, SLA
	To process personalized body data captured by a scanner.	Geomantic Freeform Plus	FDM
	Their main objective is to create data for machines by slicing 3D CAD models into layers.	Ultimaker Cura	Almost any 3D printing
Slicing software	Their main function is to slice the 3D CAD models into layers and generate data for machines.	Simplify 3D	FDM
3D simulation	To capture personalized body data captured by a scanner.	Artec Studio 14	FDM
	To print the final product of customized clothing.	Franklin Software CLO Virtual	FDM
	It can also be used as a 3D modelling tool to generate virtual product prototypes using measurements and references from the actual world.	Rhinoceros	DDP, FDM, DLP, SLA
	To generate G-Code to print.	Chitubox	FDM, SLA
G-code generator	To create a printable G-code file from a 3D design.	Cub creator	FDM

The creation of textiles and fashion goods may be made more precisely, customized, and efficiently by using these software tools combined with 3DP technology. Beyond the limits of textile production, the combination of 3D modelling, slicing, and G-Code creation makes it easier to convert virtual designs into physical objects.

3DP OF TEXTILES

In the textile and fashion industries, 3DP has the potential to completely transform the manufacturing system, but its adoption is still in its early stages. The attraction of 3DP is that a complete garment structure can be realized directly through 3DP. Due to its effective use of raw resources in comparison to other techniques, FDM techniques are mostly utilized for printing textile fabrics, textile fabric sections, or garment parts [78,79]. Furthermore, the 3DP is increasingly being used in technical textile industries to produce electrical equipment that resembles sensors, electrodes, conductors, and actuators as well as personal protective equipment (PPE). In general, these techniques may be categorized into several structures, which are covered below.

Yarn and similar textile structures

Despite the textile and apparel industries' significant interest in 3DP technology, there have been comparatively few attempts to directly manufacture a 3DP yarn structure [7]. Yarn is made up of many fibre strands that, when twisted together, create different geometric cell structures and textures. With 3DP technology, these effects may also be accomplished. Studies have looked into yarn-type structures such as needle-felted yarns [80], structures that resemble honeycomb cells [81], and the use of 3DP technology to create texture [82].

Similar to conventional felted nonwoven materials [80], Hudson [82] presented a prototype 3D printer known as a felting printer that uses a barbed needle to entangle fibres to make a needle-felted yarn. These days, 3D printing uses additive manufacturing techniques like FDM to autonomously create warp and weft yarn for woven fabrics.

To create plain weave textiles automatically, the yarn is taken into a model in the STL (Surface tessellation language) file format using 3D CAD design software and then loaded into a 3D printer [83]. Similar to synthetic yarns made using a variety of texturing techniques, the yarn surface may exhibit coiling, wrinkling, and curling [84]. Better performance 3DP technology makes it possible to create a variety of similar texture effects, which encourages the clothing sector to adopt it[80] .

Fabric structure

Although 3DP methods have historically created rigid and solid structures, more recent research aims to develop flexible structures that can adapt to shape and movement to make textiles that resemble weaving but have greater texture and significant shearing capacity [46]. Soft PLA may be used to create flexible, lace-like, glossy fabric using FDM printers, according to[46]. Traditional methods for creating a textured fabric of the tabular braid type use alternating clockwise and counter clockwise yarn runs.

To simulate helical yarn arrangement, 3DP technology introduces transversal tubular braid texture (Maypole braid) [85].

In traditional knitted structures, rows of symmetrical loops are created by interlinking yarns [86]. Because of the material's lack of flexibility, the SLS method produces a knitted-type structure that resembles single-face weft knitted fabric but has distinct mechanical characteristics [86].

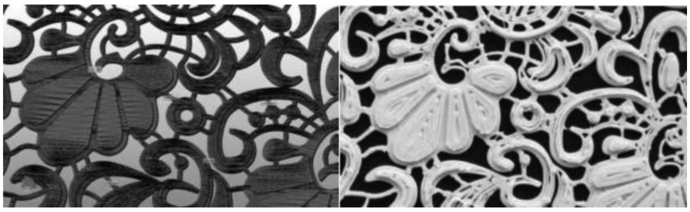


Figure 4. Multi-layer lace pattern, depicted using the Autodesk subsidiary Netfabb GmbH's Software (left panel), and the resulting 3D printed item (right panel) [36]

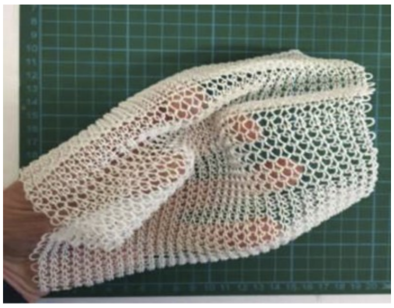


Figure 5. Flexibility of a 3DP weft-knit structure[36]

Flexible structures that stretch horizontally and return to their former shape, such as interlock and single-faced weft knit, demonstrate great flexibility [86]. Researchers are investigating if softer textiles made of thermoplastic polyurethane (TPU) are more suited for fashion applications [86]. Using TPU as the printing medium, MIT researchers have recently created a structurally better fabric that is modelled after the woven pattern of collagen [83,87].

Complete garment structure

3DP is becoming more popular in the fashion sector [87] . The "Black Drape Dress," the first completely functioning 3DP garment, was designed by Finnish conceptual artist Jane Kyttanen and Dutch industrial designer Jiri Evenhuis [88]. With hundreds of 3D-printed items strung together to make a flexible outfit, they aimed to develop clothing, purses, and accessories that could be downloaded and replicated using a 3D printer [89]. The 3DP garment, which was made from white polyamide using SLS technology and resembled limestone deposits creating shells, was part of the crystallization collection in 2010 [90].

About 15 distinct 3DP dresses have been built to date and have been displayed in various fashion shows [22].

Personal protective equipment

The research investigates 3DP as a way to create functional components in textiles that are protective against compression, impact, and penetration without causing pain like polyurethane foam and reinforced plastic [91]. FDM was used by Park and Lee to create a flexible thermoplastic polyurethane mesh cushion that would prevent falls [71]. 3D imaging and 3DP were used to create a customized protective face mask that included a melt-blown polyamide filtration membrane [92]. Utilizing TPU2-86A on polyester knitted surfaces, a textile-integrated 3DP knee and back protection has been created that maintains its effectiveness after 50 washing cycles [48]. 3DP was used on flat-knitted polyamide and elastane surfaces to construct orthopaedic devices that help repair knee injuries [2]. Additionally, textile-like constructions for shoes or bikinis may be prepared using 3DP processes such as SLS and SLA [16,93].

Table 4. A summary of the PPE products created using 3DP technology [2]

Protective wear	3DP Component	Raw Materials	3DP Method	Area of Application
Protective Face Mask	Reusable mask and filter membrane	Polyamide composite	Selective Laser Sintering (SLS	Human face
Personal Protective wear	Knee and Crotch protective components	Thermoplastic polyurethane	Additive Manufacturing (AM, Desktop 3DP)	Knee, hip joint, elbow, Crotch protector
Protective Pads	Fall-impact protection pad	Thermoplastic polyurethane (Ninja Flex)	Fused Deposition Modelling (FDM)	Human body parts vulnerable to fall Impact.
Safety Protective Clothing	Elbow and knee protective 3D shaped component	Shape memory thermoplastic polyurethane	Fused Deposition Modelling (FDM)	Elbow, Knee.

Sensors, electrodes, conductors and actuators

By incorporating new features for real-time input, textile materials are moving toward smarter performance. In contrast to traditional techniques, 3DP of conductive polymer nanocomposites with graphene Nano sheets or carbon nanotubes doesn't need a mould [94]. The solvent-cast 3DP approach was used to construct a scaffold for liquid sensors that was based on conductive nanocomposite[94]. Strain sensors, lab-on-a-chips [95], thermally reduced graphene oxide electrodes [96], and titanium interdigitated electrodes [97] are all possible applications for 3DP multifunctional nanocomposite structures. Multifunctional structures lose compatibility and convenience of assembly by requiring several materials for sensing and actuation [98].

Using desktop 3DP, materials with multifunctional capabilities have been produced via polymer nanocomposites (PNC) with conductive nano-fillers such as graphene or carbon nanotubes [99]. The heat conductivity of a boron nitride/polyvinyl alcohol composite made using the 3DP process was 1.56 and 2.22 times greater than that of cotton and PVA textiles, respectively [44]. Examples of 3DP wearable electronics are displayed in Figure 6.

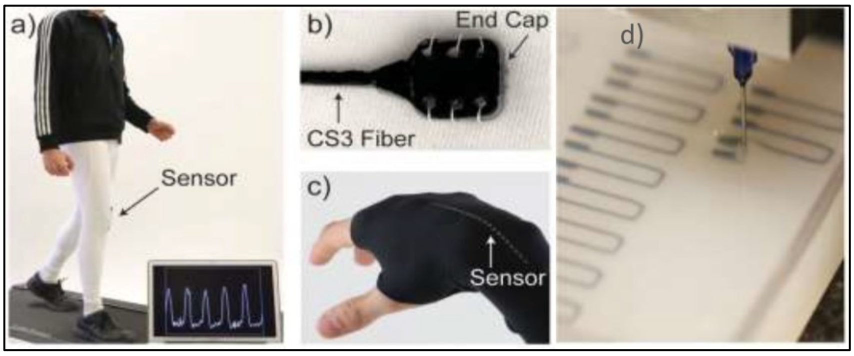


Figure 6. a) 3D Printed capacitive soft strain sensors integrated into fabric across the knee via b) sewing c) weaving, d) embedded 3D printing for the soft strain sensors[100]

A boron nitride/Polyvinyl alcohol composite fabricated through 3DP showed higher thermal conductivity than PVA and cotton fabrics [44]. Figure 6 shows examples of 3DP wearable electronic devices [100].

Conventional textile manufacturing technologies, such as sewing, embroidery, knitting, coating, braiding, and weaving, can integrate electronic sensors and actuators in an attempt to create smart textiles that can interact with their surroundings. However, these methods struggle to achieve threshold performance and accurate results [52]. 3DP technology, on the other hand, showed very good potential for use in textile-integrated circuit paths [52]. 3DP has also been used to add to a group of sensors that can be mounted on a textile for sensing different mechanical parameters [101], and embedding a sensor into the printed shape was successful [102].

3DP on textile substrates

3D printing is applied to textiles in a variety of ways for prototype or practical uses. Appropriate 3DP printing materials on certain textile substrates are being researched by researchers [93,103].

Depending on the wettability, hydrophilicity, surface roughness, and hairiness of individual samples, natural fibre textiles exhibit adherence because of their hydrophilicity and surface roughness, which facilitates the penetration of print paste [104,105] Print paste has excellent adhesive qualities because it is hydrophilic, which allows it to enter the cloth [48]. Because wool has a rough surface, it adheres well [105].

The majority of natural substrates have high adherence to the print surface and adequate print surface characteristics [36]. A floral 3DP pattern on various fabric surfaces is seen in Figure 7 [36]. The printability of textiles depends on the topographical properties of the textile [104]. Adhesion with 3DP materials can be influenced by variables such as the textiles' pre-treatment (laser and washing) [104,106]. Adhesion forces are greatly affected by several factors, such as the z-distance between the nozzle and the printing bed [52].

A textile substrate with a smooth surface and excessive thickness makes printing difficult since the print paste may not adhere to the surface well enough. When 3D objects were printed using the SLA technique, several knit fabrics composed of synthetic textile fibres like polyester, polypropylene, polyurethane, and polyethene terephthalate (PET) demonstrated acceptable printability [77].

Figure 7. Floral 3DP pattern on cotton, wool, viscose rayon and polyester net textile substrate (from left to right)[36]

A lot of work has gone into figuring out if the pre-treatment of textiles has any effect on the adherence of 3DP material and how much it affects the printed part's durability. Pre-treatments including washing and plasma treatment of cotton and polyester textiles might affect the adherence of soft PLA that has been 3D printed, according to [104]. Based on a different investigation, textiles with higher hydrophilia demonstrated superior capillary action adhesion to 3DP materials [48].

As a pre-treatment procedure, washing and treatment with sodium hydroxide solution also produced favourable results [93,06]. Examined the effects of various parameters on the adhesion force between a 3DP polymer and different knitted structures composed of different materials [51]. The researcher Fafenrot et al. suggested that the adhesion forces recorded were significantly influenced by the z-distance between the nozzle and the printing bed in particular and also concluded that the other printing factors, however, had no noticeable impact and there are no numerous links between 3DP production technologies, textile fabrics, and fabric thicknesses [52].

Adhesion

The fabrication of 3DP composites[45] on textiles is dependent on the adhesion of 3DP polymer materials to textile substrates, which opens up new possibilities over time [107]. Composites created by 3DP of polymers on textile textiles are employed to create particular featured textile items when it has become difficult to maintain adhesion between the textile substrate and the printing polymer [45]. Multilateral composites can be classified as 3DP materials by optimizing the adhesion behaviour between the 3DP polymer material composite and the base textile substrate.

The adhesion of the 3D-printed polymer to the textile substrate has presented difficulties, although this has expanded the opportunities for novel textile applications [108]. The research for adhesion improvement [48] and their testing procedures [107] have been covered in a few publications.

For example, surface modification and polymer coating can increase adhesion efficiency [44,93]. Several infill orientations of the first printed layer and related distinct pre-treatments of a cotton woven fabric for 3DP with polylactic acid were tested to determine their effects on adhesion properties.

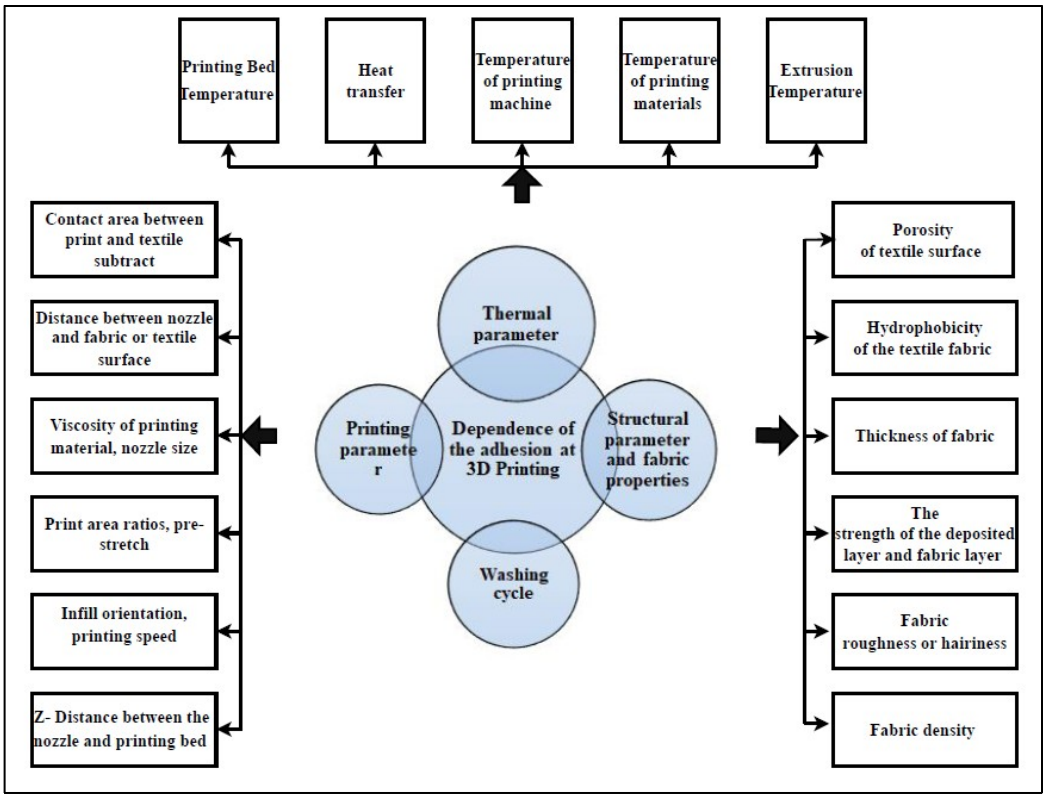


Figure 8. Factors that affect adhesion at 3DP Textiles Process [2]

Factors influencing adhesion

Several factors (as those shown in Figure 8 shows factors affecting adhesion in 3DP textiles [2]. Adhesion quality tested through perpendicular tensile, peel, and shear tests defines the degree of attraction between 3DP materials and textiles [107]. 3DP textile structures can maintain the flexibility and extensibility of textiles while taking advantage of the mechanical properties of printing materials [28]. Through chainlike, closed-loop, interlocked closed, and continuous fibre topologies, some studies have given 3DP textile constructions flexibility [5,28]. A flexible, textile-like behaviour was shown by a 3DP woven fabric structure made with ABS and FDM [83]. Because printing area ratios, pre-stretch, fabric properties, fabric configuration, fabric concentration, and opening geometry all have a significant impact on the adherence between printed polymers and the textile of hybrid three-dimensional 3DP textiles [47,52] soft PLA printed by FDM instead of SLS demonstrated greater flexibility compared to conventional textiles [46].

Since adhesion force and infill orientation are strongly correlated, the investigation of [93] revealed the practical significance of the 3DP parameter, infill angle. It has been demonstrated that the adhesion forces increase from 0° to 90° and decrease as the infill angle increases.

Tello et al. [109] demonstrated that the strong adhesion force, a 90° infill orientation may be taken into account and adhesion requires balancing between the contact area and the gap. The greater contact area between the fabrics and the print might result in better adherence. Furthermore, different 3DP parameters, like printing speed and print-platform temperature, can have a significant impact on how well polymer print materials adhere to fabrics. However, if the glass transition temperature of the material being applied is higher than this temperature, platform temperature cannot significantly affect adhesion strength [58].

There is a correlation between print speed and layer thickness, which influences 3DP's adhesive property. Lower layer thickness results from the greatest 3DP speed, whereas the highest adhesion force may be achieved by keeping printing speeds in the medium ranges [58]. Because it is printed first, the printed section's boundary exhibits a higher degree of adhesion than the centre, which has a lower amount [47].

Adhesion quality

When 3D-printed composites are being produced, the cohesion between textiles and 3DP materials is an example of adhesion quality, which is the degree of attraction between two distinct phases. Adhesion testing determines the adhesion quality of bonding between 3DP polymers and textile materials to determine the force necessary to produce fracture, which is necessary for 3DP composite structures. The adhesion of a 3DP profile on textile substrates was determined using the peel test, shear test, and perpendicular tensile test [107].

To determine the adhesion between printing materials and textile substrate, a peel strength test was performed on polyester jersey weft-knitted fabric using polylactic acid (PLA) as the printing material. Higher peel strength or adherence was observed to result from raising the fabric width ratio, but a decrease in peel strength or adhesion occurred when the printing polymer's width increased [47]. Because it influences the product's quality, durability, and ultimate uses, adhesion is a crucial component. The polymer attaches to the substrate by a variety of methods, including thermodynamic adhesion, mechanical interlocking, and molecular bonding [110].

Flexibility

3D-printed textile structures can maintain the natural flexibility and extensibility of textiles while also using the mechanical qualities of the materials used in the printing ink [28,111]. Textiles printed using SLS that incorporate several assemblies of different elements to permit flexible adaption by any design were discussed by Kamrani et al. [6].

Based on chainlike structure, closed-loop geometry, interconnected closed geometry, and continuous fibre geometry, various efforts have been conducted to provide flexibility to 3DP textile systems[28]. Bingham et al. [112] revealed how to create a 3D textile structure with a quick production approach that demonstrated the drape and flexibility of traditional fabrics. Using ABS print material and the FDM process, a 3DP textile woven fabric structure was exposed to exhibit a flexible, textile-like behaviour [83]. 3DP by FDM instead of SLS, the soft PLA weft-knitted single-faced structure, lace pattern, and multi-material model demonstrated more flexibility than their traditional textile [47].

THE ADVANTAGES AND LIMITATION OF 3D PRINTING TEXTILE

In the fashion industry, 3DP technology is developing quickly and producing results that are in some ways better than traditional methods [88]. But there are other drawbacks to the technology.

Advantages of 3D printing textile over conventional manufacturing

Compared to conventional production techniques, 3D printing has several benefits. It can produce complex models with a wide range of design variations and greatly enhances the production of prototypes and small samples [10,46]. It differs from conventional manufacturing techniques like casting and machining in that it can create structures as tiny as 0.01 mm (using SLA) [77], allowing for the construction of complex designs with a minimum of waste [113]. Although the printing speed is considered slower compared with traditional textile manufacturing, the reduction of the textile process chain length compensates for this. For instance, in 3DP garment production, traditional processes such as fibre preparation, spinning, weaving, dyeing, finishing, cutting and sewing are eliminated, reducing transportation needs and the time from idea to product while minimizing energy costs.

3DP makes it simple to use reverse engineering to modify products. It reduces the limitations of conventional subtractive techniques, including excessive material waste, complicated workflow, expensive apparatus, and high labour inputs [3,15]. SLS offers precise product rendering with high strength, whereas FDM is well-liked for its inexpensive installation costs.

The technique provides design, quick iteration, quick fabrication of flexible items from stiff materials [114], effective customization, and low waste production [20]. Its benefit is primarily due to its further expanded adaptability. Furthermore, the technique is made more adaptable [115] by the freedom to use and choose from a wide range of biological, synthetic, and multifunctional materials [98], photopolymers [114] and polymer matrix composites. Metals, polymers, ceramics, and composites in powder form may all be used by SLS [116]. According to research, 3DP components on polyester fabric exhibit superior stiffness and dimensional stability [78]. Good reinforcement is provided by directly printed 3D textile structures [72], and 3DP can increase the mechanical durability of electro-spun nanofiber mats [93].

Additionally, sensors composed of conductive and piezo response materials that may provide digital readings can be included in printed parts [42]. The 3DP method remains very cost-effective due to the removal of stages needed for traditional textile manufacturing, inventory, storage, packing, and shipping [9,20]. The equipment's broad availability and potential for cost reduction have prompted designers to produce components with unique features for a range of practical applications [88]. In contrast to conventional approaches, 3DP can provide a viable substitute for labour-intensive, high-risk, and time-consuming traditional building techniques [117]. Furthermore, zero-waste production is one of the sustainable advantages of 3DP technology [22].

Limitations of 3D printing textile

There are drawbacks to 3DP technology despite its benefits. Not every surface form, such as zigzag and double face, is appropriate for 3DP [52]. Under extension, samples may fail due to uneven printing and notch wear on wavy surfaces [118]. Two major disadvantages are the poor printing speed in comparison to traditional textile production and the raw material incompatibility with printers [119]. Challenges include viscosity [20], not being as flexible, comfortable, or strong as traditional fabrics, and not being as soft, elastic, or able to regulate moisture and heat [48,108]. Flexible filaments are especially difficult to deposit with FDM [48].

Another drawback is 3DP's limited ability to handle high volumes, which necessitates segmenting the printing components [10,31]. Other significant drawbacks are the creation of huge anisotropies as a result of irregular porosity [78] or voids [120] and longer print times. Additionally, because of the relatively tiny contact surfaces, it is challenging to combine distinct pieces [20]. Despite these limitations, 3DP is still a promising technology.

CONCLUSION

This review article covered 3D printing techniques, including equipment, supplies, and textile industry applications. The variety of materials that may be used for 3DP design elements on currently available basic textile substrates and direct printing of textile structures was emphasized. Adding 3DP components to traditional textiles improves the usefulness and uniqueness of the product. Even though 3DP has significant limits in terms of attaining the whole textile structure, it has potential, particularly for tiny objects. Wearable electronics and smart textiles provide intriguing opportunities thanks to the attachment of electrical devices using 3DP methods. 3DP is expected to rise in the textile and fashion industries in the future, which might lead to the development of novel fabrics, fibres, and applications.

Abbreviations

3DP - 3D Printing
AM - Additive Manufacturing
PLA - Polylactic acid
ABS - Acrylonitrile butadiene styrene
FDM – Fused deposition modeling
CAD - Computer Aided Design
STL - Standard Template Library
SEBS - Styrene Ethylene Butadiene Styrene
HDPE - High-Density Polyethylene
CNF - Cellulose nanofibers
PBT - Polybutylene Terephthalate
DDM - Direct digital manufacturing
DW - Direct write.

Author Contributions

Conceptualization – Lemi MT; methodology – Lemu HG; formal analysis – Lemi MT; investigation – Gutema EM; resources – Lemu HG; writing-original draft preparation – Lemi MT; writing-review and editing – Gutema EM; visualization – Lemu HG; supervision – Lemu HG. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

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