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Digital Textile Printing and Its Role in Sustainable Surface Design and Customized Fashion Products

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ABSTRACT
Digital textile printing (DTP) has proved to be one of the most radical technologies in today's textile and fashion industry and has been redefining the surface pattern design and manufacture and consumption process. DTP, unlike screen or flat-bed printing, which are conventional analogue printing technology, is based on computer-controlled inkjet system which applies dye or pigment directly to the fabric, without using a screen or plate, or much process water. Technological aspects, environmental efficiency, and design implications of digital textile printing is examined in a critical perspective, focusing on the surface design sustainability and on mass customized fashion production. Based on industry reports, lifecycle assessments and peer-reviewed literature, the study reveals that digital printing can save 60-95% water compared to screen printing, 30-75% energy and up to 95% material waste, and support on-demand, made to order production models which curb overproduction from inventory. Digital textile printing is expected to expand at a CAGR of 7-13% until the beginning of the 2030s, as both regulation towards sustainability and consumer demand for personalization help drive growth in the global digital textile printing market, which is estimated to be worth USD 5.8-6.8 billion in 2024-2025. The article also gives an in-depth literature review on the topic, as well as comparative statistical data, process diagrams and a case discussion for design, followed by an assessment of the barriers still remaining to be overcome for digital textile printing to become a key pillar of circular, low impact fashion production.

Keywords: Digital Textile Printing, Sustainable Design, Surface Pattern Design, Mass Customization, Textile Sustainability, Inkjet Printing, Fashion Technology, On-Demand Manufacturing.

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Introduction

Textiles and apparel industry is one of the major water consumers, and one of the greatest industrial chemical polluters, with the dyeing and finishing alone accounting for about 1/5 of total industrial water pollution annually [1]. In this context, digital textile printing (DTP) has gained increasing interest as a technology that can address two seemingly conflicting aspects of the contemporary fashion industry; the need for surface design that is unique, expressive and rapidly changes, and the call to decrease the ecological footprint of textile production [2]. Digital textile printing is printed with dye or pigment inks directly from a computer-controlled inkjet printhead onto a textile-based substrate, with no need for physical screens or engraved rollers, but using only a computer image file to drive the process [3]. Unlike rotary and flat-bed screen printing, DTP eliminates the need to prepare a screen, separate color and wash it, since the design is only available as digital data until it is printed. By eliminating the steps of screen preparation, color separation and screen washing, DTP is cheaper and more efficient than rotary and flat-bed screen printing [4]. The transition from analogue, plate production to an all-digital, file-to-fabric production workflow has implications for the creative practice of surface pattern design beyond its production economics and effects on the cost of color, allowing for photorealistic imagery, unlimited color gradation and single unit customization that would be commercially unfeasible without it.

This article discusses the technological, ecological and design aspects of digital printing in textiles, puts it in the context of the current discussion about sustainable fashion and critically assesses its potential to produce individual fashion products. The structured literature review is presented in Section 2, the underlying technology and process in Section 3, quantification of the sustainability performance of DTP relative to conventional printing in Section 4, surface design and mass customization application in Section 5, market statistics in Section 6, challenges and limitations in Section 7 and future research directions in Section 8, concluding remarks in Section 9.

Literature Review

The literature on digital textile printing can be summarized as being in three thematic groups: (a) technological and process-oriented studies, (b) environmental and lifecycle-assessment studies, and (c) design, customization, and consumer-behavior studies.

Technological Foundations

Ujiie [2] is one of the early technical accounts of digital textile printing, which has developed from the early piezoelectric and thermal inkjet systems to industrial single-pass printing systems with speeds up to 75 meters per minute. Later technology reviews have been recorded of a transition from dye inks to pigment inks and reactive inks that cut or eliminate the need for post-print steaming and washing [1, 6]. Patent literature also evidences ongoing improvements of pre-treatment application techniques to lower energy consumption and water pick up when compared to conventional dip and squeeze pre-treatment, such as foam-based padding [7].

Environmental and Lifecycle Studies

There are several studies quantifying the environmental benefits of DTP based on the lifecycle approach. The LCI of Kujanpää et al. [8] has been broadly referenced by other studies on the carbon footprint of the textile industry [9] and has been used to simulate the environmental effects of digital and conventional textile printing in a European electricity-grid scenario. Despite many of the savings figures commonly cited in the

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industry being hard to pinpoint and by many, if not most, factors, in a controlled, comparative study within a vertical apparel mill Hoque et al. [10] measured natural-gas consumption of 133.6 m3 for rotary-screen printing and 99.2 m3 for digital textile printing on a 1000-metre, sixteen-colour cotton print order (a 26% reduction). Water reduction in the 60-95% range, and energy reduction in the 30-75% range, are consistently reported across the board by industry-sourced data from SPGPrints [4], [11] and FESPA [6], [12] although these values are mostly derived from single-site, industry trials and are not based on peer-reviewed lifecycle assessment.

Design, Customization, and Consumer Behavior

There is a parallel body of literature that discusses digital printing to enable mass customization in apparel and interior textiles. Along with on-demand, digital production, Dissanayake [13] suggests that mass customization can also help to lower the amounts of raw materials and distribution inventory compared to forecast-based mass manufacturing, but he points out that the environmental benefits of customization have been somewhat under-researched, compared to the economic and marketing benefits. In exploring the broader paradigm shift in fashion from production-driven to consumption-driven, Musto [14] introduces digital printing as one of the personalization-enabling technologies, alongside body scanning and additive manufacturing. Digital printing and body-data-driven design tools are also cited as key enablers of the change from forecast-driven to demand-driven apparel production, by both Fibre2Fashion [15] and Kornit [16]. A Springer Nature contribution that specifically addresses DTP [17] suggests shifting digital printing to the role of co-creation tool in a ‘customize-print-make-wear' approach, to overcome overproduction and the environmental impact from the long-globalized chains of supply, but also recognizes challenges in adoption due to design-, cost-, and skills-related issues.

Digital Textile Printing: Technology and Workflow

There are several digital textile Printing processes, depending on the substrate and uses. Direct-to-fabric (roll-to-roll) systems print continuous lengths of fabric and dominate the yardage production in the industrial sector; Direct-to-garment (DTG) systems print directly onto the finished garment or semi-finished garments, and are popular for the short-run and single-unit printing; Direct-to-film (DTG) systems print onto an intermediate transfer film, which is then transferred to the garment by heat-application and is suitable for a wide range of fabric types since there is little pre-treatment required. Ink chemistries include reactive inks (natural fibres like cotton and silk), disperse and sublimation inks (polyester and synthetic blends), acid inks (protein fibres like wool and nylon) and pigment inks, which are compatible with the broadest range of substrates, require neither pre nor post wash-out, and are the fastest growing category on sustainability grounds [20]. A normal sequence for DTP production is to design the digital images, to pretreat the fabric with a fixing agent to the fibre surface, to inkjet print the images, to heat or steam the images to fix the colorant and to wash and finish the fabric to remove unfixed colourant and stabilize hand-feel.

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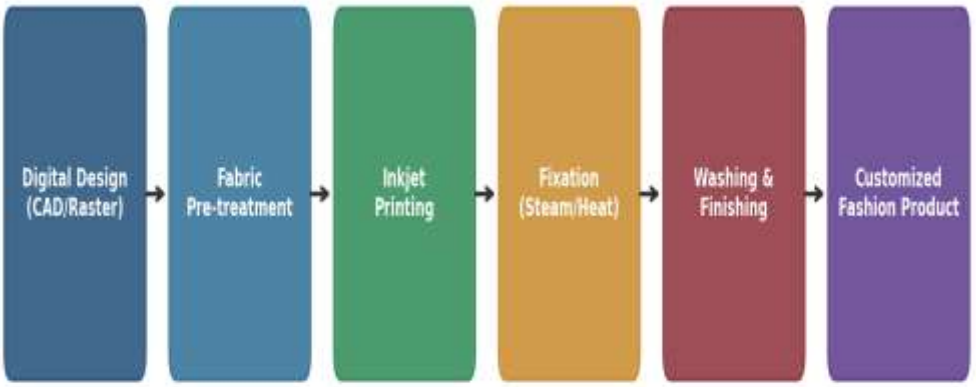
Figure 4: Typical Digital Textile Printing Workflow for Customized Fashion Products



Sustainability Dimensions of Digital Textile Printing

Digital textile printing has four key resource areas for its sustainability case: water, energy, chemicals, and material waste. Water is used in conventional rotary and flat-bed screen printing at various stages - for preparation of the screen, cleaning the screen, mixing the paste and most importantly for steaming and washing the printed cotton fabrics - in many cases 50-60 litres per linear metre of printed fabric (in some analyses up to 200 litres per metre of cotton fabric for heavily printed designs) [4], [21] and [22]. Digital printing in turn, can be measured at 14-20 litres per linear metre for digital reactive-ink printing and at close to zero printing process water consumption with digital pigment-ink printing (excluding small amounts of water used for cleaning the belt) [4] [23].

Figure 1: Water Consumption — Conventional vs. Digital Textile Printing

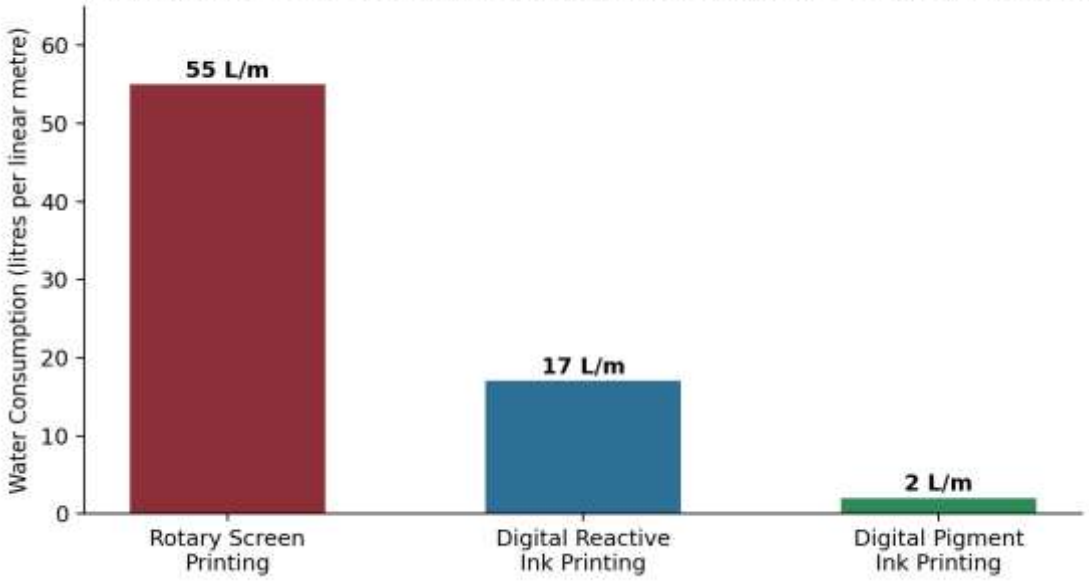


Figure 1. Comparative water consumption of rotary screen printing versus digital reactive and pigment inkjet printing (litres per linear metre) [4], [21], [23].

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The same applies to energy usage. According to industry lifecycle comparisons, digital textile printing can use 30-75% less electricity than rotary screen printing – in part because of the fact that no energy is used for screen washing, no energy is needed to operate exhaust fans for removing solvents from the air and no energy is wasted while waiting for colour mixing stations to be ready for use [11] [24]. According to a carbon-footprint study carried out by the Epson Textile Solution Centre the carbon footprint of a conventional rotary printing system was 139.56 kg CO2-equivalent, while the carbon footprint of the digital system studied was 85.66 kg CO2-equivalent, representing a reduction of almost 40% [24].

Materials efficiency is another area of sustainability, aside from water and energy. Digital printing only uses the ink where it is needed, and doesn't require the manufacture of physical screens for each colour separation, which means that there is no plate waste associated with screen-printing, and that there is a saving in ink and dyes use of around 10% compared to screen-printing, and up to 95% in overall production waste [25],[26].

Table 1 summarizes the principal quantitative comparisons reported across the reviewed sources.

Parameter	Conventional Screen Printing	Digital Textile Printing	Approx. Reduction
Water use (reactive ink, cotton)	50-60 L/linear metre	14-20 L/linear metre	60-70%
Water use (pigment ink)	50-60 L/linear metre	0-10 L/linear metre	up to 95-99%
Energy consumption	Baseline (100%)	25-70% of baseline	30-75%
Carbon footprint (per functional unit)	139.56 kg CO2-eq	85.66 kg CO2-eq	~39%
Ink/colourant consumption	35-60 cc per metre	6-9 cc per metre	~85-90%
Production waste (screens, offcuts)	Baseline (100%)	Up to 95% lower	up to 95%
Natural gas use (case study, 1000 m order)	133.6 m3	99.2 m3	~26%

Table 1. Comparative resource-use indicators for conventional screen printing versus digital textile printing.

In addition to the process level resource savings, digital printing has a second, more structural, sustainability benefit: the freedom to create designs only when an order is placed – which eliminates the overproduction that is one of the biggest sources of waste in conventional fashion manufacturing, and is widely recognized as being more significant on a systemic level than the efficiency of the printing processes themselves [13], [27, 28]].

Digital Textile Printing, Surface Design, and Customized Fashion Products

In terms of design, digital textile printing eliminates some of the restrictions that are used to keep surface pattern designers in check, when using screen-based printing. The designers are no longer bound by the few flat color registrations as DTP can handle continuous tone gradation, photographic images and virtually unlimited number of colors

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in a single design file, without extra color cost per color [5, 18]. This has led to a new vocabulary for surface pattern design, such as photorealistic floral designs, painterly digital textures, engineered placement prints, and generative or algorithmically created patterns which would be impossible to produce by rotary screen engraving [17].

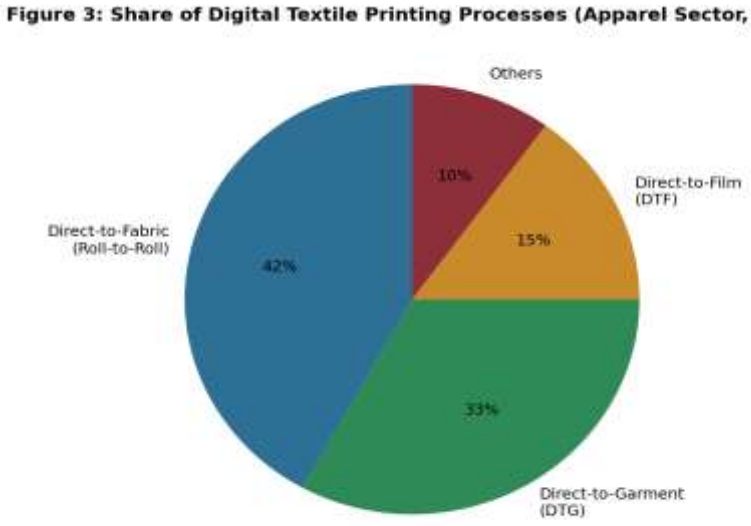

Figure 3. Estimated share of digital textile printing processes within the apparel sector, 2025, based on [19], [29].

It is the same screen-free, file-based workflow that helps designers that makes mass customization possible: no costs are associated with the screen preparation for each print run, and the marginal cost of creating a unique design—or a "personalized" design for each customer—approaches the marginal cost of creating an identical run of thousands. This has led to the development of a new print-on-demand/made-to-order fashion business model where the customer designs or uploads artwork, then chooses style, size and color and gets the garment once the order is placed [27],[32]. Academic literature on mass customization will refer to this as a transition from ‘era of the product' to ‘era of experience and individualization' in which personalization becomes a design approach, a marketing value differentiator and, when combined with on-demand production, even a solution to reduce inventory-related waste [13, 16].

In the case literature (both the trade press and academic research) examples can be found that show this convergence: the combination of digital pressing machines with on-demand production facilities has led to the possibility of printing garments to order within a few hours; local printing of garments by e-commerce brands, as enabled by the new flexible digital textile and garment production systems, has brought a new level of product customization to the market; and the flexible production of digital textile and garments for very small production runs has made it possible for very small fashion brands to be profitable and reach the consumer via the influencers. As a whole, the examples illustrate the digital textile print as an enabling infrastructure for the production of expressive surface design, as well as economically sustainable customization at scale.

Market Trends and Statistics

Sources in the market intelligence field converge on a time of sustained growth of 20%, or high-single-digit, for the global digital textile printing market. The market size for 2024-2025 has been estimated to be in the range of USD 4.3 billion to USD 6.8 billion based on the scope and methodology but the CAGR for 2025-2033 is normally in the

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range of 7% to 13% [33]-[38]. The two most prominent markets are Europe and Asia-Pacific, both of which are consistently mentioned because of sustainability regulation (e.g. Ecodesign for Sustainable Products Regulation, EU) and manufacturing scale and textile-technology investments in the region (e.g. Japan, China) [39], [40].

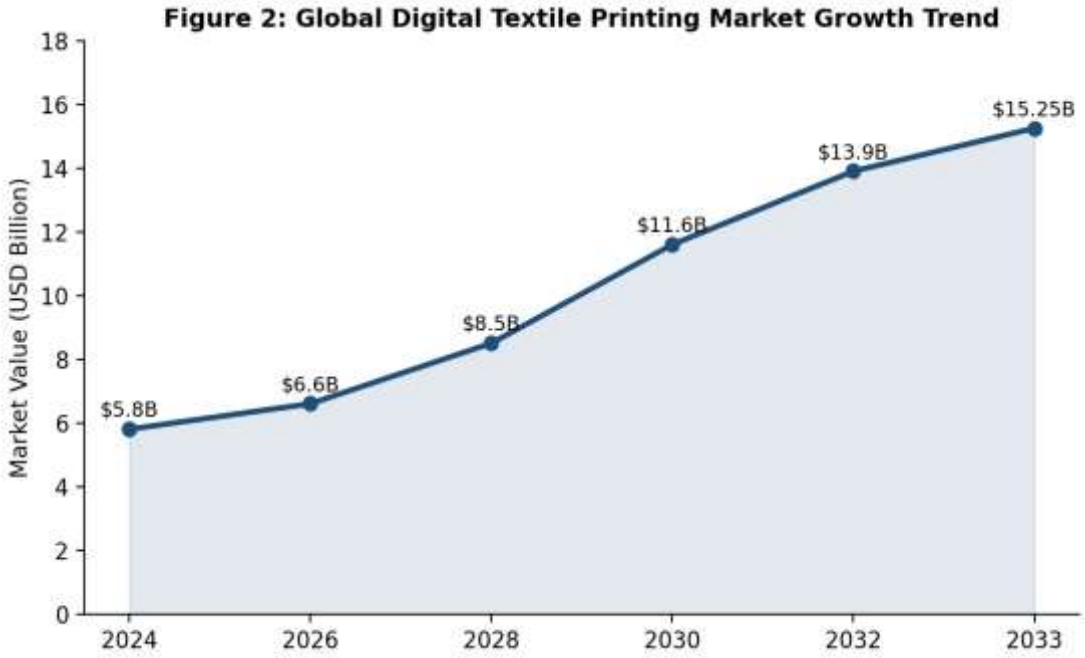

Figure 2. Indicative global digital textile printing market growth trajectory, 2024-2033 (USD billion), synthesized from multiple market-research estimates [33]-[38].

Indicator	Reported Value	Source Basis
Global market size, 2024	~USD 5.8-6.8 billion	Grand View Research; MarketsandMarkets
Projected CAGR, 2025-2033	7.1% - 13.0%	IMARC; Grand View Research; MRF
Apparel segment share, 2025	~42-64.5% of applications	Persistence Market Research
Direct-to-fabric process share	~33-67% of process volume	Grand View Research; Coherent Market Insights
Consumers willing to pay more for eco-friendly textiles	94.6%	IMARC Group industry survey
Natural fibre substrate share	~48%	Persistence Market Research
Custom/personalized apparel market, 2024 to 2032	USD 678.4M to USD 1.26B	Credence Research (via NetSuite)

Table 2. Summary of key market statistics for digital textile printing and customized apparel, compiled from [33]-[41].

Direct-to-fabric (roll-to-roll) printing is the production process most widely used by production volume and direct-to-garment printing is still gaining momentum and will continue to grow rapidly as it is suitable for short-run personalized garment production

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[19] [29]. Sublimation and pigment inks combine to make up the largest share of inks used, due to both the high polyester content of sportswear and fast-fashion areas, as well as the eco-friendly benefits of pigment chemistry for cotton and blended materials [29], [42].

Challenges and Limitations

Although digital textile printing has many merits, there are also some challenges to overcome for its adoption. First, capital costs are still high: industrial single-pass digital printers and pre/post-treatment equipment are costly, and can be a disadvantage for small and medium business compared with the well-established screen printing industry [43]. Second, in the case of very large production runs (usually larger than 3,000-5,000 linear metres), rotary screen printing will still have a cost per metre benefit from amortized screen costs and increased throughput speeds, so digital and analogue will most likely be complementary technologies rather than the analogue method being completely replaced by digital in the near future [44].

Third, there are numerous widely quoted sustainability data points that are based on case studies of individual companies or manufacturer marketing data, but are highly dependent on fabric type, design coverage, ink chemistry, and machine generation, and require more standardization in comparative metrics [10]. Fourth, on-demand and customized production models can mitigate overproduction in structures, but they also entail logistical challenges, such as smaller production lot sizes, increased per-unit packaging and shipping due to individualized order fulfilment, and more frequent job changes (batch changes) in the process, which must be balanced against the potential for upstream process savings [13], [27]. Lastly, there are still workforce and technical-skills shortages in colour management, raster image processing, and digital pre-press, which hinder colour adoption in areas that traditionally have used analogue printing methods [45].

Future Directions

There are multiple paths that digital textile printing is likely to follow in the future. The small cost difference between the single-pass printhead and rotary screen remaining for mid-volume production runs is anticipated to be further closed by continuing improvements in single-pass printhead speed and resolution [36]. The growing trend of using biodegradable, plant-based and waterless pigment inks should also help to minimise the environmental impact of both the pre-treatment and post-print finishing processes [11], [46]. Artificial intelligence-based colour management, defect detection and cloud-related production platforms are enhancing the uniformity and introducing a new paradigm of distributed, localized micro-factories and significantly reducing the supply chains of on-demand and customizable fashion products [36], [47]. Lastly, as there is growing pressure from regulatory bodies and requirements for transparency of print lifecycle information, such as the EU Digital Product Passport for textiles, there are opportunities for more robust and standardized academic life cycle assessment of digital print versus conventional print [39, 48].

Conclusion

The digital textile printing represents a unique area in the present-day fashion and textiles industry where environmental protection and creative freedom meet. The evidence presented in this article shows that digital printing can significantly cut water use, energy consumption, chemical releases and material waste compared to the conventional screen

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printing process and that digital's file based process and the elimination of the screen can provide a degree of surface design complexity and mass customization that the conventional process cannot economically match. Meanwhile, the literature warns of exaggerated claims of uniform sustainability benefits, as reported sustainability gains can vary and lifecycle assessment is still not a standard practice. The technology of digital textile printing seems to be poised to play a growing role in a more sustainable and design-focused world of textiles and fashion, albeit perhaps not a primary one, as the capital cost drops, chemistries advance and there is growing regulatory and consumer demand for sustainability and personalization.

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