Fashion Design & Apparel Technology Reviews and Letters

Digital Design, Fabric Colouration Mechanisms, Uses and Limitations: A Narrative Review

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ABSTRACT

Fashion design has moved from a craft-led, sample-heavy workflow to a digitally mediated one that includes 3D garment simulation, digital printing and data-driven product development. At the same time the sector faces scrutiny over water use, chemical pollution, emissions and textile waste [1]. This narrative review: (i). outlines the apparel design-to-production pipeline and the digital tools now embedded in it, and (ii). examines in depth how fabrics are coloured: the mechanisms by which each dye or pigment class binds to fibre, current uses, and limitations. Conventional reactive dyeing of cotton, salt-free cationised-cotton dyeing, disperse dyeing of polyester, acid, vat and pigment systems, natural dyes with mordants, supercritical CO_2 ($scCO_2$) dyeing and digital inkjet printing are compared. The principal conclusion is that no single colouration technology is universally superior: each trades off fibre scope, fastness, cost and environmental load, and the most promising waterless route ($scCO_2$) is currently confined largely to polyester [16].

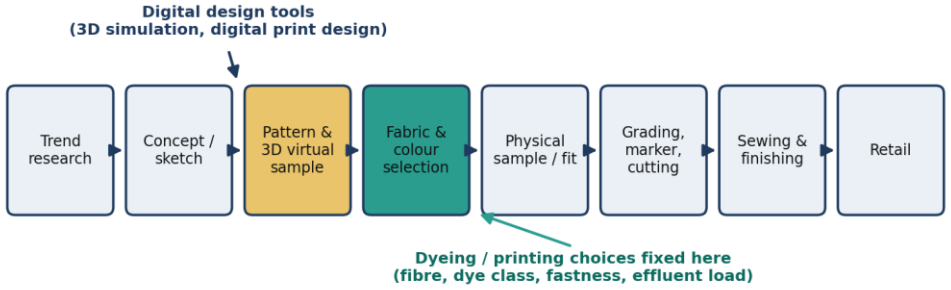
Key words: Apparel technology; fashion design; textile dyeing; reactive dyes; disperse dyes; natural dyes; mordants; supercritical CO_2; digital textile printing; 3D garment simulation.

1. Introduction

The fashion industry is a major environmental actor. A widely cited review identifies impacts at critical points of the textile and fashion value chain, focusing on water use, chemical pollution, CO_2 emissions and textile waste, and attributes much of the pressure to fast fashion, which relies on cheap manufacturing, frequent consumption and short garment lifetimes [1]. Wet processing (dyeing, printing and finishing) is a recognised hotspot because it requires significant amounts of water, energy and chemicals [2]; a UNEP figure quoted in the natural-dye literature puts the contribution of dyeing and finishing at 36% of the climate impact of the textile supply chain [2].

Two technology strands respond to these pressures. **Design-side digitalisation** reduces physical sampling and speeds iteration. **Process-side innovation in colouration** seeks to lower water, salt, energy and effluent. Because colour decisions made at the design stage determine which fibres, dyes and processes are used, the two strands are linked. This review covers both, with greater depth on colouration.

Figure 1. Simplified apparel design-to-production pipeline



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2. Scope and Method

This is a narrative, not a systematic, review. Sources were located through targeted searches on dyeing, printing, natural colorants, $scCO_2$ and 3D garment simulation. Each record was then checked for authors, title, journal and identifiers. Priority was given to peer-reviewed reviews and publisher or repository records; manufacturer and trade sources were used only for practical ink–fibre pairings and are flagged as such. Findings are indicative, and selection bias is possible. Numerical claims are reported only where a retrieved record states them, and the originating source is cited.

3. The Apparel Design-to-Production Pipeline

3.1 Digital design and 3D simulation

3D virtual simulation systems such as CLO3D and Marvelous Designer, and industrial solutions such as Browzwear V-Stitcher, Optitex PDS and Lectra Modaris 3D, provide 3D visualisation alongside digital pattern construction [3]. A study that developed 3D dynamic garments with changeable styles, colours and textile patterns in CLO3D and After Effects reported, from focus groups with designers and digital experts, industrial and social potential, together with issues such as the uncanny valley around avatars and changes to the design process itself [3].

Claimed benefit: Replacing physical samples with virtual ones is expected to reduce material waste and iteration time. The retrieved vendor interview states this as an expectation [4]; no independent quantitative evidence was located in this search, so the sustainability benefit is treated here as plausible but unquantified.

Limitations: The accuracy of simulation depends on how faithfully fabric mechanics are digitised, on-screen colour does not equal dyed colour, and software licensing and skills create adoption costs. These are general observations rather than findings of a single verified study.

3.2 Why colouration matters to designers

Colouration is not only aesthetic. The dye or pigment class determines which fibres can be used, the achievable gamut, fastness, and the environmental load of the finished garment. Designers and technologists therefore benefit from understanding the binding mechanisms summarised in Section 5.

4. Fundamentals of Colouration

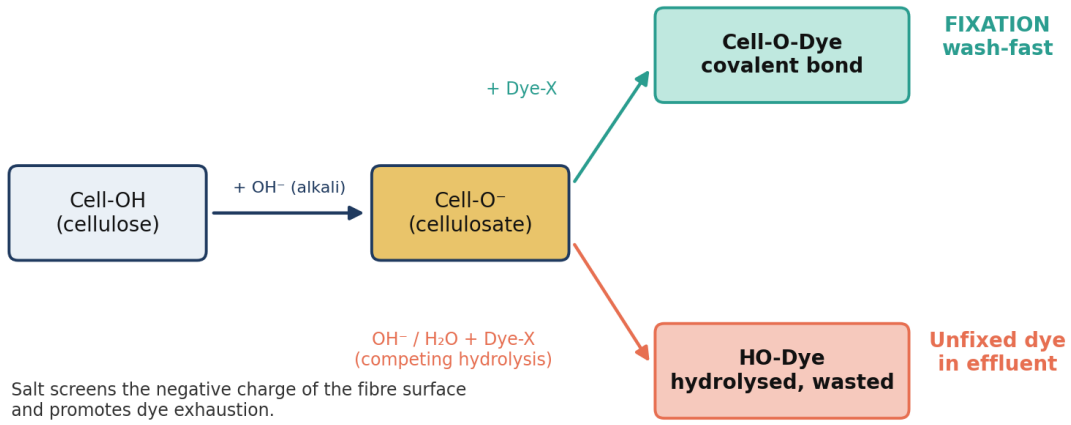
Colour is imparted either by **dyes**, which are soluble or solubilisable and bind to or within the fibre, or by **pigments**, which are insoluble and are fixed on the surface by a binder. Performance is judged by **colour fastness** (to light, washing and rubbing), shade reproducibility and cost. Fibre chemistry is decisive: Cellulosics (cotton, viscose) carry hydroxyl groups; wool, silk and nylon carry amino groups; polyester is hydrophobic and lacks reactive sites.

5. Colouration Mechanisms, Uses and Limitations by Dye Class

5.1 Reactive dyes on cotton (covalent bonding)

Reactive dyes are the most popular dyes for cellulosic fibres and are usually applied by exhaustion, with large amounts of neutral salt and alkali added to fix the dye [5]. Cotton coloured with reactive dyes represents the largest volume of apparel dyeing and contributes most to its environmental load [7]. Under alkaline conditions cellulose is activated to cellulosate, which attacks the reactive group of the dye to form a covalent ether bond; hydroxide competes by hydrolysing the dye, which can then no longer bond (Figure 2). Salt reduces electrostatic repulsion between the anionic dye and the negatively charged fibre surface and promotes exhaustion.

Figure 2. Reactive dye on cotton: fixation versus hydrolysis



Uses: Reactive dyes give a full range of bright fashion colours with a high degree of wash fastness [6].

Limitations: Salt and alkali raise dissolved solids and oxygen demand in the effluent, and unfixed dye adds colour pollution [6]. One review reports that 10–40% of the dye is not fixed to the cotton [5]. Mitigation options reviewed include developing reactive dyes, modifying machinery and processes, chemically modifying cotton before dyeing, using biodegradable organic compounds in the dyebath, and effluent treatment, each with its own limitations [6]. In one pad-steam study, replacing inorganic electrolyte and alkali with a biodegradable organic salt gave more than 90% dye fixation [9].

5.2 Salt-free reactive dyeing on cationised cotton

Cationisation introduces positive sites on cotton so that anionic reactive dyes are attracted to the fibre without added salt. In one study, treated cotton dyed from a slightly acidic bath developed positive sites by protonation of amino groups; anionic reactive dyes were attracted to these sites, the salt requirement was eliminated, and dye fixation also improved [8]. Reviews describe cationic modification of cotton as a promising way to increase dye utilisation [5].

Uses. Lower salt discharge and higher colour yield on cotton.

Limitations: Cationisation is an added pretreatment step requiring a chemical agent, and the approach has been known for a long time without yet making a major impact on the textile industry, with commercialisation problems still to be solved (stated in a review summary indexed by the University of Alberta; full text not accessed).

5.3 Disperse dyes on polyester (solid solution)

Disperse dyes are sparingly water-soluble, non-ionic molecules, dispersed in water and taken up by hydrophobic polyester at high temperature (typically around 130 °C under pressure for exhaust dyeing). They diffuse into the amorphous regions and remain there as a solid solution held by van der Waals and dipole forces. In digital printing, disperse inks are in almost all cases limited to polyester and fall into low-energy (transfer or sublimation) and high-energy categories; high-energy disperse dyes provide outstanding light fastness [11]. Sublimation printing on polyester generally gives somewhat lower fastness than direct disperse printing [10].

Limitations: Restricted to polyester and related synthetics, energy-intensive, and followed by clearing steps that generate wastewater (general knowledge).

5.4 Acid dyes (wool, silk, nylon)

Anionic, usually sulfonated dyes form ionic bonds with protonated amino groups of protein and polyamide fibres under acidic conditions. Acid inks give very bright colours [11].

Limitation: Fibre scope is limited to amino-containing fibres.

5.5 Vat, indigo and sulphur dyes (reduction–oxidation)

The insoluble dye is reduced to a soluble leuco form, absorbed by cellulose, then re-oxidised to the insoluble form trapped within the fibre. **Limitations:** the reducing agent and oxidation step add chemical load. This mechanism is general textbook knowledge and was not separately verified in this search.

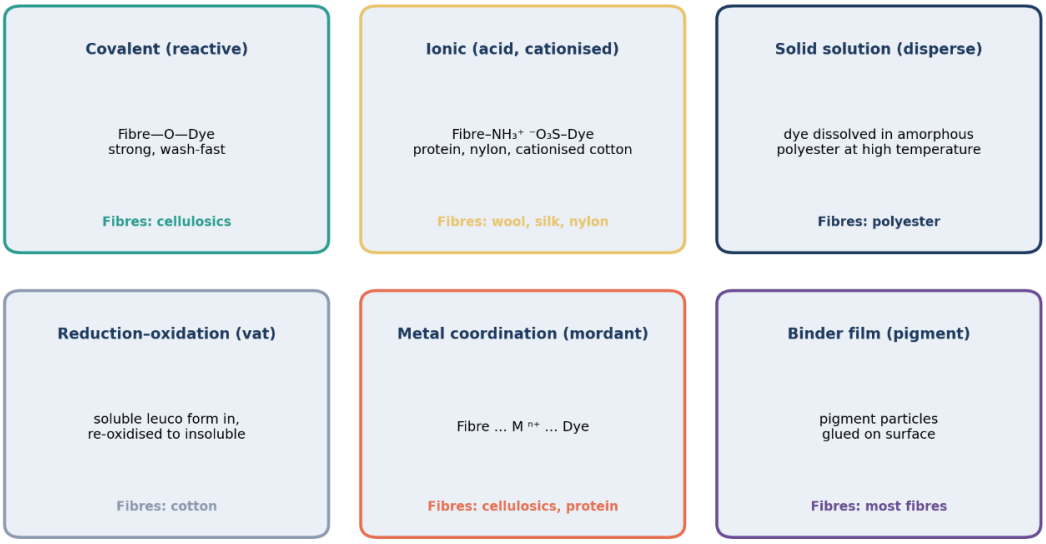
5.6 Pigments and binders

Pigments have no affinity for the fibre. A polymeric binder fixes them on the surface, so colouration is superficial. In conventional printing pigment inks dominate (a trade source cites around 60% of printed fabrics), while in digital printing their use is still in an earlier stage [10]. Digital pigment inks have been slow to develop because particles must be small enough for inkjet heads and pretreatment is needed for acceptable colour yield [10]. Pigment inks with good wash fastness typically carry less colour [11]. **Limitations:** Surface colour, generally lower colour intensity than reactive inks, and higher ink cost (trade sources) [10].

5.7 Natural dyes and mordants

Natural dyes come from plants (for example indigo and madder), minerals, animals (for example cochineal) and microbes, plants being the most common source [2]. Dyes are the colouring agents, whereas mordants are auxiliary chemicals that strengthen bonding between dye and fibre; natural dyes typically show poor light, wash and rubbing fastness unless mordants are employed [12]. Traditionally, metal salts serve as mordants because most natural dyes have little affinity for textile fibres, especially cellulosics [13]. The metal ion acts as a bridge, forming a coordination complex between dye and fibre (Figure 3).

Figure 3. Principal dye–fibre binding mechanisms



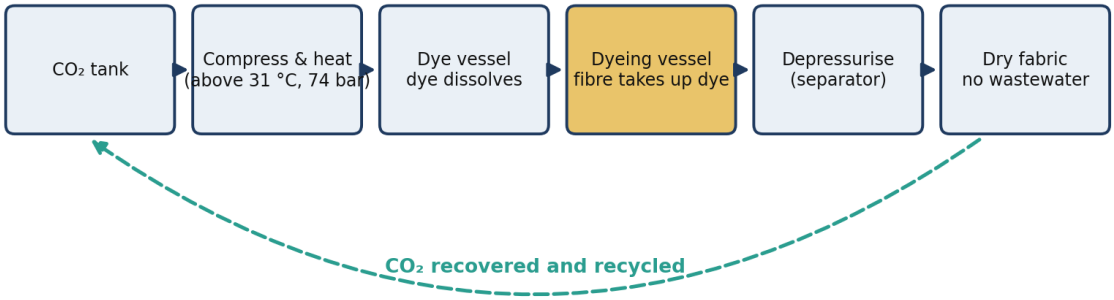
Uses: Natural dyes offer biodegradability and reduced toxicity [12], and most bio-based dyes are renewable and non-allergic, which suits niche and premium products [14].

Limitations: Poor fastness, low affinity for substrates, difficult shade reproducibility and cost-effectiveness concerns still prevent large-scale industrial adoption [2]. A constrained palette of shades is another limit [14]. Seasonal and geographic variation in dye sources contributes to inconsistency [12], and fastness depends on the fibre, the dyeing method and the mordant [15]. Conventional metallic mordants released in effluent can harm ecosystems, prompting research into bio-mordants such as tannin-rich materials [13].

5.8 Supercritical CO_2 dyeing (waterless)

$scCO_2$ is a non-aqueous medium in which suitable dyes dissolve, allowing dyeing without process water; the solubility of the dye in $scCO_2$ is a central design factor [17]. Dye dissolved in dense CO_2 is carried to the fibre. On depressurisation the CO_2 is released and can be recycled (Figure 4).

Figure 4. Supercritical CO_2 dyeing cycle (schematic)



Original schematic. CO_2 becomes supercritical above about 31 °C and 74 bar (general physical constants).

Uses: The technology has been reviewed for both synthetic and natural fabrics, with potential energy and water savings [17].

Limitations: A 2025 review concludes that $scCO_2$ dyeing is primarily suitable for polyester with disperse dyes and unsuitable for cotton, wool and other fibres because the dyes used for them are not soluble in $scCO_2$ [16]. A master's-thesis life-cycle assessment found it can be environmentally beneficial only if energy use and CO_2 losses are optimised and a greener electricity mix is used, and describes its result as a first screening requiring further validation [18]. High-pressure equipment and capital cost are additional barriers.

5.9 Other waterless and low-water approaches

Air dyeing and foam dyeing are reported as water-saving techniques with less waste, shorter working times and lower energy use [19]. Decamethylcyclopentasiloxane (D5) has emerged alongside $scCO_2$ as one of the two most promising green dyeing media [16]. The Chalmers thesis identified plasma technology, spin-dyeing, $scCO_2$ dyeing, digital printing, ozone bleaching, enzymatic treatments, electrochemical dyeing and ultrasonic treatment as emerging wet-processing technologies [18].

6. Digital Textile Printing

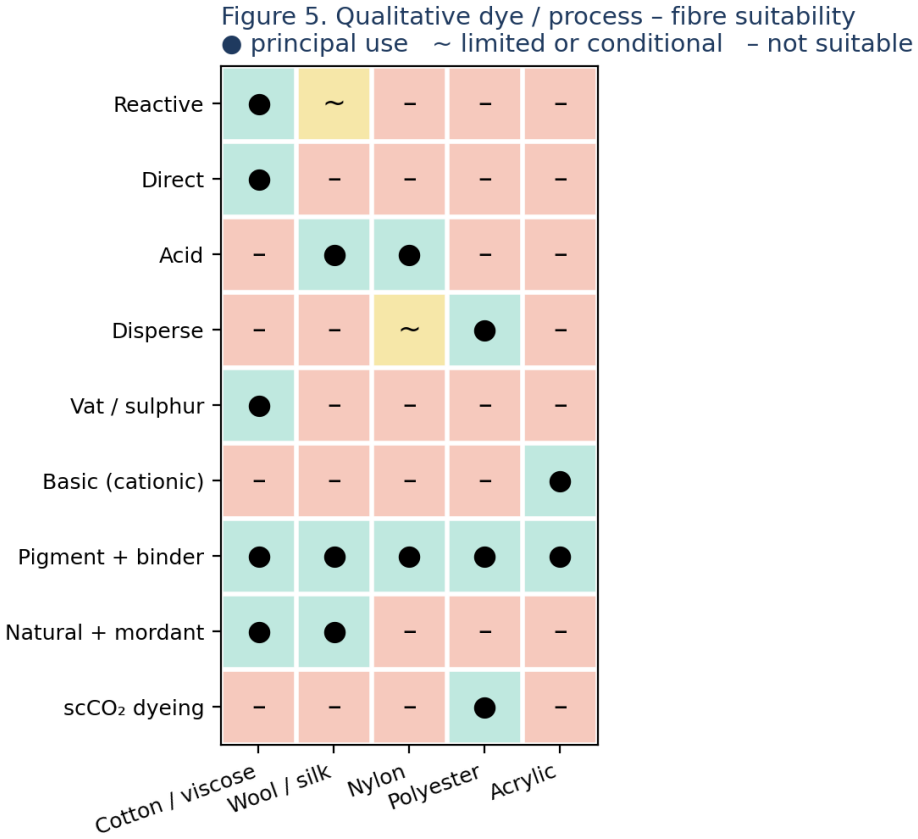
Inkjet printing applies colour as droplets only where needed. Ujiie's edited volume presents digital printing in terms of printer and print-head technology, colour management, colouration (substrate preparation, pigmented and aqueous inks, pretreatment, and reactive inks on cationised cotton) and the design and business aspects, including mass customisation and just-in-time printing [20]. A later book covers inks, fixing, washing, and the effect of inkjet printing on the textile industry and on design for printed textiles [21].

Table 1. Ink–fibre pairing (practical guidance from trade sources [10, 11])

Ink class	Typical fibre	Strength	Limitation
Reactive	Cotton, viscose	High wash fastness and high-quality colour	Needs fabric pretreatment; steaming and washing
Acid	Wool, silk, nylon	Very bright colours	Fibre-specific
Disperse (direct / sublimation)	Polyester	Brilliance; light fastness	Polyester only; sublimation gives somewhat lower fastness than direct disperse
Pigment	Natural and synthetic	Fewer process steps	Pretreatment for colour yield; less colour-intense; surface colour

Uses. Short runs, customisation and rapid design changes. **Limitations.** Ink cost, fibre-specific inks, and pretreatment and after-treatment steps that still use water and energy.

7. Comparative Summary



Original qualitative matrix synthesised from the mechanisms in Section 5 and the cited sources; it is a guide, not measured data. $scCO_2$: polyester only [16].

Table 2. Colouration technologies compared

Technology	Fibres	Mechanism	Main advantage	Main limitation
Reactive (exhaust)	Cellulosics	Covalent bond	Bright, wash-fast [6]	Salt, alkali, unfixed dye [5, 6]
Cationised reactive	Cotton	Ionic attraction, then covalent	Salt-free, better fixation [8]	Extra pretreatment; limited industry uptake
Disperse (high temperature)	Polyester	Solid solution	Good on polyester [11]	Polyester only; energy
scCO2	Mainly polyester	Dissolution in dense CO2	No process water [17]	Dye solubility, equipment; not for cotton or wool [16]
Natural + mordant	Cellulosics, protein	Metal coordination	Biodegradable, low toxicity [12]	Fastness, reproducibility, scale [2]
Digital inkjet	Ink-dependent	Ink–fibre specific	Customisation, short runs [20]	Ink cost; fibre-specific; pretreatment

8. Discussion

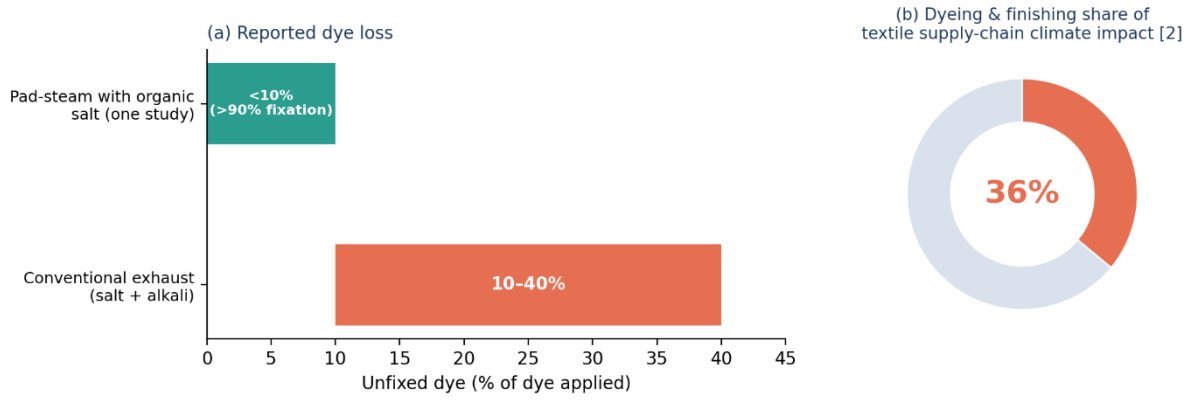
1. **No universal green dye.** Waterless $scCO_2$ works for polyester but not for the cotton that dominates much apparel [16,7]; cotton solutions such as cationisation and improved reactive chemistry remain partly developmental [5,6,8].
2. **Natural dyes remain niche** because of fastness and reproducibility, not lack of interest [2,12].
3. **Evidence gaps.** Independent quantitative evidence for 3D sampling benefits and for $scCO_2$ at industrial scale was limited in the material retrieved here [4,18].
4. **Design-process coupling.** Choices at the design stage (fibre, colour depth, print versus dye) lock in environmental load, so design software that links colour specification to dye-process data would be valuable. This is an interpretive suggestion, not a cited finding.
5. **Data caution.** The published abstract of Niinimäki et al. states 79 trillion litres of water per year, while an archived accepted-manuscript abstract states 1.5 trillion litres [1].

9. Conclusions and Outlook

Fashion design is becoming more digital, but the environmental footprint of apparel is still largely decided in wet processing. Reactive dyeing of cotton delivers bright, wash-fast colour yet generates saline, coloured effluent [6]. Salt-free routes, organic-salt formulations and cationisation can cut chemical load [8,9], though adoption is limited. Natural dyes are attractive for toxicity and biodegradability but are held back by fastness, shade consistency and scale [2]. $scCO_2$ shows that waterless dyeing is feasible, but only for polyester so far [16]. Digital printing complements these by enabling short runs and customisation [20].

Priorities for research and practice, offered as interpretation rather than as established findings, are: (i) dyes soluble in $scCO_2$ or alternative waterless media for cellulosics and protein fibres; (ii) industrially validated, low-cost cationisation or equivalent salt-free chemistry; (iii) biomordants with proven fastness on a standard test programme; and (iv) transparent life-cycle data for both digital sampling and waterless dyeing.

Figure 6. Data from the reviewed sources



(a) 10–40% from [5]; >90% fixation from [9]. Different studies and processes, so bars are illustrative, not a head-to-head comparison. (b) figure quoted in [2] from a UNEP report.

Original chart from figures stated in [2], [5] and [9]. Studies differ in process and conditions, so the two bars are illustrative, not a direct comparison.

10. Abbreviations

CAD, computer-aided design; D5, decamethylcyclopentasiloxane; LCA, life-cycle assessment; MCT, monochlorotriazine; $scCO_2$, supercritical carbon dioxide; UNEP, United Nations Environment Programme; VS, vinyl sulfone.

Declaration, Conflict of Interest, Funding, and Other Statements

Use of Artificial Intelligence (AI): Artificial intelligence (AI) tools were used to assist in preparing this narrative review, including organizing the subject matter, developing the manuscript structure, refining technical explanations, and improving the clarity and presentation of the text. AI assistance supported the discussion of digital textile design, fabric colouration mechanisms, digital printing technologies, industrial applications, and their technological and practical limitations. The author is responsible for critically reviewing and verifying the technical and scientific content, checking the accuracy of the cited literature and bibliographic information, and ensuring the integrity and accuracy of the final manuscript.

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Data Availability: No new datasets were generated or analyzed during the preparation of this review. The information discussed is derived from previously published literature and other sources cited in the manuscript.

Author Note

The manuscript entitled *"Digital Design, Fabric Colouration Mechanisms, Uses and Limitations: A Narrative Review"* presents an overview of the principles and technologies involved in digital textile design and fabric colouration. It examines the relationship between digital design systems, colour representation, printing technologies, dye–fibre interactions, and the practical requirements of textile manufacturing.

The review discusses computer-aided textile design, digital colour management, and digital printing methods, including inkjet-based approaches and their applications in textile pattern development and fabric decoration. It also considers the mechanisms through which colourants interact with textile fibres, the influence of fibre composition and fabric structure, and the importance of pretreatment, ink formulation, fixation, and post-treatment in achieving satisfactory colour quality and durability.
Particular attention is given to the benefits and limitations of digital textile technologies, including design flexibility, rapid prototyping, customization, reduced sampling requirements, production efficiency, colour reproducibility, equipment costs, ink compatibility, colour fastness and production-scale constraints. The review also considers environmental aspects, including water and chemical consumption, energy requirements, waste generation, and the conditions under which digital textile printing may offer sustainability advantages over conventional processes.
Artificial intelligence tools were used to assist in organizing and preparing the review and improving the clarity and presentation of the technical discussion. The author is responsible for independently verifying the technical information, checking the cited literature and references, evaluating the accuracy of comparisons and ensuring that the conclusions are supported by reliable evidence.
This manuscript is intended for academic, educational, and scientific purposes. It is a narrative review based on previously published literature and does not report new experimental findings. The review aims to provide a balanced understanding of the capabilities, applications, and limitations of digital textile design and fabric colouration technologies for researchers, textile technologists, designers and professionals in the textile and fashion industries.

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