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Data-Driven Frameworks for Circular and Traceable Banana Fibre Textiles: Opportunities and Challenges

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Abstract

The textile industry is one of the most resource-intensive and polluting sectors worldwide, accounting for approximately 10% of global carbon emissions and nearly 20% of industrial wastewater. The growth of fast fashion has further intensified these challenges, generating about 92 million tons of textile waste annually, with projections indicating a rise to 134 million tons by 2030. This has created an urgent need for sustainable and renewable alternatives to conventional fibers such as cotton and synthetics. Banana fiber, derived from agricultural waste in the form of pseudostems, presents a viable solution due to its biodegradability, low water footprint, and high tensile strength. This review synthesizes current research on banana fiber textiles, with an emphasis on traceability, circularity, and technological innovations that can enhance sustainability. Despite its potential, less than 5% of banana pseudostems are currently processed into fiber. The barriers include fragmented supply chains, limited infrastructure, and a lack of digital traceability systems. However, emerging technologies such as blockchain, the Internet of Things (IoT), and Digital Product Passports (DPPs) have the potential to transform these limitations by improving supply chain transparency, product authentication, and lifecycle monitoring. In addition, Life Cycle Assessment (LCA) studies indicate that banana fiber has a significantly lower carbon and water footprint compared to widely used fibers such as polyester and cotton, strengthening its case as a sustainable textile material. The review further identifies critical research and policy gaps. These include the need for integrated frameworks that combine traceability and circularity, comprehensive LCAs, inclusion of smallholder farmers in the value chain, and national policies supportive of eco-friendly fiber production. Future research should aim at building data-driven frameworks that integrate traceability tools, circular economy models, and supportive policies to unlock banana fiber's full potential in the global market.

By bridging these gaps, banana fiber can emerge as a catalyst for sustainable textile innovation, fostering environmental conservation, supporting rural livelihoods, and contributing to the achievement of the United Nations Sustainable Development Goals (SDGs 12 and 13).

Keywords

Banana Fiber, Sustainability, Traceability, Circular Economy, Eco-Textiles

1. Introduction

Traceability refers to the ability to follow the journey of a material or product across its entire supply chain, from origin to end use. Circularity refers to the design and management of products and systems that keep materials in use for as long as possible through reuse, recycling, and regeneration.

Traceability refers to the ability to follow the journey of a material or product across its entire supply chain, from origin to end use. Circularity refers to the design and management of products and systems that keep materials in use for as long as possible through reuse, recycling, and regeneration. The global textile and fashion industry is one of the most resource-intensive and polluting sectors worldwide. It accounts for nearly 10% of global carbon emissions and contributes close to 20% of industrial wastewater discharges, ranking among the highest industrial contributors to environmental degradation [1]. Over the past two decades, the rise of fast fashion has significantly exacerbated these impacts. Consumers are purchasing more clothing items at faster rates, leading to an estimated 92 million tons of textile waste generated annually, a figure projected to rise to 134 million tons by 2030 if no systemic interventions are undertaken [2]. The industry is also responsible for substantial land and water use, chemical pollution from textile dyeing and finishing, and the release of toxic substances that threaten both ecosystems and human health.

Synthetic fibers dominate the global textile market, with polyester, nylon, and acrylic accounting for more than 60% of fiber consumption [3]. While these fibers are inexpensive and versatile, their environmental footprint is immense. They are nonbiodegradable, petroleum-derived, and major contributors to microplastic pollution in aquatic ecosystems [4]. Each wash of synthetic garments releases microfibers that accumulate in rivers and oceans, posing risks to marine life and entering food chains. As the demand for low-cost fast fashion grows, reliance on synthetic fibers is expected to increase further unless sustainable alternatives are adopted. This scenario underscores the urgent need to identify and scale renewable, biodegradable, and resource-efficient natural fibers for textile production.

Natural fibers such as cotton, hemp, jute, sisal, and banana fiber are increasingly recognized as sustainable alternatives. Cotton, while renewable, requires intensive use of water, pesticides, and fertilizers, making it environmentally problematic. In contrast, fibers like hemp, jute, and banana have relatively low input requirements and strong ecological credentials [3]. Banana fiber, in particular, is gaining global attention due to its availability as an agricultural by-product, high tensile strength, durability, and biodegradability. The fiber is extracted from the pseudostem of banana plants, which are usually discarded after fruit harvest, leading to significant volumes of agricultural waste. Transforming this waste into value-added fibers not only contributes to circular economy practices but also creates new income opportunities for farming communities.

Uganda, one of the world's leading banana-producing countries, illustrates the untapped potential of banana fiber. The country produces over 6 million metric tons of bananas annually, primarily for domestic consumption [5]. However, the pseudostems, which make up the bulk of the plant biomass, are largely wasted. Globally, it is estimated that less than 5% of banana pseudostems are processed into fiber, despite their abundance and economic potential [6]. This underutilization highlights both a sustainability challenge and an opportunity: the potential to integrate banana fiber production into sustainable textile supply chains and position it as a competitive alternative to cotton and synthetics.

Despite its advantages, the commercialization and scalability of banana fiber textiles face several barriers. The most significant is the absence of effective traceability and circularity mechanisms in the supply chain. Current banana fiber production is highly fragmented, involving smallholder farmers with limited access to processing technologies, markets, and information. Without traceability, it is difficult to verify sustainability claims, ensure quality standards, or integrate banana fiber into global eco-textile value chains. Similarly, circular economy principles such as recycling, reuse, and lifecycle monitoring are poorly developed within this sector. As a result, banana fiber remains marginalized in the global textile market despite its ecological and social promise.

Technological innovations offer new possibilities for overcoming these barriers. Digital technologies such as blockchain, the Internet of Things (IoT), and Digital Product Passports (DPPs) are transforming supply chain transparency and sustainability in industries ranging from food to electronics [7]. Blockchain ensures immutable records of material origins and transactions, IoT devices can monitor production and logistics in real time, and DPPs provide digital identities for products that capture their sustainability profiles across the entire lifecycle. Applied to banana fiber textiles, these technologies could enable reliable traceability, support eco-labeling, and enhance compliance with international sustainability standards. They could also foster consumer trust and allow brands to demonstrate alignment with the UN Sustainable Development Goals (SDGs), particularly SDG 12 (responsible consumption and production) and SDG 13 (climate action).

At the same time, Life Cycle Assessment (LCA) studies provide growing evidence that banana fiber has a significantly lower carbon and water footprint compared to polyester and cotton [8]. These findings strengthen the case for banana fiber as a sustainable textile alternative. However, the lack of comprehensive LCAs across different geographical contexts, including Uganda, limits the generalization of these benefits. Furthermore, issues of scalability, market competitiveness, and integration with global textile systems remain unresolved. Without targeted research and supportive policies, the potential of banana fiber risks being overlooked in favor of more established but less sustainable fibers.

Policy frameworks and institutional support are therefore critical in enabling the sustainable growth of banana fiber textiles. Governments and international organizations are increasingly promoting eco-labeling, sustainability standards, and circular economy practices within the textile industry (European Commission, 2022). Such initiatives encourage both producers and consumers to engage with eco-textiles and create market incentives for sustainable practices. In Uganda and other banana-producing countries, policies that support farmer inclusion, investment in fiber-processing infrastructure, and integration into export markets could accelerate the adoption of banana fiber as a mainstream textile material. Partnerships between research institutions, private sector actors, and local communities will also be essential in building a resilient and sustainable value chain.

Against this backdrop, this review critically examines the state of knowledge on banana fiber textiles, focusing on traceability frameworks, circular economy practices, technological innovations, and policy initiatives, with specific reference to Uganda's banana sector. The paper highlights gaps in existing research—particularly in data-driven traceability models, integrated circularity approaches, and smallholder farmer inclusion—and proposes future directions for advancing the scalability and sustainability of banana fiber textiles. By doing so, it contributes to the broader discourse on sustainable textiles and aligns with global efforts to transition toward environmentally responsible and socially inclusive textile production systems

2. Global Textile Industry Challenges

The global textile industry is a cornerstone of the modern economy, valued at over $1.7 trillion in 2022 and expected to grow due to rising consumer demand and fast fashion trends [9]. However, this sector is also among the most environmentally damaging industries, responsible for approximately 10% of global greenhouse gas emissions and nearly 20% of all industrial wastewater [1]. The environmental footprint of textiles stems from energy-intensive manufacturing, chemical-intensive dyeing processes, and excessive water consumption. For instance, producing a single cotton T-shirt requires approximately 2700 liters of water, which is equivalent to the drinking needs of one person for 2.5 years [10].

Another pressing issue is textile waste. Fast fashion, characterized by rapid product turnover and low-cost clothing, generates 92 million tons of textile waste annually, with projections indicating this will escalate to 134 million tons by 2030 [2]. Unfortunately, less than 1% of this waste is recycled into new textiles, leading to massive landfill accumulation and resource depletion.

The reliance on synthetic fibers, such as polyester, nylon, and acrylic, worsens these challenges. Synthetic textiles, derived from petroleum-based resources, are non-biodegradable and account for over 60% of the global textile market [3]. When washed, these fibers shed microplastics, contributing significantly to marine and terrestrial pollution.

In response, there is a growing movement toward sustainable textiles, driven by policy changes, consumer awareness, and innovations in material science. Reports indicate that 62% of consumers now prefer sustainable and eco-friendly textile products, and a rising number of brands are pledging to adopt circular economy principles [11]. Despite these initiatives, significant gaps remain in traceability, supply chain transparency, and waste management, especially in developing economies where natural fiber resources are abundant but underutilized.

3. Natural Fibers vs. Synthetic Fibers

Natural fibers have re-emerged as viable alternatives to synthetic materials due to their renewability, biodegradability, and lower environmental footprint. Fibers such as cotton, hemp, jute, coir, and banana fiber have attracted attention for their sustainability potential [3]. Compared to synthetic fibers, natural fibers decompose more readily, thereby reducing landfill accumulation and long-term pollution. Their production also often requires less energy and fewer chemical inputs, particularly when derived from agricultural by-products such as banana pseudostems.

3.1. Advantages of Natural Fibers

The advantages of natural fibers are well documented. They are biodegradable and therefore avoid the persistent microplastic pollution associated with synthetic fibers. Their carbon footprint is generally lower, as most require less energy-intensive processing compared to petroleum-derived fibers. In terms of renewability, agricultural residues such as banana pseudostems provide an abundant and sustainable raw material base. Furthermore, natural fibers are appreciated for their comfort, breathability, and aesthetic qualities, making them desirable for premium textiles.

3.2. Banana Fiber as a Sustainable Option

Banana fiber stands out as a sustainable option due to its high cellulose content, tensile strength, and availability as an agricultural waste product. According to [12], one ton of banana pseudostem can yield 200 - 250 kg of fiber suitable for textiles, ropes, paper, and composite applications. Its processing requires minimal chemical inputs and water, while the fiber itself is biodegradable and compostable [13]. Banana fiber has a tensile strength ranging from 400 - 600 MPa and a Young's modulus of approximately 27 GPa, which is comparable to or higher than cotton (287 - 597 MPa, 12 GPa) and polyester (350 - 900 MPa, 10 - 14 GPa) [8] [13]. These values substantiate claims of banana fiber's mechanical competitiveness. These values substantiate claims of banana fiber's mechanical competitiveness. Economically, valorizing banana pseudostems could generate an estimated USD 2 - 3 billion annually for rural economies in banana-producing countries such as India, Uganda, and the Philippines [14].

Nevertheless, global utilization remains low, with less than 5% of pseudostems currently processed into fiber. Key challenges include non-standardized extraction methods that result in inconsistent fiber quality [15]. Inadequate infrastructure for processing and commercialization, and limited integration of digital technologies for supply chain traceability and management [7].

3.3. The Case of Synthetic Fibers

Despite the environmental promise of natural fibers, synthetic fibers continue to dominate the market because of their low cost, durability, and versatility. However, their environmental impacts are severe. These fibers are non-biodegradable and can persist for centuries in landfills. Their production is highly energy-intensive, generating substantial greenhouse gas emissions. For example, polyester alone accounts for around 40% of global textile-related emissions [16]. Transitioning toward natural fibers such as banana fiber presents a significant opportunity to reduce these environmental harms and align with global sustainability goals.

4. Global Banana Production and Fiber Potential

Bananas rank among the most widely cultivated crops, grown in more than 135 countries, with global production reaching approximately 145 million metric tons annually [12]. Despite this large output, only about 15% of bananas enter international trade, with most serving domestic consumption. Latin American countries, including Ecuador, Costa Rica, Colombia, and Guatemala, dominate exports, particularly of the Cavendish variety, which represents nearly 60% of global trade [17].

The pseudostem, left behind after harvesting, represents a vast yet underutilized biomass resource. FAO (2020) estimates that one ton of pseudostem yields 200 - 250 kg of fiber suitable for textiles, mats, ropes, and eco-friendly composites. Globally, over 114 million tons of pseudostems are generated annually [13], but less than 5% is processed into fiber [6]. The environmental and economic benefits of banana fiber—its biodegradability, low water and chemical requirements compared to cotton, and high tensile strength make it a strong candidate for sustainable textile innovation. Yet barriers such as non-standardized extraction methods, limited commercialization, and absence of robust traceability systems continue to restrict its adoption [15] [18].

4.1. Banana Production in Uganda

Uganda provides a compelling case for the integration of banana fiber into sustainable development strategies. Bananas are central to Ugandan agriculture, culture, and nutrition. The country produces over six million metric tons annually, with cultivation spanning nearly all regions [5]. Ugandans consume between 220 - 400 kg per capita annually, the highest rate in the world, with bananas contributing around 30% of daily caloric intake [19]. Approximately 75% of farmers grow bananas, predominantly the East African Highland Banana (EAHB), or matooke, which accounts for nearly 90% of production [5].

The production system is largely subsistence-oriented, with 70% of bananas consumed by producing households and only 30% entering local markets [5]. Most farmers operate on smallholdings of 0.5 - 2 hectares using low-input methods, which yield 5 - 30 tons per hectare compared to the potential 60 - 70 tons achievable with improved technologies [17]. This indicates both the socio-economic importance of bananas and the opportunities for productivity gains.

4.2. Uganda's Banana Fiber Sector

Despite Uganda's vast pseudostem biomass, the banana fiber sector remains nascent and largely informal. Key barriers include inadequate processing infrastructure, minimal research on fiber quality optimization, limited product diversification, and an absence of traceability systems that constrain access to eco-conscious export markets [5], awareness among smallholder farmers regarding the economic potential of banana fiber is also low.

Nevertheless, initiatives such as the TEXFAD project in Mukono District demonstrate the viability of banana fiber valorization. TEXFAD transforms pseudostems into textiles, décor products, and exports, showcasing the potential of small-scale innovation. Surveys suggest that about 40% of farmers would supply pseudostems if offered fair prices, while up to 70% would engage with fiber markets under favorable conditions. These findings highlight both latent supply potential and the need for supportive ecosystems to expand the sector.

4.3. Challenges and Opportunities in Uganda

Uganda's banana fiber sector faces multiple challenges, including low productivity due to nonmechanized extraction, limited investment and R&D in fiber technologies, weak value chain linkages between farmers and processors, and significant circularity gaps with most pseudostems discarded as waste.

At the same time, the country offers unique opportunities. Abundant raw material availability, coupled with growing global demand for sustainable fibers, creates a favorable context. Supportive policy frameworks—given Uganda's prioritization of bananas for food security and export diversification—further strengthen the case for investment. Additionally, integrating digital technologies such as blockchain and Digital Product Passports could enhance traceability and sustainability verification, positioning Uganda as a leader in eco-textile innovation.

5. Traceability in Textile Supply Chains

5.1. Importance of Traceability in Sustainable Textiles

Traceability, defined as the ability to track a product's journey from raw material to final consumer, is increasingly critical for sustainable textile supply chains. It ensures transparency by allowing brands to verify sourcing practices and certify ethical labor and sustainability credentials. It also promotes accountability, enabling stakeholders to monitor environmental impacts throughout the production cycle, and enhances market access, as many international buyers now require supply chain transparency to meet environmental, social, and governance (ESG) standards [18].

The lack of traceability is a major barrier to sustainability. Research indicates that over 80% of textile companies lack visibility in their raw material sourcing, making it difficult to substantiate eco-friendly claims [16]. For natural fibers such as banana fiber, establishing robust traceability systems is essential to meet global sustainability standards and gain consumer trust.

5.2. Digital Technologies for Traceability

Recent advancements in digital technologies have enabled real-time data capture, supply chain monitoring, and authentication of sustainable materials. These technologies can be leveraged to improve the banana fiber value chain. Blockchain technology, for instance, offers an immutable, decentralized ledger to record every step from pseudostem collection to textile production [7]. Blockchain ensures tamper-proof data, facilitates ethical sourcing claims, and supports regulatory compliance, and has been successfully applied in agri-food traceability systems [7], which share parallels with natural fiber supply chains. Recent pilots demonstrate applicability to natural fibers. For example, [8] reported a blockchain-enabled DPP pilot for hemp textiles, achieving 95% data integrity across the value chain. Similarly, [20] demonstrated a DPP-based cotton traceability framework in China, highlighting scalability potential for banana fibre supply chains. The Internet of Things (IoT) and QR codes further enhance traceability. IoT sensors can monitor environmental conditions during processing and transportation, while QR codes or NFC tags on finished products can provide consumers with detailed information about material origin and processing methods. Digital Product Passports (DPPs), introduced under the European Commission's Ecodesign for Sustainable Products Regulation (ESPR, 2023), digitally store key product information such as material composition, origin, and recyclability. When integrated with blockchain, DPPs can provide full lifecycle transparency, tracking banana fiber through multiple use and recycling cycles, as demonstrated by [18] and [20].

5.3. Traceability Gaps in Banana Fiber Supply Chains

Despite these technological advancements, banana fiber supply chains remain largely informal and unstructured. The sector is dominated by smallholder farmers who often lack digital literacy or access to modern technologies. Manual record-keeping, fragmented networks, and the absence of standardized tracking from pseudostem harvesting to fiber processing create significant traceability gaps. This limits the marketability of banana fiber in international sustainable textile markets. Unlike cotton or hemp, which are increasingly certified through initiatives like the Better Cotton Initiative or Global Organic Textile Standard (GOTS), banana fiber currently lacks a comparable certification framework.

5.4. Potential Technology-Enabled Framework for Traceability

A robust traceability framework for banana fiber could integrate multiple digital solutions. Mobile data collection applications would allow farmers to record pseudostem harvest data efficiently. Blockchain-based platforms could serve as digital ledgers for each batch of fiber, ensuring data integrity. IoT-enabled quality monitoring during fiber extraction and drying would enhance product consistency, while integration with Digital Product Passports would provide end-users with detailed information about fiber origin, processing methods, and recyclability.

Such an integrated framework would not only build trust among consumers and buyers but also enable circular economy practices by monitoring fiber reuse and recycling. By combining mobile applications, blockchain, IoT, and DPPs, the banana fiber sector could significantly enhance supply chain transparency, compliance with sustainability standards, and competitiveness in global markets.

6. Circular Economy and Waste Management in Banana Fiber Textiles

6.1. The Circular Economy Concept

The circular economy (CE) model represents a paradigm shift from the traditional linear "take make-dispose" approach to a closed-loop system that emphasizes resource efficiency, waste reduction, and product lifecycle extension. In the textile sector, a circular economy aims to design out waste and pollution, keep materials in use through recycling, upcycling, and reuse, and regenerate natural systems by utilizing renewable and biodegradable resources (Ellen MacArthur Foundation, 2020). Despite growing awareness, the global textile industry, particularly fast fashion, remains far from circular. Less than 1% of textile waste is recycled into new fibers, while the majority is incinerated or discarded in landfills [2]. Natural fibers, especially banana fiber, offer a compelling opportunity to drive circular textile innovations due to their biodegradability, renewability, and potential to valorize agricultural waste.

6.2. Banana Fiber as a Circular Resource

Banana fiber is extracted from pseudostems, which are usually discarded after harvesting, creating significant agricultural residue. Utilizing pseudostems for textile production aligns directly with circular economy principles by converting waste into a valuable resource, reducing environmental pollution, and minimizing energy and chemical inputs compared to conventional fibers like cotton [10]. Banana fiber is naturally biodegradable, and its textiles decompose without leaving long-lasting pollutants, while banana-based composites can be upcycled into ropes, mats, eco-friendly fashion products, and home décor items. Integrating banana fiber into circular systems not only reduces environmental harm but also creates potential revenue streams for banana-producing countries, including Uganda.

6.3. Waste Management Challenges

Despite these advantages, the utilization of banana fiber remains limited due to several challenges. Extraction and processing methods are often non-standardized, resulting in inconsistent fiber quality [15]. Organized collection and processing infrastructure are largely absent, causing most pseudostems to rot in the fields. Once banana fiber textiles are discarded, few recycling frameworks exist to recover and repurpose them. Additionally, consumer awareness of the recyclability and sustainability of banana fiber products remains low, limiting demand for circular products.

6.4. Digital Tools for Circularity

Emerging digital technologies can facilitate circularity in banana fiber textiles. Blockchain and Internet of Things (IoT) devices can track the fiber lifecycle from pseudostem collection through processing to end-of-life recycling. Digital Product Passports (DPPs), introduced under the European Commission's Ecodesign for Sustainable Products Regulation (2023), can store detailed product information including material composition, origin, recyclability, and environmental footprint. Data analytics can further optimize resource use and predict production waste [18]. For instance, a DPP-enabled banana fiber product could display the fiber's origin alongside clear guidance for reuse, composting, or mechanical recycling, effectively closing the loop and enhancing both environmental and economic value.

6.5. Opportunities for Uganda

The adoption of circular practices in Uganda's banana fiber sector could generate significant socio-economic and environmental benefits. New industries in fiber extraction, upcycling, and recycling could emerge, creating rural employment and reducing post-harvest losses, as over 95% of pseudostems are currently underutilized [6]. Furthermore, circular banana fiber products could access eco-conscious global markets, particularly in Europe and North America, where sustainable materials are increasingly sought after. To fully unlock these opportunities, strategic policy interventions, capacity building, and investment in technology driven waste management solutions are required.

6.6. Research Gaps in Circularity

Although the literature on circularity in textiles is extensive, studies specifically addressing circular economy applications for banana fiber remain scarce. Most research either addresses circular textiles broadly or examines natural fibers without emphasizing digital integration and traceability frameworks. This gap highlights the need for holistic models that combine traceability, recycling, and digital tools to fully realize the potential of banana fiber textiles in sustainable and circular supply chains.

6.7. Socio-Economic Dimensions

Banana fibre valorization has strong socio-economic implications. Income opportunities arise from selling pseudostems that would otherwise be waste. Studies suggest that fibre markets could raise rural household incomes by 15% - 25% [5]. Gender impacts are notable: fibre extraction and weaving in Uganda often engage women's groups, supporting livelihoods and empowerment. Integration of banana fibre into export markets could therefore contribute to poverty reduction, gender inclusion, and rural development.

7. Technological Integration and Digital Solutions in Banana Fiber Textiles

The rapid evolution of digital technologies has transformed supply chain management, enhancing transparency, efficiency, and sustainability. In the textile industry, data-driven systems monitor raw material sourcing, optimize manufacturing, and promote circularity. Technologies such as blockchain, the Internet of Things (IoT), Artificial Intelligence (AI), and mobile applications can address key challenges in traceability and waste reduction, particularly for natural fibers like banana fiber. Technological integration is especially critical for banana fiber due to the fragmented, smallholder-driven nature of the supply chain. A data-driven framework can connect farmers, processors, and manufacturers through real-time data collection, creating a transparent and verifiable record of fiber origin, processing, and lifecycle management.

Blockchain technology provides a decentralized, tamper-proof ledger to track every transaction in the supply chain. It allows verification of origin, authentication of sustainability claims, and consumer transparency, as end-users can view the entire product journey. Successful blockchain pilots in agri-food supply chains highlight its potential applicability to banana fiber textiles, which face similar traceability challenges.

Digital Product Passports (DPPs), introduced by the European Commission's Ecodesign for Sustainable Products Regulation (ESPR), store information on material composition, recyclability, environmental impact, and production history. For banana fiber, a DPP could include details about the farm, extraction methods, dyeing processes, and end-of-life recommendations. When integrated with blockchain, DPPs enable end-to-end supply chain visibility, supporting export markets that demand sustainability credentials and facilitating closed-loop recycling systems.

IoT devices and mobile applications enhance real-time data collection and decision-making. Sensors can monitor moisture content during fiber drying to ensure consistent quality, while mobile platforms allow farmers and processors to log harvests and extraction activities. Geotagging can map production hotspots to support logistics and planning. In rural contexts like Uganda, low-cost mobile solutions provide smallholder farmers with digital tools even in areas with limited connectivity.

Big data and machine learning improve processing efficiency by forecasting pseudostem availability, optimizing fiber cutting, spinning, and weaving, and integrating Life Cycle Assessment (LCA) metrics to continuously evaluate environmental impacts.

However, integrating these technologies faces barriers including high initial costs, low digital literacy, fragmented supply chains, and data security concerns. According to the Technology Adoption Model (TAM), perceived ease of use and usefulness strongly influence adoption rates, highlighting the need for user-friendly and affordable solutions.

Opportunities exist in developing open-source blockchain frameworks for small-scale producers, hybrid systems that combine cloud databases with offline mobile data capture, and integration with existing agricultural digital platforms to leverage synergies in rural communities. These innovations can strengthen banana fiber value chains, improve traceability, and enable sustainable circular practices.

8. Life Cycle Assessment (LCA) of Banana Fiber Textiles

Life Cycle Assessment (LCA) is a systematic methodology used to evaluate the environmental impacts of a product throughout its entire lifecycle, from raw material extraction to end-of-life disposal. According to ISO 14040 (2006), an LCA typically involves four phases: defining the goal and scope, collecting inventory data on resource use and emissions, assessing environmental impacts such as carbon footprint, water usage, and toxicity, and interpreting results to identify hotspots and suggest improvements. In the textile industry, LCAs are widely used to compare the sustainability performance of different fibers, production methods, and waste management strategies [3].

Conventional fibers present significant environmental challenges. Synthetic fibers like polyester and nylon dominate the global textile market but are energy-intensive and nonbiodegradable. Polyester production alone accounts for approximately 40% of textile-related greenhouse gas emissions [16], and synthetic textiles contribute substantially to microplastic pollution, with over 500,000 tons released annually from washing [1]. Cotton, although natural and biodegradable, requires extensive water and pesticide inputs, with production of one kilogram consuming between 10,000 and 20,000 liters of water [10].

By contrast, banana fiber exhibits a much lower environmental footprint. Its production relies on agricultural waste, requiring minimal irrigation, and does not necessitate pesticides or herbicides. The extraction process is non-energy-intensive, resulting in significantly lower carbon emissions. At the end of its lifecycle, banana fiber is fully biodegradable and compostable, avoiding the persistence issues associated with synthetic fibers. Studies indicate that banana fiber generates 70% - 80% fewer greenhouse gas emissions compared to polyester and nylon [6]. Furthermore, the use of pseudostems as a raw material reduces agricultural residue, contributing to circularity and waste-to-resource conversion.

Comparatively, banana fiber performs better than other major fibers in water use, carbon footprint, and chemical requirements. While polyester requires roughly 20 liters of water per kilogram and emits 9 - 12 kg CO_2e/kg, cotton consumes 10,000 - 20,000 liters and emits 5 - 7 kg CO_2e/kg. Hemp requires around 2000 liters and 2 - 3 kg CO_2e/kg. Banana fiber, by contrast, uses less than 500 liters of water per kilogram, emits under 2 kg CO_2e/kg, and requires no pesticides, demonstrating both environmental efficiency and biodegradability [3] [6] [12]. Despite these advantages, LCA data for banana fiber is not yet fully integrated into supply chain decision-making. Digital Product Passports (DPPs) can incorporate LCA metrics such as carbon footprint and water savings, while blockchain-enabled platforms can document and communicate sustainability impacts to consumers. IoT sensors can provide real-time monitoring of energy and resource usage during fiber processing, further supporting data driven sustainability frameworks.

However, gaps in LCA research persist. Most studies focus on laboratory-scale extractions rather than large-scale commercial operations and lack region-specific data for countries like Uganda, where processing infrastructure is still developing. Additionally, current LCAs rarely account for circularity benefits, including multiple reuse cycles and upcycling potential. Future research should expand LCAs to include comparative analyses with cotton, hemp, and bamboo fibers while integrating circularity parameters to reflect real-world conditions, ensuring that banana fiber's full environmental and economic potential is accurately assessed.

9. Policy and Regulatory Frameworks for Sustainable Textiles

The transition of the textile industry toward sustainable and circular models is influenced not only by consumer preferences and technological innovations but also by governmental policies, international regulations, and industry standards. Effective policies provide an enabling environment for practices such as traceability, recycling, and eco-design, which are essential for the growth of banana fiber textiles in global markets. Without clear regulatory frameworks, small-scale producers face challenges in achieving compliance, obtaining certifications, and remaining competitive.

Several international initiatives are driving the textile sector toward sustainability. The United Nations Sustainable Development Goals (SDGs), particularly SDG 12 on Responsible Consumption and Production and SDG 13 on Climate Action, emphasize sustainable material use and reduction of greenhouse gas emissions, aligning directly with banana fiber's low carbon profile. The Paris Agreement and related climate policies encourage industries to adopt renewable and low-carbon alternatives to synthetic fibers. In addition, the European Union's Ecodesign for Sustainable Products Regulation (ESPR) introduces Digital Product Passports (DPPs), requiring detailed product information including sourcing and recyclability (European Commission, 2023), which is crucial for accessing eco-conscious markets in the EU. Certification frameworks such as the Global Organic Textile Standard (GOTS), while primarily used for cotton, could serve as a model for standardizing banana fiber products internationally.

At the national level, Uganda recognizes bananas as a strategic crop for food security and economic development, but the banana fiber sector remains largely under-regulated. Existing agricultural policies focus predominantly on food crop productivity, leaving non-food value chains underserved. Major gaps in Uganda's regulatory environment include the absence of formal standards for banana fiber extraction, processing, and product quality, as well as a lack of certification schemes to verify sustainability and traceability. Furthermore, incentives for investment in processing infrastructure and digital technologies are limited. Nonetheless, regional initiatives such as the East African Bioeconomy Strategy emphasize the need to valorize agricultural waste [5], and mission-oriented policies that focus on research, technology adoption, and export promotion could accelerate the commercialization of banana fiber textiles.

Traceability and circularity frameworks rely on data standardization and digital infrastructure. International examples, including the EU Circular Economy Action Plan (CEAP) and national e-Government initiatives in India and Kenya, demonstrate how digital platforms and blockchain technologies can empower small-scale farmers by linking them to broader markets. For Uganda, integrating blockchain and DPP frameworks into agro-industrial supply chains would enhance banana fiber traceability while opening access to premium international markets.

Despite these policy developments, significant implementation gaps remain. Most policies are designed for large-scale textile industries, often neglecting emerging natural fibers like banana fiber. Limited funding for research and development constrains innovation in fiber extraction and recycling, and practical guidelines translating international standards into actionable steps for smallholder farmers are largely absent. Addressing these challenges requires collaborative policy design involving governments, NGOs, research institutions, and private sector actors.

Opportunities for policy innovation include the development of national standards for banana fiber processing and quality assurance, creation of incentives such as tax breaks or grants for startups producing sustainable textiles, integration of banana fiber into Uganda's export strategy with particular attention to EU markets, and adoption of DPP frameworks through public-private partnerships to establish transparent and traceable value chains.

10. Research Gaps and Future Directions

The literature on sustainable textiles demonstrates significant potential for natural fibers such as banana fiber; however, research remains fragmented, leaving critical gaps that must be addressed to fully realize banana fiber's potential in global markets. One major limitation is the lack of integrated frameworks. Most studies examine traceability or circularity separately, with very few attempting to unify these concepts into a technology-driven model that addresses transparency, waste management, and environmental sustainability concurrently [7].

Digital technology adoption in banana fiber textiles is also limited. While blockchain, IoT, and Digital Product Passports (DPPs) have been explored in other agricultural and apparel supply chains, their application to banana fiber remains minimal [18]. Research on scalable, cost-effective solutions tailored to smallholder-driven banana value chains, particularly in regions such as Uganda, is scarce.

Underutilization of banana fiber further restricts its impact. Globally, less than five percent of banana pseudostems are processed into fiber due to a combination of factors, including the absence of standardized extraction technologies [15], weak linkages between farmers, processors, and manufacturers, and minimal R&D investment in product development and quality optimization. Most sustainable textile frameworks are designed for industrial-scale production, leaving smallholder farmers—who account for 75% of banana cultivation in Uganda—underserved [5].

Policy implementation challenges exacerbate these gaps. Although international regulations such as the EU Ecodesign Regulation (ESPR) and the SDGs promote sustainable materials, there is no clear pathway to translate these policies into practical guidelines for small-scale banana fiber production. Uganda, for instance, lacks formal quality standards, traceability or organic certification schemes, and incentives for investment in fiber processing or recycling.

Life Cycle Assessment (LCA) studies, though promising, are limited in scope. While preliminary research indicates that banana fiber has a low carbon and water footprint, comprehensive LCAs covering all stages of processing and recycling are rare. Comparative analyses with other natural fibers under real-world production conditions are also lacking [3].

To address these gaps, future research should focus on developing integrated traceability circularity models that combine blockchain, IoT, and DPPs to track banana fiber from pseudostem collection to end-of-life recycling. Pilot projects in banana-producing regions, such as Uganda, could validate the feasibility of such frameworks. Scaling banana fiber production requires investment in optimized mechanical and chemical extraction technologies and the exploration of small-scale, decentralized processing units suitable for rural adoption. Advanced LCA studies should compare banana fiber with synthetic and other natural fibers, focusing on carbon footprint, energy consumption, and biodegradability, while integrating LCA metrics into digital tools like DPPs for real-time sustainability monitoring.

Policy-driven research is essential to develop quality standards, certification schemes, and financial incentives to promote R&D and private-sector investment in banana fiber value chains. Smallholder empowerment through training in digital literacy, mobile technology adoption, waste collection, fiber extraction, and record-keeping is also critical. Finally, research should explore circular business models, including product-service systems and take-back programs, to enable closed-loop recycling, while studying global market opportunities for banana fiber-based products in niches such as luxury fashion, sustainable apparel, and eco-friendly home décor.

Emerging research questions include how blockchain and IoT systems can be adapted for rural, low-tech value chains; which circular business models can ensure profitable upcycling of banana fiber textiles; how international policies like the EU ESPR can accommodate nontraditional fibers; and the comparative economic viability of banana fiber relative to cotton and synthetic alternatives in export markets.

11. Conclusions

The global textile industry is at a pivotal moment, facing increasing scrutiny over its environmental impacts, including high carbon emissions, excessive water use, and the generation of massive textile waste. In response, the search for sustainable alternatives has intensified, with banana fiber emerging as a promising eco-friendly solution. Derived from agricultural waste in the form of pseudostems, banana fiber is renewable, biodegradable, and low in carbon emissions, offering a viable alternative to conventional fibers such as cotton and synthetics. Its utilization aligns with circular economy principles and contributes directly to achieving the United Nations Sustainable Development Goals (SDGs).

This review underscores that despite its potential, the adoption of banana fiber faces several challenges. Fragmented supply chains, limited traceability, minimal research and development, and weak policy frameworks—particularly in banana-producing countries like Uganda—constrain its wider use. Advanced technologies, including blockchain, the Internet of Things (IoT), and Digital Product Passports (DPPs), provide practical solutions to these challenges by enabling traceability, transparency, and lifecycle monitoring. Life Cycle Assessment (LCA) studies further demonstrate banana fiber's lower environmental footprint, reinforcing its suitability for sustainable textile innovation.

Realizing this potential requires integrated, multi-stakeholder approaches. Key components include the implementation of technology-driven traceability frameworks to enhance market trust and competitiveness, circularity models that support fiber reuse and closed-loop recycling, supportive policies and certification schemes to attract investment and facilitate market access, and capacity-building initiatives that promote digital inclusion among smallholder farmers, who constitute the backbone of banana fiber supply chains.

Looking ahead, research and industry collaborations should focus on pilot projects that validate data-driven frameworks and circular systems tailored to the socio-economic realities of banana producing regions. Such initiatives can reduce agricultural waste, create sustainable livelihoods, stimulate green economic growth, and position banana fiber as a central material in the future of sustainable fashion and textiles.

Limitations

This review relies primarily on laboratory-scale LCA studies, which may not fully reflect commercial-scale operations. Data gaps remain in lifecycle emissions, socio-economic costs, and long-term scalability. These limitations should be considered when interpreting findings.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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