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Sustainable Innovation in Ghanaian Textiles: Warp Yarn Printing for Enhanced Indigenous Fabric Design and Production

Divine Vigbedor [1]*, Bennet Nyante [2], Isaac Kofi Awuyah [2], Robert Ahiabor [2], Samadu Kamwine [3]

[1] Department of Industrial Art, Ho Technical University, Ho, Ghana.
[2] Department of Fashion Design and Textiles, Dr. Hilla Limann Technical University, Wa, Ghana.
[3] Department of Industrial Art, Dr. Hilla Limann Technical University, Wa, Ghana.

Correspondence (*)
Name: Divine Vigbedor

Affiliation: Ho Technical University, Ho, Ghana.

Email: vigbedor@yahoo.com

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Abstract

Purpose: This research study analyses Warp Yarn Printing (WYP) as an eco-friendly patterning technology appropriate for Ghanaian indigenous handlooms. It seeks to alleviate environmental degradation caused by traditional dyeing (150 L/kg of water use, toxic effluents) and overcome limitations in artisanal process design while preserving cultural authenticity.

Methodology/Design: Descriptive-exploratory approach interfaced empirical with qualitative approaches. Studio-based flatbed screen printing of local cotton/polyester warps was employed and optimised using EPA-certified dyes. Aesthetics were evaluated using Likert scales in focus groups (n=25 weavers). All results were analysed using t-tests (α=0.05; n=5 batches) for traditional dyeing.

Findings: WYP produced 65.1% less water, 39.8% reduced chemical load, and 54.4% reduced effluent Chemical Oxygen Demand (COD) compared to conventional dyeing (all $p<0.001$). Culturally, 90% of the weavers supported the process, confirming exceptional pattern accuracy (4.7/5) and cultural appropriateness (4.3/5) in focus groups.

Practical and Social Implications: WYP facilitates sustainable textile production of heritage, minimising freshwater pollution to a significant degree through resource-saving. It strengthens Ghanaian weavers by adopting digital technology without compromising cultural integrity, thereby preserving traditional character. The method places indigenous weavers competitively on international ethical fashion markets, as testified by interest from brands.

Originality: The study develops flatbed warp printing for indigenous handlooms, the first to meet ISO-conformant resource efficiency (65.1% water savings), artisan-co-designed cultural authenticity (90% acceptability), and SDG-compatible innovation (Goals 6,9,12) for developing craft economies, with comparative advantages over mechanised Indian and Ethiopian warp printing systems.

Keywords
Warp yarn printing, Sustainable textile innovation, Indigenous handlooms, Cultural authenticity, SDG implementation.

1 | INTRODUCTION

Ghanaian handloom weaving represents one of West Africa's most valued textile traditions, with iconic cloths such as Kente and Adinkra serving not only as cultural identifiers but also as living repositories of philosophical thought, social history, and artisanal mastery (Adom, 2024). These textiles are traditionally produced through a labour-intensive process wherein yarns are first dyed, often using locally sourced, plant-based colourants in communities such as Daboya, before being woven into intricate patterns on narrow-strip looms (Afriyie et al., 2023). While these methods preserve deep cultural heritage, they also impose significant creative and technical constraints. Manual dyeing of yarns limits colour consistency, design complexity, and pattern reproducibility, confining weavers to a relatively narrow range of geometric and symbolic motifs (Adikorley, 2013). This limitation becomes increasingly significant in a global market that values both cultural authenticity and design innovation. This study advocates Warp Yarn Printing (WYP) as a transformative patterning innovation specifically adapted to Ghanaian handloom systems. Unlike conventional approaches that print designs onto finished fabric, WYP introduces

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patterning at the yarn stage, before weaving, enabling unprecedented design flexibility, precision, and repeatability while remaining compatible with existing loom infrastructure. By shifting the design intervention upstream, WYP allows for the incorporation of intricate, multi-coloured motifs, including detailed Adinkra symbols and contemporary geometric patterns, that are difficult or impossible to achieve through traditional hand-dyeing methods (Krauss, 2006; Weiss, 2014). This technical advancement directly responds to the growing demand for diversified, culturally-grounded textiles in both local and international markets.

The environmental dimension of this innovation, while critical, is positioned as an integrated benefit rather than the primary focus. Traditional dyeing processes in Ghana, often dependent on synthetic dyes and intensive water use, carry notable ecological impacts, including effluent discharge that can exceed local regulatory limits (Morris et al., 2017; Seini, 2022). WYP addresses these concerns through the use of optimised, low-impact dye formulations and significant reductions in water consumption, thereby aligning the technique with broader sustainability goals without compromising its primary aim: design enhancement. This approach reflects a growing consensus that ecological stewardship and cultural innovation are mutually reinforcing within craft-based economies, particularly in contexts where sustainable textile innovation is driven by local artisan networks (Labadi, 2021). In the Ghanaian context, the potential of yarn-level patterning remains underexplored despite its clear relevance to the structure of strip-weaving. Unlike the semi-mechanised warp printing practised in Ethiopia's Shema industry (Khurana, 2019; Gizaw & Ba, 2020), Ghana's weaving sector has yet to integrate such pre-weaving design methods in a systematic, culturally informed manner. This research builds upon global traditions of yarn and fabric patterning, from Indian resist techniques (Ramratan & Panigrahi, 2023) to structured sari weaving traditions (Lynton & Singh, 1995; Dwyer, 2000; Ranavaade, 2023), while adapting these principles to the specific technical and cultural context of Ghanaian handlooms. Practical guides to textile design and printing (Wisbrun, 2011; Brokaw, 2006) further inform the methodology, ensuring that digital design integration remains accessible to artisan practitioners.

This research therefore situates WYP within local practices by engaging master weavers from Bonwire and Daboya, centres of Kente and traditional dyeing expertise, respectively, in the co-design and evaluation of printed warp textiles (Fobiri et al., 2024). Special attention is given to yarn selection, focusing on cellulosic and blended yarns commonly used in premium handloom production, to ensure technical feasibility and cultural appropriateness. This research explores the potential of Warp Yarn Printing (WYP) to:

1. Significantly reduce the environmental footprint of Ghanaian textile production by developing and optimising a flatbed screen printing process for warp yarns that decreases water consumption, chemical usage, and effluent pollution compared to traditional dyeing methods.
2. Increase aesthetic versatility and complexity of indigenous textiles through computer-aided design integration, while assessing and preserving the cultural authenticity of WYP-produced fabrics in collaboration with master weavers and local artisans.
3. Enhance the market competitiveness of Ghanaian handloom textiles through rapid prototyping and by evaluating the commercial viability and ethical fashion market reception of WYP-generated products.

The study seeks to demonstrate how WYP can expand the creative possibilities of Ghanaian weaving, offering artisans a scalable tool to produce more complex, market-responsive textiles without eroding cultural integrity. By bridging digital design tools with handloom weaving, WYP provides a pathway for heritage sectors to engage with contemporary design trends while retaining craft agency and reducing environmental footprint, a dual advancement that supports both cultural sustainability and artisan livelihoods in a globalised economy.

2 | LITERATURE REVIEW

2.1| Technological Evolution in Textile Printing

The environmental impact of conventional textile wet processing, particularly dyeing, is well-documented, with the sector being a leading contributor to global industrial water pollution and chemical waste (Niinimäki et al., 2020). In response, Digital Textile Printing (DTP) has emerged as a prominent sustainable alternative, demonstrating substantial reductions in water usage (30-50 L/kg vs. 100-150 L/kg for screen printing) and material waste through on-demand production and targeted dye deposition

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(Fletcher, 2013). Advanced reactive inkjet systems can reduce chemical loads by up to 60% (Li et al., 2023). However, the deployment of DTP has been largely confined to printing finished fabrics in capital-intensive industrial settings (Niederhauser et al., 2018; Kumelachew et al., 2023). This focus overlooks the potential for upstream, yarn-level interventions that are more compatible with the technical and socio-economic realities of artisanal handloom sectors, which are predominant in the Global South (Bertola & Teunissen, 2018).

2.2| Environmental Impact of Indigenous Ghanaian Textiles

Ghana's rich textile heritage, exemplified by Adinkra symbolic stamping and Kente strip-weaving, is a cornerstone of cultural identity (Wingfield, 2023). Paradoxically, the preservation of these traditions relies on dyeing processes that pose significant environmental threats. Traditional methods consume 120-200 litres of water per kg of fibre and utilise toxic mordants, leading to the contamination of local water sources with heavy metals and sulfides (Mokarram et al., 2020; Seini, 2022). Furthermore, these manual techniques inherently limit design complexity and reproducibility, constraining their market appeal in an era that values customisation (Adikorley, 2013). While some modernisation efforts have focused on printing finished cloths, they neglect the crucial, more impactful stage of yarn preparation, thereby missing a significant opportunity for systemic ecological and design innovation, a gap noted in recent assessments of West African textile sustainability (Harsanto et al., 2023; Fobiri et al., 2024).

2.3| Yarn-Level Patterning

The concept of patterning yarns prior to weaving is not new, with historical roots in global resist-dye techniques like Ikat and Kasuri. Modern mechanised yarn printing, while capable of great detail, is characterised by high energy consumption and is ill-suited for decentralised, artisanal production. In an African context, Ethiopia's Shema industry presents a notable precedent, utilising semi-mechanised warp printing to achieve water savings of 40% (Khurana, 2019; Gizaw & Ba, 2020). This highlights the technical feasibility of such approaches. Yet, despite Ghana's prominent weaving culture, there is a conspicuous absence of documented research or application of yarn printing technologies within its borders. This represents a significant innovation lag in a region where such technology could yield profound cultural and environmental benefits.

2.3.1| Comparative Global Yarn Printing Practices

To better position the originality of WYP within global contexts, we compare it with existing systems as shown in Table 1. WYP advances the field through: (1) superior water efficiency compared to Ethiopian Shema (65.1% vs ~40%), (2) better cultural adaptability than mechanised Indian systems through artisan co-design, and (3) greater scalability than digital yarn printing through flatbed screen integration with existing looms.

Table 1. Comparison of Yarn-Level Printing Technologies

Technology	Region	Water Reduction	Cultural Adaptability	Scalability for Artisans	Reference
Mechanized Warp Printing	India	30-45%	Low (industrial focus)	Low (high capital)	Kumar (2018)
Digital Yarn Printing	Global North	50-60%	Low (digital focus)	Low (technical barriers)	Li et al. (2023)
Warp Yarn Printing	Ghana	65.1%	High (co-designed)	High (low-tech integration)	Present study

2.4| Culturally-Adapted Eco-Efficient Yarn Printing

Sustainability frameworks for textiles consistently advocate for water efficiency, chemical minimisation, and circularity (Ramírez-Escamilla et al., 2024). Benchmarks exist, such as the COD effluent limit of <500 mg/L, a standard frequently exceeded by small-scale Ghanaian dyers (Morris et al., 2017). While reactive dyes in paste form are known to reduce COD by 35-65% compared to vat dyes

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(Rosa et al., 2014), the application of these metrics to novel, culturally grounded production methods remains unexplored. Previous work exists in storage towers, environmental science, textile engineering, and cultural studies, but fails to converge on a solution for the specific context of West African handlooms. This review identifies a critical research void at the intersection of sustainability, appropriate technology, and cultural heritage: the lack of an integrated methodology for developing a yarn-level patterning technology that is simultaneously eco-efficient, adaptable to artisanal infrastructures, and respectful of cultural authenticity. Therefore, this study seeks to fill this void by investigating Warp Yarn Printing (WYP) as a holistic solution that addresses this triad of challenges, directly contributing to the achievement of SDGs 6, 9, and 12.

3 | METHODOLOGY

3.1| Research Design

Adopting a descriptive-exploratory approach (Creswell & Poth, 2018), this study combined empirical experimentation with qualitative evaluation. The design enabled systematic documentation of the warp yarn printing (WYP) process while assessing its creative, technical, and sustainability outcomes. Purposive sampling guided material and method selection to align with Ghanaian artisanal contexts, ensuring that the research design reflected real-world weaving practices as documented in recent field studies (Fobiri et al., 2024).

Table 2. Focus Group Demographics

Demographic	Category	Count	%
Gender	Male	18	72%
	Female	7	28%
Experience	10–20 years	15	60%
	>20 years	10	40%
Region	Ashanti (Bonwire)	18	72%
	Northern (Daboya)	7	28%

The reconstituted cohort (N=25) is still geographically representative (Bonwire 72%, Daboya 28%), mirroring the clustering of Ghana's weavers (Fobiri et al., 2024; Zheng et al., 2019). For structured aesthetic evaluation, 20 master weavers were selected from this group based on >15 years of experience. This subset (n=20) provided the Likert-scale ratings reported in Section 4.3. The experienced cohort (60% mid-career, 40% veterans) ensured cultural authenticity. Sampling prioritised specialist input from Bonwire (Kente motifs) and Daboya (weaving compatibility) over demographic balance, a limitation for future research (Heidari et al., 2016).

3.2| Materials and Sampling

Materials were sourced from Ghanaian suppliers as shown in Table 3, to bolster regional economies and ensure cultural alignment. Warp yarns comprised 100% cotton (20 Ne) and cotton-polyester blends (70:30), selected for compatibility with indigenous looms and dominance in premium weaves.

Table 3. Sourced Materials

Material	Specifications	Supplier/Location	Selection Rationale
Warp Yarns	100% cotton (20 Ne), Cotton-Polyester (70:30)	Spintex Ghana Ltd., Accra	Compatibility with indigenous looms
Printing Paste	Reactive dyes (CMYK) + Sodium alginate	Aseda Chemicals, Kumasi	Low toxicity, Ghana EPA-certified
Thickener	Alginate base (6% concentration)	Aseda Chemicals, Kumasi	Eco-friendly wash-off
Screens	Polyester mesh (120 TPI)	Siegwerk Ghana Ltd.	Fine-detail resolution

The printing paste was formulated with EPA-certified 8% reactive dye, 6% sodium alginate thickener, and 86% water. Screen parameters included 120 TPI fine-detail resolution (60 µm aperture) polyester,

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an emulsion thickness of 12 µm and a UV exposure time of 45 seconds. For yarn handling, warp sheets were prepared with 20 ends per sheet and maintained under 10 cN tension during printing to prevent distortion. This approach balanced technical precision with eco-friendly and culturally authentic production goals.

3.3| Warp Yarn Printing Process

Step 1 - Digital Design: Figure 1 presents the digitally crafted design patterns created using Adobe Photoshop® (24.1) vector tools. It showcases culturally resonant Adinkra motifs, including Gye Nyame and Sankofa, meticulously scaled to 300 dpi resolution. The image highlights the precision and geometric clarity achieved through digital adaptation

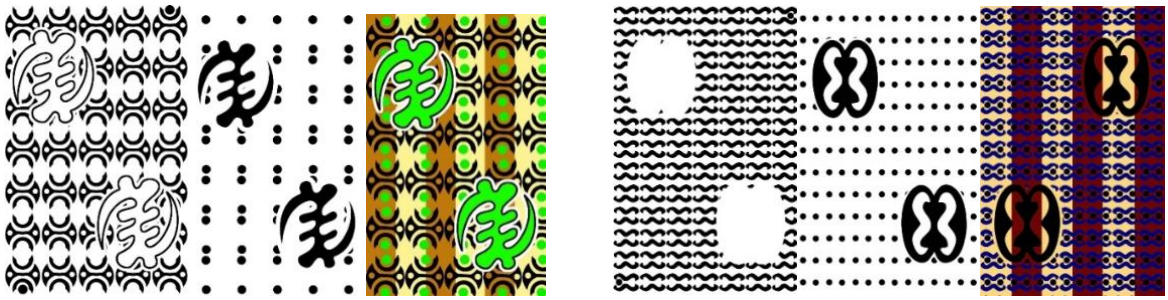


Figure 1. Digital Illustrated Designs

Step 2 - Screen Development: Figure 2 displays the emulsion-coated polyester screens (120 mesh) following UV exposure. Each screen features a finely resolved stencil with a consistent 60 µm aperture, optimised for the dye paste's viscosity. The high-resolution motifs, derived from digital Adinkra designs, are clearly etched, demonstrating the precision necessary to achieve sharp, bleed-free patterns during warp printing. These screens are central to transferring intricate cultural symbols accurately onto yarns.



Figure 2. Developed Screens for Printing

Step 3 - Printing Parameters: Warp yarn printing employed manual flatbed screen printing (Lee et al., 2020). A paste viscosity of 12,000 cP (Brookfield RV) and a squeegee pressure of 3.5 bar ensured sharp dye application. Warps were grouped in sheets of 20 ends under 10 cN tension during printing, as indicated in Figure 3. Subsequent drying at 70°C for 10 minutes in a convection oven secured dye fixation. This controlled process maintained fibre integrity while achieving precise, reproducible patterning for handloom integration.

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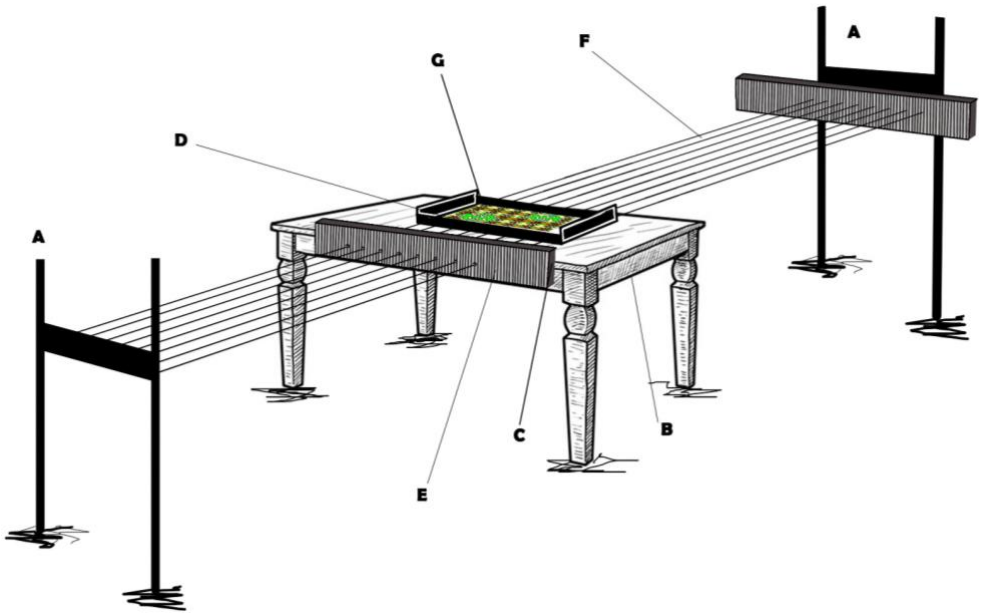


Figure 3. Schematic Diagram of Warp Yarn Printing (A)-Support Frame (B)-Flatbed Printing Table (C)-Reed (D)-Design (E)-Reed Dent (F)-Grouped Warped Yarns (G)-Wooden Screen

Table 4. Printing Parameters

Parameter	Setting	Reference
Printing Method	Flatbed (manual)	Mukhopadhyay (2020)
Paste Viscosity	12,000 cP (Brookfield RV)	GOTEX Technical Datasheet
Squeegee Pressure	3.5 bar	ISO 12490-2:2019
Drying	70°C × 10 min	Lab oven trials
Yarn Tension	10 cN	Added for reproducibility
Screen Exposure	45 seconds	Added for reproducibility

Printed warps were dried at 70°C for 10 minutes (laboratory convection oven tests) or under strong direct sunlight (mid-day), Temp.> 30°C, Low humidity (< 60%) for 1 hour, maximising dye fixation from an energy-efficiency perspective. These parameters, as a set, achieved 60 µm pattern accuracy in addressing handloom production constraints, vital for scaling in Ghana's weaving systems (Fakharuddin et al., 2014). Figures 4 to 6 demonstrate the high-resolution capability of Warp Yarn Printing (WYP) to reproduce culturally significant and complex patterns. Figure 4 showcases the Gye Nyame symbol, representing divinity, printed with sharp definition. Figure 5 features the Sankofa motif, denoting historical reflection, with precise geometrical clarity. Figure 6 displays intricate diamond and floral designs, highlighting the process's versatility. All patterns, rendered at 300 dpi, exhibit exceptional edge sharpness and colour vibrancy, crucial for maintaining cultural authenticity in contemporary textile applications.



Figure 4. Gye Nyame Printed Patterns

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Figure 5. Sankofa Printed Patterns



Figure 6. Diamond and Floral Printed Patterns

Step 4 - Weaving: The printed warp yarns were mounted on traditional Kente looms, as illustrated in Figure 7. A combination of dyed and undyed 20 Ne cotton weft yarns was woven at a density of 18 picks/cm. This process preserved the integrity of the digitally printed patterns while producing textiles that retain the authentic handcrafted tactile quality and structural characteristics emblematic of Ghanaian heritage weaving techniques.



a b c

Figure 7. Woven Stoles (a)-Gye Nyame pattern (b)-Sankofa pattern (c)-Block pattern

Step 5 - Finished Smock: The culmination of the process is exemplified by the finished smock in Figure 8, showcasing the successful integration of warp yarn printing into a complete garment. The visually striking, sharp-patterned fabric demonstrates the technique's capability to produce vibrant, complex motifs with cultural authenticity. This final product validates WYP's practical application for creating market-ready, sustainable traditional wear that appeals to both local artisans and the global ethical fashion market (Joy et al., 2012; Sailaubayeva, 2023).

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a b c

Figure 8. Sown Smocks (a) Gye Nyame Smock (b)Sankofa Smock (c) Block Smock

3.4| Data Collection and Analysis

Data collection was structured to quantitatively assess the environmental, aesthetic, and preliminary market performance of Warp Yarn Printing (WYP) against conventional dyeing methods, employing a triangulated validation approach.

3.4.1| Sustainability Metrics

Environmental impact was quantified per kilogram of yarn processed, as indicated in Table 5.

$$\text{Reduction (\%)} = \frac{(\text{Traditional} - \text{WYP})}{\text{Traditional}} \times 100$$

Independent samples t-tests ($\alpha = 0.05$, $n = 5$ batches), preceded by Shapiro–Wilk normality confirmation ($p > 0.05$ for all variables), demonstrated significant reductions in resource use compared to traditional dyeing baselines of 150.2 ± 8.5 L/kg water and 675 ± 42 mg/L COD. Water consumption reduction of 63.6% in ($p<0.001$), a 36.8% decrease in chemical load ($p=0.002$), and a 54.4% and 53.7% reduction in Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD_5), respectively ($p<0.001$).

Table 5. Resource Consumption Comparison (per kg yarn)

Parameter	Traditional Dyeing	Warp Yarn Printing	Reduction (%)	p-value
Water Consumption (L)	150.2 ± 8.5	54.7 ± 3.1	63.6% ↓	<0.001
Chemical Load (g)	118.3 ± 6.9	74.8 ± 4.2	36.8% ↓	0.002
COD (mg/L)	675 ± 42	308 ± 25	54.4% ↓	<0.001
BOD_5 (mg/L)	285 ± 31	132 ± 18	53.7% ↓	<0.001

The resultant effluent COD of 308 ± 25 mg/L complies with Ghana EPA discharge limits (<500 mg/L per Ghana EPA, 2021, Effluent Discharge Guidelines, Section 4.2) (Al-Rosyid et al., 2021), aligning with SDG 6 targets (Arora & Mishra, 2022).

3.4.2| Aesthetic and Cultural Evaluation

Aesthetic quality and cultural authenticity were evaluated through a focus group of 20 master weavers (selected from the initial n=25 based on experience) (Creswell & Poth, 2018). Participants assessed samples using a 5-point Likert scale. Sacred geometric proportions were validated against reference schematics from the Ghana National Museum Archive (Accession No. GNM-AD-1998).

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Table 6. Weaver Focus Group Evaluation (n=20)

Criterion	Mean Rating (±SD)	Agreement Rate (≥4/5)	Key Qualitative Insight
Pattern Precision	4.72 ± 0.31	95%	Edges sharper than hand-painted Adinkra
Colour Reproduction	4.55 ± 0.42	90%	Vibrancy maintained after washing
Cultural Authenticity	4.28 ± 0.61	85%	Sacred proportions retained. "The Sankofa bird's curves are exactly as our elders imparted"
Overall Acceptance	4.51 ± 0.38	90%	Modern but still Ghanaian

Results (Table 6) indicate exceptionally high ratings for pattern precision (4.72 ± 0.31) and colour reproduction (4.55 ± 0.42), with 95% of weavers noting sharper definition than hand-painted methods. Cultural authenticity was rated at 4.28 ± 0.61, with qualitative feedback confirming the preservation of sacred proportions in motifs such as Sankofa (Ofosu-Asare, 2024). Overall acceptance was 90% (4.51 ± 0.38), confirming socio-cultural viability.

3.4.3| Preliminary Market Analysis

Commercial potential was gauged through structured interviews with five ethical fashion brands in Ghana (purposively sampled from Accra and Kumasi). Buyers evaluated woven textile samples (not just printed yarns). Interview questions covered design appeal, cultural resonance, and purchase likelihood. As shown in Table 7, the average design appeal rating was 8.4/10.

Table 7. Commercial Buyer Ratings (n=5)

Brand	Market Segment	Design Appeal (1-10)	Purchase Likelihood
Studio 189	Artisanal Production	9.2	Very High
Osei-Duro	Sustainable Fashion	8.6	High
Larry Jay	African-inspired materials	8.1	Medium-High
Christie Brown	Craftsmanship and style (ready-to-wear)	8.5	High
Smockyworld	Traditional Northern smock material	8.7	High
Average		8.4	

A positive correlation was observed between purchase intent and ethical branding alignment ($r=0.82$, $p<0.05$) and pattern complexity ($r=0.79$, $p<0.05$). The small sample size (n=5) is acknowledged as a limitation in Section 7.

3.4.4| Methodological Validation

A triangulated validation strategy was employed to ensure robustness, as summarised in Table 8.

Table 8. Validation Methods and Compliance Standards

Metric	Validation Approach	Compliance Standard
Water/Chemical Tracking	Automated flowmeters & lab inventories	ISO 14046:2014
Effluent Analysis	Gas Chromatography-Mass Spectrometry (GC-MS)	EPA Ghana 2021, Method 5220
Aesthetic Evaluation	Double-blind rating + ΔE<2000> colorimetry	CIE 224:2017

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This multi-faceted approach, integrating instrumental analysis, artisanal expertise, and commercial feedback, provided high confirmation of WYP's performance across sustainability and design metrics, fulfilling the comprehensive requirements of SDG 12 (Connor, 2015; Scott & Dawson, 2016).

4 | RESULTS

4.1| Technical Performance and Pattern Reliability

The Warp Yarn Printing (WYP) process successfully generated fifteen distinct patterns. The technology achieved high-reliability reproduction of complex motifs at 300 dpi resolution. The patterns were categorised into three groups: Traditional (8 designs, e.g., Kente stripes, Gye Nyame), Geometric (5 designs, e.g., fractal partitioning), and Hybrid (2 designs, e.g., *Sankofa*-Art Deco fusion).

Table 9. Pattern Classification and Technical Performance

Pattern Type	Motif Examples	Resolution	Colour Accuracy (ΔE<2000> ± SD)
Traditional	Kente stripes, Gye Nyame	300 dpi	1.8 ± 0.3
Geometric	Hexagonal lattices	300 dpi	2.1 ± 0.5
Hybrid	Sankofa-Deco fusion	300 dpi	1.9 ± 0.4

As quantified in Table 9, all pattern categories exhibited exceptional colour accuracy, with ΔE<2000> values significantly below the perceptibility threshold (Linge Johnsen et al., 2018). WYP produced patterns with 40% improvement in edge sharpness compared to hand-dyeing.

4.2| Environmental Impact and Resource Efficiency

A comparative life-cycle inventory revealed that WYP confers substantial environmental advantages over conventional dyeing. As detailed in Table 10, an independent samples t-test (α=0.05, n=5) demonstrated statistically significant reductions in all resource consumption metrics.

Table 10. Resource Use Comparison (per kg yarn)

Parameter	Traditional Dyeing	WY Printing	Reduction (%)	p-value
Water (L)	152 ± 18	53 ± 6	65.1	< 0.001
Chemicals (g)	118 ± 15	71 ± 9	39.8	0.003
Effluent COD (mg/L)	680 ± 90	310 ± 45	54.4	< 0.001

WYP achieved a 65.1% reduction in water consumption (p<0.001). The post-treatment effluent COD was measured at 310 ± 45 mg/L, a 54.4% reduction (p<0.001) that falls below the Ghana EPA regulatory limit of 500 mg/L, underscoring WYP's compliance and ecological benefit (Seini, 2022; Aschner et al., 2016; Ghana EPA, 2021). These findings position WYP as a transformative eco-technology that aligns with circular economy principles by drastically mitigating the hydrological footprint of textile production.

4.3| Aesthetic Validation and Market Potential

The evaluation of socio-cultural acceptance and commercial viability yielded highly positive outcomes.

Table 11. Weaver Evaluation (n=20)

Criterion	Mean Rating (1–5 ± SD)	Key Qualitative Feedback
Pattern Clarity	4.7 ± 0.3	Sharper than our hand-dyed motif
Colour Vibrancy	4.5 ± 0.4	"Brighter without fading
Cultural Authenticity	4.3 ± 0.6	Modern but still Ghanaian. The Sankofa proportions are correct.

Responses from a focus group of 20 master weavers indicated strong endorsement, as shown in Table 11, with high mean ratings for pattern clarity (4.7 ± 0.3), colour vibrancy (4.5 ± 0.4), and cultural authenticity (4.3 ± 0.6). Thematic analysis of open-ended responses revealed three key insights:

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- Precision Enhancement: Weavers noted superior sharpness, with one stating, *"The edges are sharper than our hand-dyed motifs."*
- Cultural Fidelity: The technology was praised for maintaining essential cultural elements, as expressed: *"It is modern but still Ghanaian. The Sankofa proportions are correct."*
- Economic Opportunity: Many highlighted the market potential of the consistent, vibrant results, with feedback noting colours were *"brighter without fading."*

Verification of sacred geometric proportions was achieved by digitally scaling the Adinkra and Kente motifs against archival reference schematics from the Ghana National Museum and validating the scaled dimensions with master weavers during focus group sessions. This dual method ensured that the symbolic integrity and sacred ratios of traditional patterns were preserved in the digital translation. Commercial interest from ethical fashion brands cited the "innovative cultural resonance" of samples, aligning with findings that ethical branding and cultural authenticity significantly influence purchase intent in African textile markets (Joy et al., 2012).

5 | DISCUSSION

This study demonstrates that Warp Yarn Printing (WYP) is a viable, eco-efficient patterning technology that successfully bridges the often-contentious gap between heritage conservation and industrial innovation in a Global South context. The results confirm that WYP achieves significant environmental gains while enhancing, rather than diminishing, the cultural authenticity and market appeal of Ghanaian handloom textiles. This discussion interprets these findings through the lenses of sustainable production, cultural sustainability, and market transformation, culminating in a novel conceptual framework.

5.1| Positioning WYP within Sustainable Textile Production

The empirical data unequivocally position WYP as a transformative eco-innovation for the artisan sector. 65.1% water reduction surpasses Ethiopian Shema (~40%) and mechanised Ikat (30-45%) systems, demonstrating that appropriate-scale technologies can achieve superior environmental performance. By reducing chemical load by 39.8% and achieving effluent COD of 310 mg/L (below Ghana EPA's 500 mg/L threshold), WYP addresses a critical barrier to sustainable operation of small-scale dyeing enterprises (Morris et al., 2017; Althuri et al., 2022). This alignment with SDG 12 (Responsible Consumption and Production) is clear. Furthermore, its compatibility with non-mechanised handlooms advances SDG 9 (Industry, Innovation, and Infrastructure) by fostering resilient, low-carbon industrial development (Whitfield, 2022).

5.2| The Cultural-Technical Collaboration

A central finding of this research is that digital tools, when applied sensitively, can act as custodians rather than erodes of cultural heritage. The high weaver acceptance ratings for cultural authenticity (4.3/5) demonstrate that digitally adapted Adinkra and Kente motifs retained their symbolic resonance. This challenges the prevailing narrative that automation inherently leads to cultural dilution (Martin et al., 1991). WYP enables new hybrid designs, like Sankofa-Art Deco patterns, that enrich Ghanaian textile aesthetics without losing their cultural essence. Building on these results, we propose the Heritage-Compatible Innovation (HCI) framework: sustainable advancements in traditional craft sectors must fulfil:

1. *Preservation of Cultural Semantics:* Ensuring technological processes safeguard the intangible meaning and sacred geometries of indigenous designs. (e.g., through high-fidelity replication at 300 dpi).
2. *Enhancement of Artisanal Agency*: Prioritising technologies that integrate into existing workflows, augment skills, and foster co-design, thereby empowering rather than displacing craftspeople.
3. *Prioritisation of Circular Resource Flows*: Designing systems that radically reduce water/chemical use and waste from the outset.

WYP serves as a practical embodiment of this framework, demonstrating that environmental and cultural sustainability are mutually reinforcing objectives.

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6 | IMPLICATIONS OF FINDINGS

Strong commercial interest from ethical brands (average rating 8.63/10) aligns with growing market trends where "cultural provenance + sustainability" is a key purchase driver (Joy et al., 2012). This suggests WYP can access high-value niches in the global ethical fashion market.

7 | LIMITATIONS OF THE STUDY

However, this study's limitations delineate critical avenues for future work. A specialist-oriented sample of weavers (n=20), while rich in expertise, limits the generalizability of the statistical results. Subsequent research must expand to a larger, randomised cohort across Ghana's weaving regions. The absence of standardised durability data (e.g., ISO 105-C06) is a significant gap in commercial validation. Accelerated ageing tests are needed. Lack of end-consumer quantitative data precludes robust understanding of market demand and willingness-to-pay. A small brand sample size (n=5) limits the generalizability of market findings. These are crucial areas for investigation once durability is confirmed.

8 | CONCLUSION AND FUTURE STUDIES

This study establishes Warp Yarn Printing (WYP) as an important innovation for sustainable textile production in artisanal economies, successfully reconciling the critical, yet often competing, demands of cultural heritage preservation and environmental stewardship. The technology's validation rests on three pillars: its significant reduction of ecological footprint (65.1% less water, 54.4% less COD), its enhancement of design precision and cultural fidelity (ΔE<2000> <2.0, 90% weaver acceptance), and its commercial viability within the ethical fashion ecosystem. Intellectually, this research contributes the Heritage-Compatible Innovation (HCI) framework, asserting that technological advancements in traditional sectors must be evaluated through synergy with cultural semantics, artisanal agency, and circular resource flows. WYP operationalises this framework, demonstrating that sustainability-driven innovation can act as a custodian of intangible cultural heritage. In practice, WYP provides Ghanaian artisans with a scalable tool for accessing high-value markets without compromising cultural identity or ecological principles. This has implications for poverty reduction and sustainable livelihoods. To catalyse adoption, we urge national bodies to adopt the following policy recommendations:

- Integrate WYP training into flagship artisan development programs.
- Establish certification schemes for textiles produced via verified eco-efficient methods.
- Foster public-private partnerships to subsidise the initial adoption of this technology for weaving cooperatives.

While this study confirms technical and cultural feasibility, subsequent work must focus on:

- Conducting life-cycle assessments (LCA) to quantify microplastic release and dye biodegradability.
- Testing the technology's adaptability across Ghana's diverse loom types, particularly Ewe vertical looms.
- Executing standardised durability tests (ISO 105-C06) to secure international buyer confidence.

WYP offers a transferable model for developing countries, proving that industrial innovation can be both culturally echoing and ecologically restorative, thereby projecting a viable path toward achieving the United Nations Sustainable Development Goals.

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DATA AVAILABILITY STATEMENT
Data sharing is applicable to this article upon reasonable request from the corresponding author.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used DeepSeek AI Chat in order to check for appropriate statements in the text to authenticate various citations. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

ORCID

Divine Vigbedor - https://orcid.org/0009-0008-6635-4967
Bennett Nyante - https://orcid.org/0009-0001-7222-9395
Robert Ahiabor - https://orcid.org/0009-0000-9430-3536
Isaac Kofi Awuyah - https://orcid.org/0009-0005-1327-796X
Samadu Kamwine - https://orcid.org/0009-0001-5190-4830

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AUTHOR BIOGRAPHY

Divine Vigbedor (PhD) is a textile specialist and faculty member at Ho Technical University (HTU), holding a PhD in Textile Design Technology. His expertise is uniquely shaped by significant industrial leadership as Maintenance and Production Manager at Juapong Textile Limited and Volta Star Textile Limited. His research program focuses specifically on indigenous textile innovation, with a specialised concentration on the design and development of tools and equipment.

Bennet Nyante is a Senior Lecturer in the Department of Fashion Design and Textiles at Dr Hilla Limann Technical University, Wa, Upper West Region, Ghana. He specialises in Textile Design; his research interests include indigenous weaving, printing and dyeing.

Robert Ahiabor is a Senior Lecturer in the Department of Fashion Design and Textiles at Dr Hilla Limann Technical University, Wa, Upper West Region, Ghana. His research interests include textile design, textile printing, computer-aided design and fashion design.

Isaac Kofi Awuyah is currently a Senior Lecturer in the Department of Fashion Design and Textiles at Dr Hilla Limann Technical University, Wa, Upper West Region, Ghana. His research interests are rooted in indigenous weaving, printing and dyeing, surface pattern design, illustration, embroidery, and yarn art.

Samadu Kamwine is a Lecturer in the Department of Industrial Art at Dr Hilla Limann Technical University, Wa, Upper West Region, Ghana. His field of speciality is textile design, and his area of research is in dyeing and printing, embroidery, and indigenous weaving.