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Article

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ABSTRACT

The global textile and apparel industry faces critical challenges in supply chain transparency and substantiating sustainability claims. Conventional textile labeling, while mandated to disclose fiber composition and origin, offers only static data that is inadequate for tracking complex manufacturing processes or verifying environmental performance. The European Union's forthcoming Digital Product Passport (DPP) is set to create a dynamic, data-rich digital record for textile products. This paper addresses the crucial challenge of ensuring data integrity and validity for textile product attributes such as fiber traceability, chemical usage, and circularity data. We propose and evaluate a sustainable product tracking system that integrates labeling regulations with the DPP, underpinned by a permissioned blockchain architecture. To validate the framework's feasibility and efficacy, we developed a prototype system based on Hyperledger Fabric and conducted performance evaluations and a case study. The system's architecture is designed to ensure immutable tracking throughout the textile supply chain. Through an end-to-end tracking experiment of an organic cotton garment from raw fiber to finished apparel, the prototype demonstrated a transaction latency of approximately 3.2 seconds and a stable throughput of over 45 TPS under realistic network constraints, proving its technical viability. The analysis confirms that leveraging blockchain as the data backbone for the DPP provides a verifiable and immutable record, effectively combating greenwashing and fostering a circular economy for textiles and apparel.

KEYWORDS

digital product passport, blockchain, textile industry, fiber traceability, apparel manufacturing

INTRODUCTION

The textile and apparel industry, a cornerstone of the global economy, is increasingly recognized for its significant environmental and social impacts. From extensive water and chemical usage in cotton cultivation and dyeing processes to high carbon emissions throughout its complex supply chains and the pervasive issue of post-consumer waste, the industry faces a critical need for a paradigm shift towards sustainability [1]. In response, consumers, advocacy groups, and regulatory bodies are demanding greater transparency and accountability from brands [2]. This demand has exposed the profound limitations of traditional product communication methods, particularly the physical textile label. Governed by regulations such as the U.S. Textile Fiber Products Identification Act and the EU Regulation No. 1007/2011, these labels are restricted to providing static information, primarily fiber content, country of origin, and care instructions [3]. While essential for consumer protection, they fail to convey the dynamic and multifaceted data required to substantiate sustainability claims, such as carbon footprint, water usage, chemical certifications, or adherence to fair labor practices [4]. This information gap has inadvertently created an environment where “greenwashing”—the practice of making unsubstantiated or misleading environmental claims—can thrive, eroding consumer trust and hindering genuine progress toward sustainability [5].

To address these challenges, the European Union has introduced the Digital Product Passport (DPP) as a key component of its Ecodesign for Sustainable Products Regulation (ESPR) [6]. The DPP is envisioned as a comprehensive digital record that accompanies a product throughout its lifecycle, providing detailed information on its origin, composition, environmental impact, and circularity potential, including repairability and recyclability [7-9]. This initiative represents a monumental step toward data-driven transparency. However, the mere creation of a digital passport does not inherently guarantee the trustworthiness of its contents [10]. The core challenge shifts from the availability of information to the verification of its integrity. In a fragmented and globally dispersed textile supply chain, where data is passed through numerous actors—from farmers and spinners to weavers, dyers, and manufacturers—the risk of data manipulation, error, and fraud is substantial [11,12]. A centralized database controlled by a single entity would be vulnerable to both internal and external tampering, failing to build the requisite trust among all stakeholders [13]. Therefore, a critical research gap exists in defining a robust technological framework that can not only host the DPP’s data but also ensure its immutability, verifiability, and accessibility throughout the product’s entire journey.

This paper addresses this gap by proposing a conceptual framework for a sustainable product tracking system that integrates the informational requirements of traditional labeling regulations with the expansive data scope of the DPP, all underpinned by blockchain technology. We argue that a permissioned blockchain provides the necessary infrastructure to create a decentralized, immutable, and transparent ledger for tracking sustainability data points from the raw material source to the end-of-life stage. Furthermore, to validate this concept's practical viability, this research develops a functional prototype system and evaluates its core functions and performance through a representative baseline case study that simulates a real-world supply chain scenario. The objective is to demonstrate how this integration can move beyond regulatory compliance to establish a new standard for product transparency, empowering consumers, validating brands' sustainability efforts, and providing regulators with a reliable tool for verification, thereby fostering a truly circular and accountable textile ecosystem.

BACKGROUND AND LITERATURE REVIEW

Limitations of Current Textile Labeling Regulations

For decades, textile labeling has been the primary vehicle for communicating product information to consumers at the point of sale. In the United States, the Federal Trade Commission (FTC) enforces rules under the Textile Fiber Products Identification Act and the Wool Products Labeling Act, mandating the disclosure of fiber content, country of origin, and the identity of the manufacturer or marketer [14-16]. Similarly, EU Regulation No. 1007/2011 standardizes the naming of textile fibers and related labeling for products sold within the European market[17].

While these regulations have been effective in standardizing basic product information, their inherent limitations are now profoundly exposed by the demands of the circular economy. The core deficiency lies in their static and unidirectional nature. These frameworks were designed for a linear "take-make-waste" model, not a circular one [18,19]. Key performance indicators crucial for sustainability assessment—such as water consumption (e.g., liters per kilogram of fabric), carbon footprint (CO_2 per item), the use of hazardous chemicals (verified by standards like OEKO-TEX®), or confirmation of ethical labor practices (audited by bodies like Fair Wear Foundation)—are entirely absent [14, 20]. Furthermore, the physical label is, by its static nature, a point-in-time snapshot. It cannot be updated post-purchase to reflect repair history or end-of-life processing, which is critical data for enabling circularity [21]. This inherent disconnect between the static physical item and its dynamic lifecycle data is precisely the gap that the Digital Product Passport (which our system prototypes) aims to bridge by linking the product to an updatable digital record. This information void creates a fertile ground for “greenwashing,” where brands leverage vague marketing terms that consumers cannot independently verify. The resulting proliferation of over 100 different eco-labels has led to significant consumer confusion and skepticism, ultimately undermining trust and hindering genuine market transformation.

The Emergence of the DPP

The DPP, proposed under the EU’s ESPR, is a direct regulatory response to these limitations. It conceptualizes a structured, dynamic collection of product-related data, accessible electronically via a data carrier. According to the European Commission’s proposals, the DPP will be mandatory for several product categories, with textiles identified as a high-priority sector due to its complex environmental footprint [22].

The intended scope of the DPP is extensive, covering sustainability, circularity, and supply chain information [23]. However, the ESPR outlines the required data but leaves the implementation technology open to development [8]. This creates a critical challenge: ensuring data integrity and interoperability across a fragmented, global, and often low-trust supply chain. A centralized database, controlled by a single brand or authority, would be a single point of failure and vulnerable to manipulation, failing to build the necessary ecosystem-wide trust. Therefore, the central problem for the successful implementation of the DPP is not just data collection, but the establishment of a trusted, decentralized, and verifiable data governance framework.

Blockchain Technology for Supply Chain Integrity

Blockchain technology emerges as a compelling solution to this data governance challenge. It functions as a distributed, immutable, and transparent digital ledger. In a supply chain context, each event—a batch of cotton being certified, a fabric roll being dyed, a garment being shipped—is recorded as a cryptographically signed transaction [24,25]. These transactions are grouped into blocks, which are then sequentially linked to form an immutable chain.

For the textile DPP, a permissioned blockchain (or consortium blockchain) like Hyperledger Fabric is particularly suitable compared to public blockchains such as Bitcoin or Ethereum [26,27]. Unlike public blockchains where anyone can participate, a permissioned network restricts access to known and vetted entities (e.g., suppliers, brands, auditors, regulators). This walled-garden approach provides several critical advantages for a business context: higher transaction speeds, lower energy consumption, and, most importantly, the ability to protect commercially sensitive information through private data channels while still ensuring the immutability of shared data [28,29]. Previous studies and pilots have demonstrated blockchain's potential in enhancing traceability [12]. Our research builds upon this by proposing a specific architectural framework that directly integrates these capabilities as the foundational trust layer for the mandatory DPP, moving from theoretical potential to a concrete, regulation-aligned application model. The conceptual evolution from traditional labeling limitations to the proposed blockchain-enabled framework is illustrated in Figure 1.

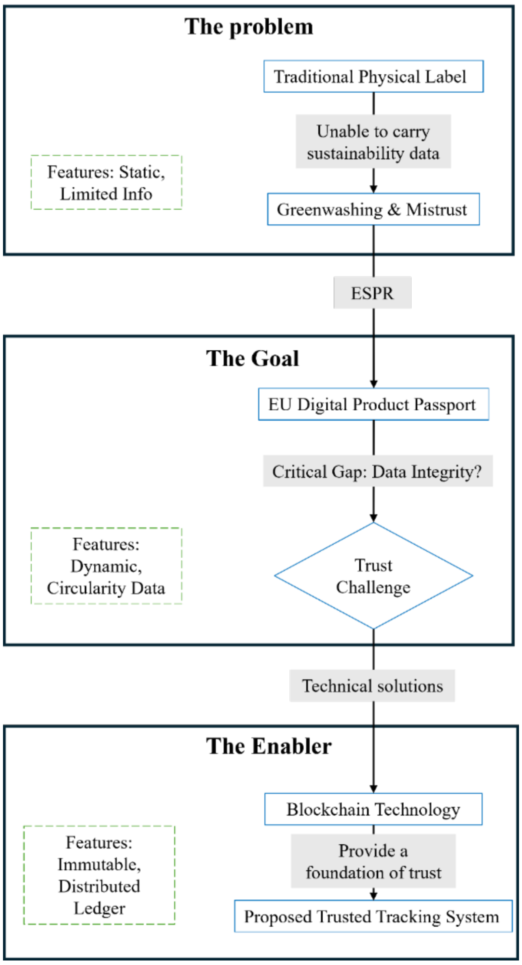

Figure 1. The conceptual framework: Evolving from traditional static labeling to a blockchain-enabled Digital Product Passport

SYSTEM DESIGN AND EXPERIMENTAL METHODOLOGY

To address the challenges of data integrity and traceability, we designed and implemented a multi-layered system architecture that integrates a unique physical product identifier with a blockchain-backed Digital Product Passport. This section details the system architecture, data model, smart contract logic, and the experimental setup used to validate the system.

System Architecture

The proposed system is structured in four distinct layers, as illustrated in Figure 2.

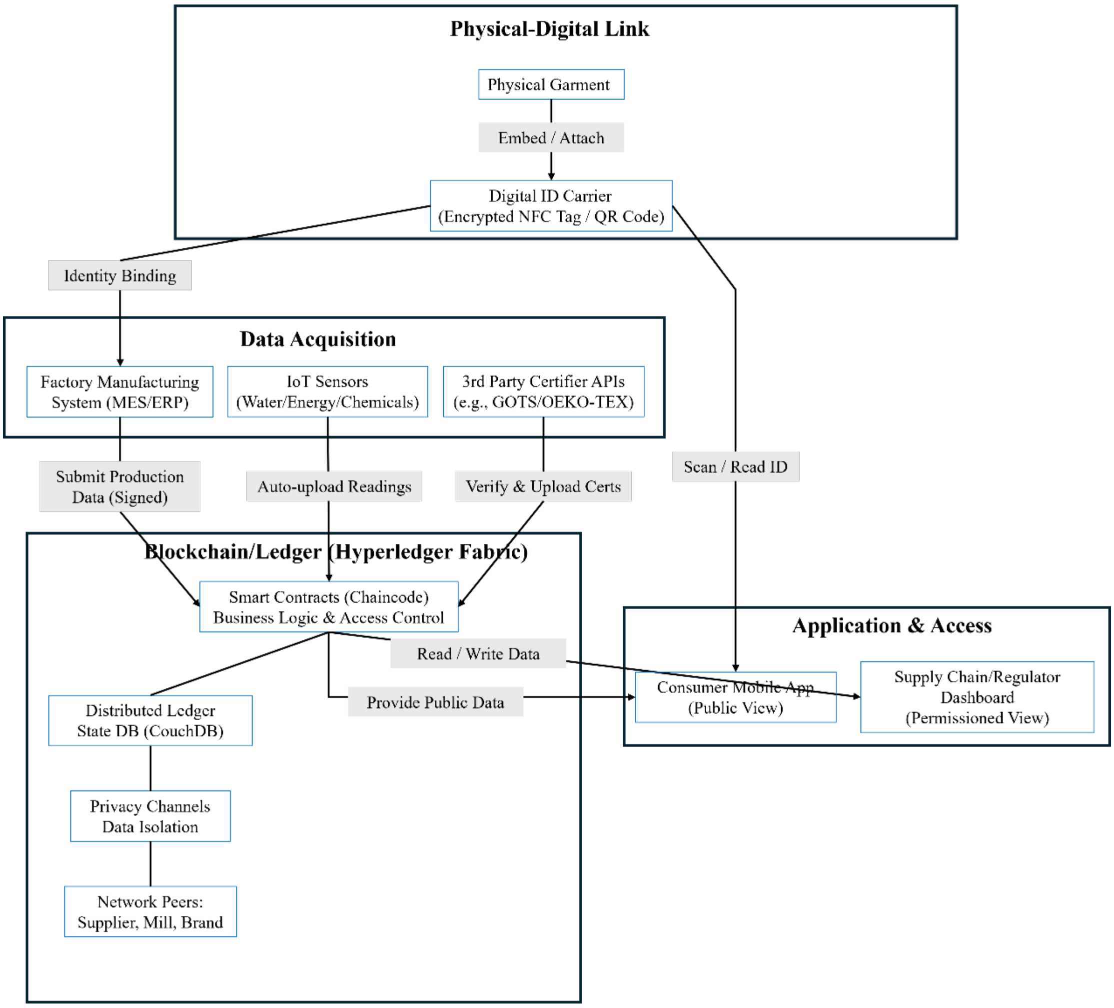

Figure 2. depicts the detailed interactions within this four-layer architecture

Physical-Digital Link Layer: This is the bridge between the physical garment and its digital identity. Each item is assigned a unique identifier, physically embedded as an encrypted NFC tag or a secure QR code. Using encrypted tags is crucial to significantly mitigate the risk of tag cloning and identity spoofing. While not physically uncloneable, cryptographic verification ensures that the interaction involves an authentic tag issued by the system, thereby creating a robust binding between the physical product and its digital record on the ledger.

Data Acquisition Layer: This layer involves the collection and input of data from stakeholders. This process is event-driven; data is submitted only when a key lifecycle event occurs (e.g., completion of a dyeing process, issuance of a certificate). Data sources include direct integration with factory Manufacturing Execution Systems (MES) for production data, IoT sensors for real-time water and energy readings, and secure APIs for third-party certifiers (e.g., GOTS, OEKO-TEX®) to directly attest to a product's compliance. This minimizes manual data entry, reducing the risk of human error and fraud.

To address the critical security concern of this input layer, the architecture's governance model mandates that each participating organization (e.g., the supplier, the certifier) owns and maintains its own private keys and API credentials. The Brand, for example, does not control the credentials for the Supplier's MES. Instead, when a factory's MES submits data, it signs that data with its own digital identity, issued by the network's Certificate Authority (CA). The blockchain's smart contracts then enforce that only the Supplier can submit Supplier data, and only the Certifier can submit Certificate data. This principle of distributed credential ownership is fundamental to ensuring that the system does not reintroduce the very single point of trust or failure it is designed to eliminate.

Blockchain/Ledger Layer: This is the core trust engine of the system. Our prototype is built upon Hyperledger Fabric v2.2, a permissioned blockchain framework designed for enterprise applications. We established a simulated network of four peers representing the Raw Material Supplier, Processing Mill (Dyeing), Garment Manufacturer, and Brand. The architecture leverages Fabric's channels feature to enable need-to-know data sharing, protecting commercially sensitive information. While channels isolate sensitive data payloads (e.g., specific contract terms), the system utilizes transaction hashes as cross-reference pointers to maintain end-to-end traceability. These hashes act as digital fingerprints that prove the existence and sequence of production steps without revealing the underlying private data to unauthorized actors. This tiered architecture ensures that while the chain of custody is verifiable by all stakeholders, the content of custody remains visible only to authorized channel members. Its chaincode (smart contract) functionality allows for the automation of business logic. All validated transactions are timestamped and permanently recorded, creating a single, auditable source of truth.

Application & Access Layer: This is the user-facing interface that interprets and presents the DPP. Access is governed by role-based permissions defined on the blockchain. Consumers access a public-facing, mobile-friendly interface, while supply chain partners and regulators are given more comprehensive, permissioned views into the data relevant to their functions.

Data Model and Smart Contracts

The effectiveness of the DPP depends on a standardized and comprehensive data model. Our designed model balances the need for radical transparency with commercial confidentiality. The data model proposed for the DPP of textiles based on blockchain technology is shown in Table 1.

Table 1. Proposed Data Model for a Blockchain-Enabled Textile DPP

Data Category	Data Points	Example Entry / Format	Data Source Actor
Product Identity	Unique Product ID, Product Name, Brand, SKU, Manufacturing Date & Location	ID: 9A7B3C..., Men's Organic Tee, BrandX, SKU12345	Manufacturer
Material Composition	Fiber Type, Percentage, Origin of Raw Material, Recycled Content (%)	100% GOTS Cotton, Farm: GreenFarms, India, Recycled: 0%	Raw Material Supplier
Sustainability Metrics	Water Footprint (L/product), Carbon Footprint (kgCO2/product), Chemical Certifications, Social Compliance Audits	Water: 2,700 L, Carbon: 7.1 kgCO2e, OEKO-TEX: YES, SA8000: YES	Tier 1–3 Suppliers, Auditors
Supply Chain Traceability	Transaction Hashes linking all production stages (Ginning, Spinning, Weaving, Dyeing, Cut-Make-Trim)	TxID_Dyeing: 0x123..., TxID_CMT: 0x456...	All Supply Chain Actors
Circularity Data	Repair Instructions, Disassembly Guide, Material Recyclability Code, Recommended End-of-Life Path	Link to repair video, Disassemble: Remove buttons, Code: MONO-01	Brand, Recycler
Regulatory Compliance	Conformance to EU regulations (e.g., REACH), Country of Origin (for labeling), Care Instructions (ISO 3758)	REACH: Compliant, Origin: Vietnam, Wash at 30°C	Manufacturer, Brand

To operationalize this architecture, we wrote smart contracts (chaincode) in Go, which were deployed on the prototype network. Key chaincode functions include:

- **createProduct (productID, brand, initialData):** Called only by a verified manufacturer to create the initial digital twin of a garment.

- **addTraceabilityEvent (productID, eventType, eventData, actorSignature):** Used by supply chain partners to add a new lifecycle event, such as Dyeing or CMT.
- **attachCertificate (productID, certificateID, certifierSignature):** Restricted to trusted third-party entities like GOTS to directly link a valid certificate.
- **queryProductHistory (productID):** Called by the application layer to retrieve the full, immutable history of a specific product.

To enforce the security of these functions, particularly the *attachCertificate* function, the system leverages Hyperledger Fabric's native identity management features. A trusted third-party entity (like GOTS or OEKO-TEX) is not an anonymous user; they are onboarded as a formal member of the permissioned network's consortium. This process involves the consortium's CA issuing a unique X.509 digital certificate to that entity. This certificate serves as their verifiable identity. The smart contract contains critical access control logic: it programmatically inspects the digital certificate of the function's caller (using Fabric's *GetCreator()* API) and verifies that their identity (a) is valid within the network's Membership Service Provider (MSP) and (b) possesses a predefined Certifier role or attribute. This mechanism ensures that only entities formally registered and vetted by the consortium can attach verifiable credentials, forming a core part of the system's defense against fraudulent data.

Experimental Setup

To evaluate the prototype's performance and functionality, we designed the following experiments:

- **Performance Benchmarking:** Using a simulated network, we employed a performance testing tool (Hyperledger Caliper) to measure the system's transaction throughput (TPS) and average transaction latency. The network components (four peers and one orderer) were deployed as Docker containers. To strictly replicate the realistic network conditions of a globally dispersed textile supply chain (e.g., cross-border communication between suppliers and brands), we introduced an artificial Round-Trip Time (RTT) latency of 100 ms with a jitter of ±10 ms between nodes using Linux Traffic Control (TC). This configuration mitigates the limitations of a single-host simulation and allows for a robust evaluation of consensus efficiency under realistic Wide Area Network (WAN) constraints. Each peer container was allocated a 2-core CPU and 4 GB RAM. Crucially, to meet the complex data retrieval requirements of the

DPP, all peer nodes were configured with CouchDB as the state database instead of the default LevelDB. While CouchDB introduces higher verification overhead compared to key-value stores, it supports content-based rich queries (e.g., filtering products by specific certification standards or origin). We also deployed JSON-based index definitions to optimize these query performances, ensuring the system provides not just immutability, but also practical auditability for regulators and consumers.

- **Functional Case Validation:** We executed the complete organic cotton T-shirt case study, as described in Section 4, on the prototype system. We recorded the actual transaction IDs and data entry processes for each step to generate a final consumer-facing DPP interface.

RESULTS AND ANALYSIS

This section presents the performance test results from the prototype system and provides a detailed analysis of how the system achieves end-to-end product traceability in the case study.

System Performance Evaluation

The prototype system demonstrated strong efficiency and stability during performance benchmarks, sufficient to support real-world business application scenarios.

The results, illustrated in Figure 3, reflect the system’s performance under realistic constraints. As the transaction load increased, the system demonstrated stable scalability up to a saturation point. Specifically, under a load of 50 concurrent users, the system achieved a peak throughput of 48.7 TPS with an average latency of 3.20 seconds. Beyond this point (at 100 concurrent users), the throughput saturated at 46.5 TPS, while latency increased significantly to 5.45 seconds, indicating the network’s capacity limit. Compared to theoretical baselines using LevelDB, the throughput is lower due to the overhead of JSON indexing required for the DPP’s rich queries and the consensus latency induced by the simulated Wide Area Network. However, this performance is strictly sufficient for the target industrial scenario.

As contextualized in our supply chain model, a medium-sized supply chain processing 10,000 items daily generates approximately 80,000 traceability events, requiring an average throughput of only 2.78 TPS. The demonstrated throughput of 48.7 TPS is approximately 17 times higher than this peak operational demand.

This confirms that even with the necessary overhead for data richness (CouchDB) and network realism, the system provides a robust safety margin for scaling without creating a bottleneck in daily operations.

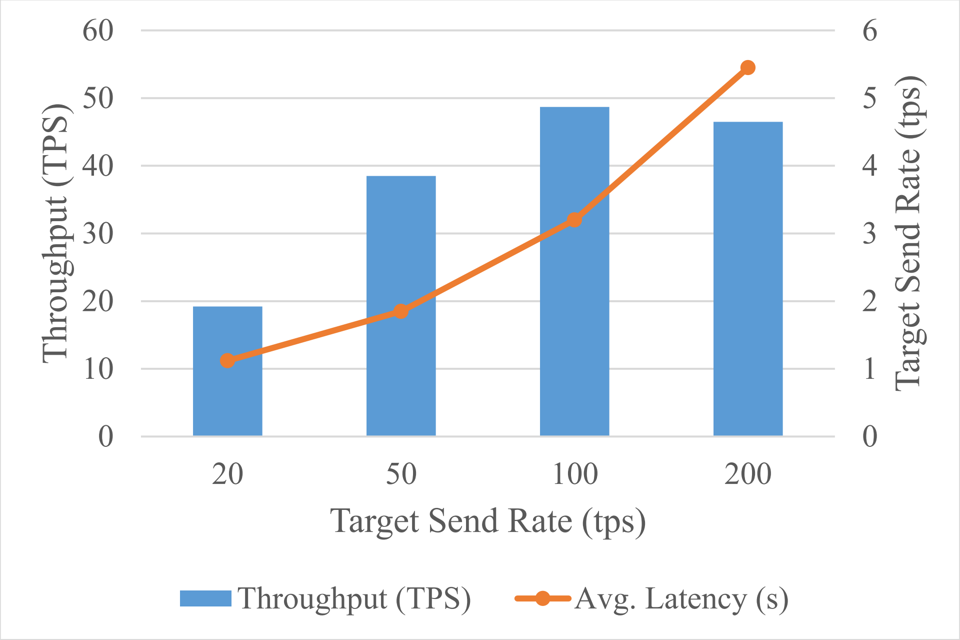

Figure 3. Prototype System Performance Benchmark Results

Case Study: Lifecycle Tracking of an Organic Cotton T-Shirt

We successfully completed the end-to-end tracking of the organic cotton T-shirt on the prototype. A detailed comparison between the information available via a traditional physical label and the blockchain-generated DPP is presented in Table 2.

Table 2. Information Comparison – Traditional Label vs. Prototype-Generated DPP

Information Aspect	Traditional Physical Label	Prototype DPP (Read from Blockchain via API)	Verifiability
Fiber Content	“100% Organic Cotton”	Data: “100% Organic Cotton.” Proof: GOTS Certificate (ID: GOTS-IN-1234) attached. TxID: [0x1a2b...] signed by certifier.	High: Claim is backed by an immutable transaction from a trusted third-party certifier (GOTS).
Country of Origin	“Made in Vietnam”	Full Traceability Path:1. Cotton Farming: India (TxID: [0x2b3c...])2. Spinning/Weaving: India (TxID: [0x3c4d...])3. Dyeing: India (TxID: [0x4d5e...])4. CMT: Vietnam (TxID: [0x5e6f...])	High: The Made in claim is substantiated by a complete, unalterable supply chain map.

Environmental Impact	(No Information)	Verified Metrics: Water Usage (Dyeing): 50 L/kg (TxID: [0x4d5e...]); Chemical Usage: Bluesign® Certified (ID: BS-9876) (TxID: [0x6f7a...])	High: Data is input directly by the certified dyehouse and is auditable on the ledger.
Social Responsibility	(No Information)	Audited Compliance: Facility in Vietnam linked to Fair Wear Foundation audit report (ID: FWF-VN-5432). Audit Date: 02/10/2025 (TxID: [0x7a8e...])	High: The link to the audit is recorded by a trusted third-party auditor, preventing false claims.
Circularity	"Wash at 30°C. Do not tumble dry."	Lifecycle Instructions: Includes standard care, repair guides, material recyclability code, and take-back program locator.	Medium to High: Provides actionable information to extend product life and facilitate proper end-of-life management.

The successful execution of this case study practically demonstrates that our designed system can capture and credibly present granular sustainability data that traditional labels cannot provide.

DISCUSSION

Through prototype development and experimentation, this research has successfully validated the feasibility of integrating textile labeling regulations and the DPP via blockchain. Our architecture is not only theoretically sound, but the performance test results also confirm its efficiency for real-world industry demands. However, during the development and testing process, we also identified several challenges beyond the theoretical level.

First, the "garbage-in, garbage-out" problem remains a critical vulnerability, but it can be mitigated through technical means. In our prototype, we embedded logic checks within the smart contracts. For instance, the chaincode automatically rejects a transaction for a Dyeing event if its timestamp precedes the Weaving event for the same batch. This protocol-level automated verification, while not a complete solution for source data accuracy, effectively prevents logical process errors and enhances data integrity. To fundamentally address the "garbage-in, garbage-out" vulnerability, a multi-layered data assurance framework must be established to bolster the veracity of source data. Future iterations of this system should integrate three key technological pathways:

IoT-Based Automated Data Acquisition: To minimize the risk of human error or fraud associated with manual data entry, the system should prioritize direct integration with Internet of Things (IoT) devices. For instance, installing encrypted smart meters and chemical sensors in a dyehouse could automatically and directly record water consumption and chemical usage data onto the blockchain. Data generated and cryptographically signed by machines possesses a higher degree of objectivity and trustworthiness, forming a reliable data foundation for the DPP.

Decentralized Oracle Mechanisms: For critical information requiring external verification, such as the validity of a GOTS certificate or a Fair Wear Foundation audit, oracles can serve as trusted data bridges. An oracle functions as an independent service that fetches data from authoritative off-chain sources (e.g., a certifier's public database), verifies its authenticity through a decentralized consensus mechanism, and then feeds it into the blockchain. This prevents a single supply chain actor from self-attesting to external claims, ensuring the neutrality and authority of the verification data.

On-Chain Reputation Systems: Within the permissioned blockchain's governance framework, a dynamic reputation score could be established for each data-contributing entity. This score would be programmatically calculated based on the historical accuracy, timeliness, and completeness of their data submissions. For example, periodic, random audits by third-party verifiers could validate on-chain data, with the results directly impacting a supplier's reputation score. High-reputation actors could be rewarded with incentives, while low-reputation actors might face stricter scrutiny or even temporary suspension of network privileges, creating a powerful economic and governance incentive for all stakeholders to maintain data integrity.

> It must be acknowledged, however, that these technical mitigations—IoT, oracles, and reputation systems—are necessary but not sufficient to entirely solve the garbage-in, garbage-out problem. They fundamentally address data integrity but cannot, by technology alone, solve the human and economic incentive to commit fraud. Notably, the system's efficacy still hinges on a crucial assumption: that the economic incentive (e.g., maintaining a high reputation score) outweighs the benefit of falsifying data. In a low-trust jurisdiction where physical audits are rare and costly, an SME may still be economically motivated to report false metrics to maintain its reputation. This highlights a fundamental socio-economic limitation: technology can provide a verifiable record of a claim, but it cannot guarantee the absolute physical truth of that claim without a robust, frequent, and costly off-chain audit framework to anchor the digital data to reality.

Second, regarding adoption barriers for small and medium-sized enterprises (SMEs), our development process underscored the critical importance of data standardization. Production data from different suppliers (e.g., units for water consumption, chemical names) can vary widely. A successful system requires not only a simple user interface but also an industry-wide data input standard. This suggests that the role of a governing consortium is not just to manage the network but, more importantly, to enforce a shared data dictionary.

Beyond data integrity and SME adoption, the prototype development and evaluation process highlighted three additional strategic challenges that are critical for the successful real-world deployment of such a system: consortium governance, data privacy, and system interoperability.

The Complexity of Consortium Governance: This system's permissioned architecture necessitates a robust governing body to manage the network. The responsibilities of this consortium extend far beyond technical maintenance; it must define and enforce a clear set of rules, including member onboarding and offboarding criteria, data ownership and access rights policies, the enforcement of data standardization protocols, and, crucially, a dispute resolution mechanism. For instance, if a supplier is found to have uploaded fraudulent data, the governance framework must provide an unambiguous process to adjudicate the issue, apply penalties, and correct the on-chain record. A poorly defined or weakly enforced governance model would fundamentally undermine the trust the system is designed to create.

Balancing Data Privacy with Commercial Sensitivity: While Hyperledger Fabric's channels feature provides a foundational layer of data segregation, complex supply chains demand more granular privacy controls. A brand, for example, may need to prove to its upstream suppliers that it procured a sufficient quantity of certified organic cotton without revealing its total purchase volume, which could be a strategic business secret. Advanced cryptographic techniques are required to solve this dilemma. Zero-Knowledge Proofs (ZKPs), for instance, offer a powerful solution by allowing one party to prove to another that a statement is true without revealing any underlying data. In our system, a brand could generate and post a ZKP on-chain to cryptographically verify a claim (e.g., "total organic cotton inputs ≥ total organic garment outputs") without disclosing the exact figures. While a full implementation is beyond this prototype's scope, a conceptual mapping for this use case would likely favor a scheme such as zk-SNARKs (Zero-Knowledge Succinct Non-Interactive Argument of Knowledge). Although newer variations are emerging, traditional zk-SNARKs often require a trusted setup, but this is a solvable governance challenge within the defined, permissioned consortium. The primary advantages would be their succinctness—resulting in very small proof sizes—which is critical for minimizing on-chain data storage (a key challenge identified earlier), and their extremely fast verification times. This would allow a brand to efficiently prove complex assertions about its supply chain quantities without revealing any commercially sensitive data, thereby achieving auditable transparency.

Interoperability with Legacy Enterprise Systems: Stakeholders across the textile industry, particularly large brands and manufacturers, are deeply invested in their existing Enterprise Resource Planning (ERP), MES, and Supply Chain Management (SCM) systems. A solution that requires them to abandon these legacy systems is not viable. Therefore, seamless interoperability is a prerequisite for widespread adoption. The solution lies in developing standardized APIs and middleware that act as a translator between the blockchain ledger and traditional enterprise software. This would not only ensure that production and logistics data flow smoothly from existing systems onto the blockchain but also allow verifiable traceability data from the blockchain to be integrated back into corporate dashboards for data-driven decision-making. A lack of seamless integration presents one of the most significant technical barriers to the system's scalability and adoption. Furthermore, this interoperability challenge extends far beyond legacy systems to address the critical issue of cross-platform interoperability between different DPP platforms. Notably, while our permissioned model addresses the single point of technical failure, a single consortium itself introduces a single point of governance risk. In a realistic global market, it is inevitable that multiple, rival DPP consortia and platforms (e.g., some using Fabric, others using different ledgers like Corda, or different data standards) will coexist. Without a clear strategy for interoperability, this will create new, fragmented data silos on different ledgers. Therefore, a critical challenge and a vital area for future research is the development of industry-wide interoperability standards. Technologies such as Decentralized Identifiers (DIDs) and Verifiable Credentials (VCs) from W3C could provide a blockchain-agnostic framework to allow for verifiable data to be securely exchanged between these disparate platforms. Lacking this cross-platform interoperability, the industry risks trading one form of fragmentation for another, severely undermining the ultimate utility of the DPP.

Moreover, a significant practical and economic barrier to adoption, which was not evaluated in our prototype, is the long-term cost of data storage and archival. The DPP regulation mandates data availability for potentially up to a decade, and in a blockchain system, this ledger is immutable and ever-growing. As millions of product passports and traceability events are recorded, the cumulative data storage required by all peers in the Hyperledger Fabric network will become non-trivial. This raises substantial operational cost concerns, particularly for the SMEs who form the backbone of the textile supply chain. Future work must therefore investigate strategies for managing ledger size, such as data pruning, off-chain storage solutions, or archival mechanisms that can satisfy regulatory requirements for verifiability without incurring prohibitive long-term storage costs for all network participants.

> Finally, we acknowledge that the case study presented—a single-material organic cotton supply chain—represents a best-case scenario where identity preservation is straightforward. While this effectively validates the system’s architectural integrity and data flow, it does not address the Mass Balance challenge inherent in complex blended textiles (e.g., mixing cotton batches from different origins or blending cotton with polyester). In such scenarios, the direct link between a specific input batch and a specific output unit becomes probabilistic rather than deterministic. Therefore, this case study should be interpreted as a foundational validation. Future extensions of our smart contracts will need to incorporate rigorous input-output mass balance algorithms to handle the splitting and merging of material streams, which remains a critical frontier for the entire blockchain traceability field.

Finally, our performance results offer key insights. While the observed throughput of 48.7 TPS is sufficient for most current supply chains, future large-scale systems with hundreds of millions of products and high-frequency updates (e.g., second-hand resale) may require an exploration of Layer-2 scaling solutions or optimized data structures to ensure long-term scalability.

CONCLUSION

The inherent limitations of traditional textile labels have set the stage for a technological evolution in product information. This paper has designed and, through a prototype, validated a sustainable product tracking system that synergizes existing labeling regulations with the data-rich vision of the Digital Product Passport. At the core of this system is a permissioned blockchain architecture, serving as a foundational trust layer for sustainability data throughout a garment’s lifecycle.

The primary contribution of this research is that it not only proposes a conceptual framework but also confirms its technical feasibility and effectiveness through the development of a functional prototype and quantitative performance evaluation. The successful case study clearly illustrates how this system replaces ambiguous claims with verifiable, granular data, thereby empowering consumers, enabling brands to substantiate their sustainability efforts, and equipping regulators with a powerful tool for compliance.

While significant challenges in data verification, stakeholder adoption, and interoperability must be addressed, the potential of this technological convergence is transformative. By anchoring the Digital Product Passport in a secure and decentralized ledger, this system replaces ambiguous claims with immutable, verifiable records. While it cannot physically guarantee the veracity of manual inputs, it establishes a tamper-proof digital provenance that significantly raises the cost of fraud and empowers regulators with an auditable history.

Author Contributions

Xuejie Zhao designed, collected and analyzed the data, and drafted the manuscript. Xuejie Zhao conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Xuejie Zhao participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Conflicts of Interest

The author declares no conflict of interest.

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Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

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