

## REVIEW ARTICLE

# Resource Efficiency in Digital Textile Printing: A Critical Synthesis of Ink, Substrate and Pre-treatment Evidence

*Mapping material savings, energy trade-offs and unresolved measurement gaps across ten applied studies*

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## ABSTRACT

Digital textile printing is frequently presented as a resource-efficient alternative to screen printing, but the evidence base for that claim is fragmented across ink chemistry, substrate pre-treatment, surface modification and value-chain studies. This editorial synthesis examines ten supplied sources to distinguish demonstrated resource effects from inferred ones. Water-based bio-based pigment inks show good light and weathering fastness and satisfactory wash and rub resistance, with biopolymer pre-treatment improving fixation on cotton and synthetic binder improving wash fastness on polyester [1]. Plasma pre-treatment of cotton and lyocell improves pigment coverage, distribution uniformity and some wash fastness [8], while yarn type and pre-treatment alter shade, colourfulness, colour strength and crockfastness on PET [3]. Laser engraving of cotton velvet before inkjet printing measurably changes colour outcomes through pile-height variation [2] [7]. Eco-friendly formaldehyde-free finishes improve performance of digitally printed cotton [5]. At value-chain level, brand-owner collaboration is proposed to accelerate the shift from screen to digital printing [6], and national readiness assessments highlight investment uncertainty and skills requirements [4] [10]. Bibliometric mapping shows fluctuating research attention and positions digital printing as both opportunity and threat to batik preservation [9]. Across sources, resource-efficiency claims are stronger for chemistry and pre-treatment than for quantified water, energy or waste reduction. Evidence is largely laboratory-scale, geographically concentrated and methodologically heterogeneous, limiting generalisable manufacturing conclusions.

*Keywords: digital textile printing; resource efficiency; pigment inks; pre-treatment; plasma activation; colour fastness; value chain; manufacturing readiness*

## SECTION 01

## Framing resource efficiency beyond the screen-printing comparison

Digital textile printing is widely positioned as a more sustainable coloration route than conventional screen printing, but the supplied literature rarely quantifies resource efficiency directly. Instead, efficiency is inferred from ink chemistry, pre-treatment choices, substrate behaviour and value-chain organisation. This creates a persistent gap between the rhetorical claim and the measurable evidence. The most explicit value-chain argument appears in a collaborative business model that treats the shift from conventional screen printing to digital textile printing as an environmentally sustainable transition, accelerated when brand owners join forces [6]. That study frames sustainability primarily through economic and environmental dimensions, noting that apparel companies tend to prioritise economic sustainability while environmental and social issues remain underrated [6]. This is an important corrective: resource efficiency in digital printing is not only a machine-level question but also a question of who bears the cost of transition and how demand is aggregated.

A second framing comes from an assessment of digital textile printing as a concrete path toward Indonesia 4.0, which emphasises readiness of textile-garment manufacturers to adopt digital equipment and workflow [10]. That work is concerned with competitiveness and productivity rather than resource accounting, yet it implicitly links digital adoption to industrial upgrading. A related evaluation of digital printing innovations describes the technology as attractive for apparel and home textile pattern design while stressing constraints, investment uncertainty and the need for sufficient knowledge and feasibility studies before adoption [4]. Together, these sources suggest that resource-efficiency arguments are embedded in broader industrial-policy and investment narratives, not in controlled comparisons of water, energy or chemical consumption [4] [6] [10].

The bibliometric analysis of digital textile printing and batik preservation adds a cultural and temporal dimension. It reports fluctuating publication counts over 2018-2023, with an increase from 116 to 200 articles in 2018-2019, a decrease to 167 in 2020, and increases to 198 and 238 in 2021 and 2022 respectively [9]. The same study identifies digital printing as both an opportunity and a threat to batik preservation, clustering terms such as ink, textile, technology, fabric and application [9]. This matters for resource-efficiency debates because it shows that adoption is not neutral: it can displace established craft practices even as it reduces certain material inputs. Any credible efficiency claim must therefore specify which resources are saved, at what scale, and with what cultural or economic trade-offs [6] [9] [10].

#### SECTION 02

## Ink chemistry and the bio-based pigment evidence

The strongest direct evidence for reduced resource intensity comes from water-based pigment inks formulated with bio-based pigments derived from bacterial fermentation intermediates. Two pigments, indigo and quinacridone, were incorporated into ink formulations and applied to cotton and polyester via valve-jet inkjet printing, with ink physical properties analysed for equipment compatibility and printed fabrics assessed for wash, rub, artificial weathering and artificial light fastness [1]. The reported results indicate excellent light and weathering fastness and satisfactory wash and rub resistance, supporting integration of biotechnologically sourced pigments into eco-friendly digital printing workflows [1]. This is a meaningful contribution because pigment printing avoids the washing and steaming steps associated with reactive dye fixation, which are typically water- and energy-intensive.

However, the evidence is not a full resource audit. The study reports fastness performance and pre-treatment effects rather than quantified water, energy or chemical savings [1]. It also shows that pre-treatment chemistry matters: a biopolymer pre-treatment enhanced pigment fixation on cotton, while a synthetic binder improved wash fastness on polyester [1]. This is a nuanced finding with practical implications. A bio-based ink does not automatically deliver a bio-based or low-impact overall process if the auxiliary chemistry remains synthetic or if fixation requires additional binder. The resource-efficiency benefit is therefore conditional on the full formulation and pre-treatment package, not on the pigment origin alone [1].

This conditionality is reinforced by work on eco-friendly finishes for digitally printed cotton. That study optimises a pre-printing recipe and then investigates three sustainable formaldehyde-free cross-linkers, three softeners, a C8-free oil and water repellent, and a halogen-free flame retardant, applied to steamed and non-steamed digitally printed samples [5]. The results show that the proposed sustainable finishes significantly improved performance compared with a non-finished reference [5]. The authors also note that research on finishing of digitally printed fabric is very limited and has focused on non-sustainable finishes [5]. This is a critical evidence limitation: the finishing stage, which can dominate chemical and energy inputs, is under-studied relative to ink and printer development. Resource-efficiency claims that stop at the ink therefore risk omitting a major part of the lifecycle [1] [5].

#### SECTION 03

## Substrate pre-treatment as the decisive efficiency lever

Across the supplied sources, pre-treatment emerges as the most consistent determinant of print quality and, by extension, of material efficiency. Poor fixation or uneven coverage leads to rejects, reprints and higher ink consumption, so pre-treatment quality is directly relevant to resource use even when the studies do not measure it in those terms. On PET fabrics, pretreatment and yarn type alter surface characteristics and affect colourfastness, colour shade, colourfulness and colour strength; printed pigments are subject to crocking because they attach physically to the fibre surface without diffusing into the fibre, increasing colour transfer to another fabric [3]. That study explicitly identifies this as a challenge for obtaining high colourfastness as well as full shade, colourfulness and colour strength, and it also observes fabric wettability to examine impacts on printing quality [3].

Plasma activation offers a more process-oriented route to improving pigment printing on cellulose. Argon and oxygen cold low-pressure plasma were applied to 100% raw cotton and lyocell knitted fabrics before digital pigment inkjet printing with water-based pigment ink [8]. The research reported a positive influence of plasma pre-treatment on coverage of the fibre surface with pigments, uniformity of pigment distribution along the fibre surface, and uniformity of the polymeric binder layer, with positive effects on colour reproduction and certain improvements in colourfastness to washing [8]. The authors frame this as contributing to the possibility of industrial plasma transformation as an ecologically sustainable functionalisation of textiles, while noting that such industrial adoption has not yet been established [8]. This is a careful statement of potential rather than proven industrial resource saving.

The plasma study also acknowledges that, given the complexity of the topic, the research is not sufficient in itself and opens new questions for further work [8]. That self-assessment is important for an evidence synthesis. Plasma treatment can improve print quality, but the resource balance depends on the energy and gas requirements of the plasma process, the reduced need for wet chemical pre-treatment, and the reduction in rejects. None of the supplied sources provides a full life-cycle comparison of plasma versus conventional pre-treatment [8]. Similarly, the PET study establishes relationships between pre-treatment, yarn type and print quality but does not quantify waste reduction or ink savings [3]. The practical implication is that pre-treatment should be treated as a system variable in resource-efficiency planning, not as a fixed upstream step [3] [8].

#### SECTION 04

## Surface modification, colour yield and the limits of instrumental evidence

A distinct line of work combines CO<sub>2</sub> laser engraving with digital inkjet printing to modify surface contour before printing. In cotton velvet, laser engraving created pile height variation before printing with reactive dye ink, and the objective was to determine whether this variation affects resulting colour [2] [7]. Laser settings were held constant at 100% speed, 55% power and 400 dots per inch resolution, with intensity controlled through 0%, 50%, 75% and 100% grayscale patterns; higher intensities removed more surface pile [2]. After treatment, seven solid cyan, magenta, yellow, black, red, green and blue stripes were printed, and colour properties were measured with a spectrophotometer under D65 daylight and 10 degrees standard observer, yielding reflectance curves, C\*, Ecmc and K/S values [2].

The reported outcome is that pile height variation causes a measurable effect on colour results in inkjet printing using instrumental measures [2] [7]. This is a robust but narrow finding. It demonstrates that substrate topography is a colour-determining variable, which has implications for resource efficiency because colour inconsistency can drive reprints and shade matching adjustments. However, the studies do not report ink consumption, energy use or waste rates, and they are limited to a specific pile fabric and a specific laser configuration [2] [7]. The evidence therefore supports a design and process-control conclusion rather than a resource-efficiency conclusion: surface modification can be used to engineer colour effects, but its net material impact remains unquantified.

The two laser-related sources are closely related in scope and authorship, which reduces the independence of the evidence [2] [7]. This matters for synthesis because convergent findings from related studies should not be treated as multiple independent confirmations. The same caution applies to the broader literature: several sources are exploratory, production-observation based or bibliometric rather than controlled experimental comparisons [4] [9] [10]. The instrumental colour evidence is valuable for understanding mechanisms, but it cannot by itself support claims about reduced water, energy or chemical

consumption in manufacturing [2] [7].

#### SECTION 05

## Value-chain readiness, skills and the economics of adoption

Resource efficiency in digital textile printing is inseparable from adoption economics and workforce capability. An evaluation of digital printing innovations describes the technology as making apparel and home textile pattern design more attractive while containing constraints, and it stresses that improvements are ongoing and not yet complete [4]. The same source argues that it may be difficult for investors to decide at this stage, that sufficient knowledge and experience is needed to invest, and that counselling and feasibility studies should precede investment [4]. It also describes digital printing machines as complex structures intertwining electronics, mechanics, chemistry, textiles, fashion and art, requiring a strong team including pattern designers, calibration and colour specialists, machine operators, electronic and mechanical support, fabric pre- and post-treatment personnel, and logistics support [4]. The most problematic parts are identified as the printheads where dye is sent to the fabric surface, with new developments occurring continuously [4].

This human and organisational dimension is easy to overlook in resource-efficiency debates that focus on ink and machinery. If efficient operation depends on a multidisciplinary team and on calibration expertise, then resource performance is partly a skills outcome [4]. The Indonesia 4.0 assessment similarly focuses on readiness of textile-garment manufacturers to adopt digital equipment and workflow, with the stated purpose of giving a clear picture of industry readiness to meet domestic and global demand [10]. It identifies root issues beneath the industry and aims to formulate approaches and solutions, but it does not provide quantified resource-efficiency metrics [10]. The value-chain collaboration model goes further by proposing that brand owners join forces to accelerate the shift from conventional screen printing to digital printing, on the basis that brand owners have the highest impact on improving sustainability in the apparel industry [6].

Taken together, these sources suggest that resource efficiency is a coordination problem as much as a technical one. The collaboration model explicitly notes that apparel companies pay higher attention to economic sustainability while environmental and social sustainability issues are often underrated [6]. That asymmetry helps explain why digital printing adoption may be driven by flexibility, design variety and lead-time reduction rather than by measured resource savings [4] [6] [10]. For product developers and manufacturing specialists, the practical implication is that efficiency arguments should be built into investment cases alongside agility and quality benefits, and that skills development and calibration discipline are part of the resource strategy [4] [6] [10].

#### SECTION 06

## Disagreements, uncertainties and what the evidence cannot yet settle

The supplied sources do not directly contradict one another, but they diverge in what they treat as the primary lever of improvement. Ink-focused work emphasises bio-based pigment chemistry and pre-treatment compatibility [1]; finishing-focused work emphasises formaldehyde-free cross-linkers, softeners, repellents and flame retardants for printed cotton [5]; substrate-focused work emphasises yarn type, wettability and crocking on PET [3]; and plasma work emphasises surface activation of cellulose [8]. Each identifies a different stage as decisive, which means that a single intervention is unlikely to deliver system-level resource efficiency. The absence of integrated studies spanning ink, pre-treatment, printing, finishing and end-of-life is the most important structural gap in this evidence base [1] [3] [5] [8].

There is also uncertainty about fastness trade-offs. Bio-based pigment inks are reported to have excellent light and weathering fastness and satisfactory wash and rub resistance, with fixation and wash fastness depending on whether biopolymer or synthetic binder pre-treatment is used [1]. Plasma pre-treatment yields certain improvements in colourfastness to washing [8], while pigment printing on PET faces crocking because pigments attach physically without diffusing into the fibre [3]. These findings are compatible but not directly comparable, because they involve different substrates, inks, pre-treatments and test regimes. The result is a patchwork of conditional claims rather than a coherent performance model.

A further uncertainty concerns scale and geography. The bibliometric study shows fluctuating research attention and a concentration of terms around batik preservation, ink, textile, technology, fabric and application [9]. The readiness assessment is specific to Indonesia [10], and the value-chain model is a proposed collaborative business model rather than a measured industrial trial [6]. Laboratory findings on plasma, laser engraving and bio-based inks have not been shown in the supplied sources to translate into verified factory-level resource savings [1] [2] [7] [8]. Claims of eco-friendliness should therefore be read as promising and mechanistically plausible, not as established resource-efficiency outcomes.

#### CONCLUSION

## Conclusions

The supplied evidence supports a cautious, stage-specific view of resource efficiency in digital textile printing. Bio-based pigment inks can deliver strong light and weathering fastness with satisfactory wash and rub resistance, but their performance depends on pre-treatment chemistry, with biopolymer aiding fixation on cotton and synthetic binder improving wash fastness on polyester [1]. Plasma activation improves pigment coverage, distribution uniformity and some wash fastness on cotton and lyocell, though industrial adoption is not yet established [8]. Yarn type and pre-treatment govern shade, colourfulness, colour strength and crockfastness on PET, where physical pigment attachment remains a fastness challenge [3]. Laser engraving of cotton velvet measurably alters colour through pile-height variation, confirming substrate topography as a colour variable [2] [7]. Sustainable formaldehyde-free finishes improve the performance of digitally printed cotton, addressing an under-researched finishing stage [5]. At value-chain level, brand-owner collaboration and readiness assessments frame digital adoption as an economic, organisational and skills challenge as much as a technical one [4] [6] [10], while bibliometric mapping shows fluctuating attention and cultural tensions around batik preservation [9]. The practical implication for applied textile design and manufacturing is that resource-efficiency strategies should be designed as integrated packages covering ink, pre-treatment, printing, finishing and workforce capability, and should be evaluated with explicit resource metrics rather than inferred from fastness or colour quality alone.

#### SCOPE

## Limitations

This editorial synthesis relies exclusively on ten supplied source records and their abstracts; full texts, supplementary data and independent replication were not available. Several sources are exploratory, production-observation based or bibliometric rather than controlled comparative experiments [4] [9] [10]. Two laser-related sources are closely related in scope and authorship, reducing evidential independence [2] [7]. None of the supplied sources provides a complete life-cycle assessment quantifying water, energy, chemical or waste savings for digital textile printing relative to screen printing, and none reports factory-scale verification of laboratory findings on bio-based inks, plasma pre-treatment or laser surface modification [1] [2] [7] [8]. Fastness and colour results are conditional on specific substrates, inks, pre-treatments and test methods, limiting direct comparability across studies [1] [3] [5] [8]. Geographic and sectoral coverage is uneven, with readiness evidence focused on Indonesia [10] and value-chain proposals remaining conceptual [6]. No claims are made here about commercial products, and no systematic-review methodology was applied.

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