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SUSTAINABLE IKAT REVIVAL THROUGH NATURAL DYES AND SCREEN-PRINTED SMART FEATURES

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ABSTRACT

The traditional art of Ikat weaving is currently facing an existential crisis driven by the labor-intensive nature of resist dyeing, the prevalence of synthetic chemical pollutants, and the market pressure from mass-produced counterfeits. To revive this heritage craft within a sustainable and economically viable framework, this paper proposes a novel methodological convergence of eco-friendly natural dyeing and advanced screen-printing technologies. We integrate the use of natural sensitizers extracted from mangosteen peel and grass jelly leaves with high-tech screen-printed functional elements, including graphene-based RFID transponders and optically transparent conductive layers. This hybrid approach not only reduces the ecological footprint through the elimination of toxic synthetic mordants but also embeds digital intelligence into the fabric, enabling provenance tracking and authentication. By leveraging recent advancements in screen-printed electronics and natural material chemistry, we present a roadmap for a "Smart Ikat" textile that preserves cultural aesthetics while adopting modern functional capabilities suitable for the Internet of Things (IoT) era.

Keywords: *Sustainable Ikat; Ikat Revival;, Natural Dyes; Eco-Friendly Textiles; Screen Printing; Smart Textiles; Sustainable Textile Design; Traditional Craft Preservation; Textile Innovation; Cultural Heritage Textile; Slow Fashion; Ethical Fashion*

1.INTRODUCTION

Ikat is a dyeing technique used to pattern textiles that employs resist dyeing on the yarns prior to dyeing and weaving the fabric. However, the traditional process is incredibly time-consuming and increasingly reliant on synthetic dyes that pose significant environmental hazards. Furthermore, the global textile market is flooded with printed imitations that devalue the work of genuine artisans. The motivation behind this research is to address these challenges by introducing a sustainable, technology-driven revival strategy. We define the problem scope as the need to modernize the fabrication workflow of Ikat-style aesthetics without losing the craft's essence, while simultaneously introducing "smart" features that can verify authenticity and add value.

Existing approaches to textile revival have largely been insufficient because they treat sustainability and technology as separate domains. Most efforts focus solely on organic cotton or vegetable dyes without addressing the manufacturing scalability or the functional utility of the cloth in a digital society. Conversely, developments in smart textiles often rely on complex, expensive fabrication methods incompatible with rural artisan workshops. For instance, while reconfigurable intelligent surfaces and advanced communication components are being developed for 5G applications, their integration into traditional textiles remains unexplored (Yang et al., 2025). Similarly, standard screen-printing is widely used for graphic tees but rarely utilized to create

sophisticated, functional resist patterns or integrated sensors in heritage fabrics.

This paper makes the following primary contributions to the field of sustainable smart textiles:

- We propose a dual-layer screen-printing framework that utilizes natural dye extracts (specifically adopting protocols for mangosteen and grass jelly) to create eco-friendly aesthetic patterns.
- We introduce a method for embedding provenance authentication directly into the Ikat fabric using screen-printed graphene RFID antennas and conductive inks, effectively creating a "digital passport" for handmade goods.
- We bridge the gap between high-frequency electronic engineering and traditional craftsmanship by demonstrating how low-cost screen-printing techniques can serve both artistic and functional roles.

Related Work

Screen-Printed Electronic Architectures

The versatility of screen printing has been extensively demonstrated in the field of electronics, providing a foundational technology for our proposed textile modernization. Yang et al. have shown that screen printing can achieve optically transparent wideband surfaces using silver nanowires, which suggests that functional conductive layers can be applied to textiles without obscuring the underlying visual patterns (Yang et al., 2025). Furthermore, the ability to print complex switching mechanisms, such as vanadium dioxide (VO2) switches, highlights the precision and scalability of this manufacturing method (Yang et al., 2024). These technologies allow for the creation of via-less designs that reduce fabrication difficulty and cost (Yang et al., 2023), which is a critical requirement when transferring high-tech processes to the resource-constrained environments of traditional textile workshops. While these studies focus on 5G mmWave applications, the core advantage—low-cost, large-area fabrication—is directly transferable to textile production.

Natural Dyes and Material Chemistry

Sustainability in the Ikat revival hinges on replacing toxic synthetic dyes with natural alternatives. Nurfani et al. investigated the optical and morphological properties of natural dyes extracted from mangosteen peel and grass jelly leaves (Nurfani et al., 2025). Although their work primarily focuses on Dye-Sensitized Solar Cells (DSSCs), their extraction protocols and the characterization of UV-Vis absorption spectra provide vital data for textile applications. They demonstrated that mangosteen peel contributes to absorption in the UV-blue region, while grass jelly contributes to the red region (Nurfani et al., 2025). This related work confirms the chemical viability of these biological sources for creating a broad color palette. However, a weakness of current natural dye research is the frequent lack of integration with industrial application methods like screen printing, which this paper aims to rectify.

Functional Inks for Sensing and Identification

The integration of smart features into fabrics requires inks that are both conductive and durable. Jaakkola et al. have extensively documented the development of screen-printed UHF RFID transponders using graphene antennas (Jaakkola et al., 2019)(Jaakkola et al., 2019). They note that while graphene has higher resistivity than copper, it offers a low-cost, eco-friendly alternative that can be printed on flexible substrates like Kapton or paper (Jaakkola et al., 2019). This is particularly relevant for "Smart Ikat," as it enables the printing of Near-Field Communication (NFC) or RFID tags directly onto the fabric for inventory tracking and anti-counterfeiting. Additionally, Bellani et al. reported on wet-jet milling exfoliation to produce scalable graphene inks for micro-supercapacitors, achieving high areal capacitance and flexibility (Bellani et al., 2019). This suggests that energy storage could also be integrated into the textile, powering the onboard sensors or identification tags.

Method/Approach

Framework Overview

Our proposed methodology, the "Eco-Smart Ikat Fabrication Pipeline," consists of three integrated modules: (1) Natural Dye Preparation, (2) Screen-Printed Patterning and Resist, and (3) Functional Electronic Integration. This approach moves away from the purely manual tying of yarns, substituting it with precise screen-printing of resist pastes and dyes, followed by the deposition of functional electronic inks.

Module 1: Natural Dye Synthesis

We adopt the extraction methodology described by Nurfani et al., utilizing mangosteen peel (MP) and grass jelly leaves (GJL) (Nurfani et al., 2025). The raw materials are cleaned, dried, and crushed into a powder before being macerated in solvents (methanol or ethanol) to extract anthocyanins and chlorophyll.

- **Preparation:** Solutions are prepared at a fixed concentration (e.g., 0.6 g/mL) to ensure consistent viscosity for printing (Nurfani et al., 2025).
- **Rationale:** Using these specific biological sources covers a necessary spectrum of colors (reds/purples from MP and greens/browns from GJL) while ensuring the process remains non-toxic.

Module 2: Screen-Printed Application

Instead of the traditional dip-dyeing of tied bundles, we utilize screen printing to apply these natural dyes directly onto the warp threads or finished fabric. For areas requiring "white space" (the resist effect), a hydrophobic paste is screen-printed first.

- **Technique:** We propose using screens with mesh counts optimized for the viscosity of natural dye pastes.
- **Sensors:** Concurrently, we integrate screen-printed sensors for monitoring environmental conditions (pH, humidity) during the manufacturing process. As demonstrated by Albay et al., low-cost microfluidic testbeds with screen-printed sensors can be rapidly fabricated to control chemical signals (Albay et al., 2025). We adapt this concept to monitor the pH of the dye bath, ensuring color consistency without expensive industrial equipment.

Module 3: Functional Integration (RFID and Conductive Layers)

To modernize the Ikat, we apply a final layer of conductive ink to form passive RFID tags.

- **Materials:** We utilize graphene-based inks due to their flexibility and lower environmental impact compared to etched metals (Jaakkola et al., 2019)(Jaakkola et al., 2019). For areas requiring transparency (so as not to hide the Ikat pattern), silver nanowire (AgNW) inks are employed, as they offer high optical transparency (>80%) and decent conductivity (Yang et al., 2025).
- **Design:** The antenna design follows a hybrid structure to match impedance and avoid bonding issues, ensuring the tag is readable by standard UHF readers (Jaakkola et al., 2019).

Evaluation Plan

To validate this methodology, hypothetical samples will be subjected to the following tests:

1. **Wash Fastness and Durability:** Samples will undergo repeated wash cycles. We will measure color retention and the electrical resistance of the printed antennas. Long-term stability will be assessed using protocols similar to those used for resistive plate chamber coatings, involving humidity and temperature cycling (Costa et al., 2025).
2. **Read Range Testing:** The screen-printed RFID tags will be tested for read range and angular stability. We aim for a read distance comparable to the 10mm-11m range reported in graphene RFID studies (Jaakkola et al., 2019)(Jaakkola et al., 2019).
3. **Authentication Rate:** A blind test where users verify the "digital passport" of the Ikat via a smartphone app linked to the RFID tag.

Discussion

Practical Implications and Deployment

The deployment of screen-printed natural dyes offers a scalable alternative to traditional weaving without sacrificing the "handmade" ethos, as the screen preparation itself can remain an artisanal process. The addition of RFID technology addresses the critical market failure of counterfeiting. By screen-printing a unique graphene-based identifier (Jaakkola et al., 2019), an artisan can cryptographically link a physical garment to a digital record of its origin. Furthermore, the use of transparent conductive surfaces (Yang et al., 2025) implies that these textiles could eventually interact with 5G/6G environments, acting as passive reflectors to improve indoor connectivity, thereby adding immense utilitarian value to home textiles (curtains, wall hangings).

Limitations and Failure Modes

Despite the promise, several limitations exist:

4. **Conductivity vs. Flexibility:** As noted in studies of graphene antennas, high resistivity

compared to metals presents a challenge for antenna efficiency (Jaakkola et al., 2019). Furthermore, the flexing and folding of textiles can lead to micro-cracks in the printed conductive traces, degrading performance over time.

5. **Natural Dye Stability:** While mangosteen and grass jelly provide eco-friendly pigments (Nurfani et al., 2025), natural dyes generally exhibit lower light fastness than synthetic counterparts. Without advanced mordants, the "smart" textile might outlast its own aesthetic pattern.
6. **Interference Issues:** Printing conductive layers (AgNW or graphene) directly over complex geometric Ikat patterns may introduce unpredictable parasitic capacitances or interference, similar to the challenges faced when designing bias lines for reconfigurable intelligent surfaces (Yang et al., 2024).

Ethical Considerations

The introduction of industrial techniques like screen printing into a craft defined by manual weaving raises ethical risks regarding the displacement of labor. There is a risk that this technology could be co-opted by large manufacturers to completely bypass artisans. Therefore, the technology transfer must be focused on "empowering the artisan" with tools that reduce occupational hazards (toxic dyes) and increase market power (provenance tracking), rather than mere automation. Additionally, the sourcing of biological materials (mangosteen/grass jelly) must remain sustainable and not compete with food supply chains (Nurfani et al., 2025).

Future Work

Future research should focus on:

7. **Energy Harvesting:** Integrating the micro-supercapacitors described by Bellani et al. (Bellani et al., 2019) to create self-powered Ikat textiles that do not require external batteries for their sensing capabilities.
8. **Advanced Resistive Coatings:** Adapting the robust, radiation-tolerant resistive coatings mentioned by Costa et al. (Costa et al., 2025) to create protective layers for the natural dyes, potentially solving the light-fastness issue.

Conclusion

This paper has outlined a comprehensive strategy for the sustainable revival of Ikat textiles by merging the ancient chemistry of natural dyes with the futuristic capabilities of screen-printed electronics. By utilizing extracts from mangosteen and grass jelly (Nurfani et al., 2025), we address the environmental toxicity of the dyeing process. Simultaneously, by adapting screen-printing techniques used in 5G intelligent surfaces (Yang et al., 2025)(Yang et al., 2023) and graphene RFID transponders (Jaakkola et al., 2019)(Jaakkola et al., 2019), we propose a textile that is not only visually authentic but digitally verifiable. While challenges regarding durability and conductivity remain, this hybrid "Eco-Smart" framework offers a promising path forward, ensuring that the cultural heritage of Ikat remains relevant and economically viable in a technologically driven future.Additionally, natural dyes from mangosteen peel and grass jelly demonstrate promising photovoltaic efficiency and environmental benefits in related applications, supporting their role in sustainable textile innovation (Nurfani et al., 2025).

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