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Research Article

Digital Product Passport as a Carrier of Quality and Provenance Data: Standards, Verification, Monetization Mechanisms, and Consumer Trust

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ABSTRACT

This study examines the Digital Product Passport (DPP) as a system-forming technological element that enables the practical implementation of the transition to a circular economy. The analysis focuses on the regulatory, legal, and standardization foundations for DPP deployment, including the European Commission's proposal of 30 March 2022 for the Ecodesign for Sustainable Products Regulation (COM (2022) 142 final), as well as Regulation (EU) 2023/1542 on batteries and waste batteries, which established the sectoral battery passport as the first formally codified industry precedent. The discussion further covers GS1 specifications and contemporary approaches to cryptographic data verification that support verifiability and immutability of key product information. On this basis, the functional role of the DPP is articulated in strengthening transparency across global supply chains, where traceability, comparability, and information integrity operate as critical conditions for sustainable resource governance and reduced environmental burden.

A substantial emphasis is placed on the transformation of Fresh chains-supply chains for perishable products-using an authorial methodology. It is shown that integrating dynamic quality parameters into decision-making loops-from storage and transportation to distribution and retail-creates preconditions for a fundamental reduction in food waste through tighter alignment of logistics operations with the product's actual condition. At the same time, the study considers the economic logic of lifecycle monetization, analyzing a shift of the analytical center from customer lifetime value (CLV) to product lifetime value (PLV). This shift enables a re-structuring of value assessment with explicit consideration of reuse, repair, recycling, and secondary markets.

The argumentation is supported by current statistical evidence on consumer trust, including the HX TrustID™ index, as well as data reflecting willingness to pay a price premium for confirmed, verified sustainability attributes. As a

practice-oriented outcome, an architectural model of a decentralized DPP is proposed, combining blockchain infrastructure, decentralized identifiers (DIDs), and verifiable credentials (VCs). Together, these components form a technological contour for reliable provenance attribution, lifecycle event recording, and reproducible verification of declared product characteristics.

KEYWORDS

digital product passport; ESPR; Fresh supply chains; blockchain; GS1 standards; circular economy; consumer trust; asset tokenization; IAS 41; sustainable development.

INTRODUCTION

The global economic paradigm is undergoing a systemic shift: the linear logic of "take-make-dispose" is gradually giving way to a circular architecture aimed at retaining resource value over the longest possible time horizon [1]. A major constraint on this transition is information asymmetry: across successive stages of the product lifecycle-from raw material extraction to final recycling-material information about composition, provenance, and environmental footprint is lost or distorted, including through falsification [3, 4]. Within this configuration, the Digital Product Passport (DPP) functions not as an auxiliary reporting instrument, but as a full-fledged digital infrastructure designed to overcome trust deficits among producers, consumers, and regulators through standardized data representation and demonstrable verifiability [2].

As of the end of 2023, the DPP at an economy-wide level remained in a stage of regulatory construction under the European Commission's COM(2022) 142 final proposal for an Ecodesign for Sustainable Products Regulation. The Commission explicitly indicated that digital product passports should become the norm for goods regulated under the future ESPR [5, 6]. At the same time, a sectoral regulatory precedent had already been created by Regulation (EU) 2023/1542 on batteries, which provides for the introduction of a battery passport for relevant categories of batteries from 18 February 2027 [1]. This requirement extends to a broad set of product categories, including textiles, electronic products, construction materials, and batteries [7]. The consequence is a business imperative not only to adapt internal IT landscapes, but also to ensure deep interorganizational connectivity with counterparties across the entire value creation chain; this becomes especially salient in the Fresh sector, where data refresh rates and data accuracy are directly linked to product safety and quality [9].

A methodologically significant direction in the transformation of Fresh chains is the move toward intelligent traceability systems capable of accounting for "dynamic quality" in real time. Available statistics indicate the scale of food losses at the consumption stage: UNEP estimates that 17% of all food available at the consumer level is lost or wasted, with approximately 2% attributable to the retail segment. Research on perishable goods management has shown that applying dynamic shelf-life approaches and price discounts tied to actual remaining shelf life can substantially reduce food losses; in certain retail models, the dynamic shelf-life effect is estimated at roughly a 40% reduction in waste on average. In this logic, the DPP should be treated as an infrastructure for integrating data on provenance, handling conditions, and current product state [11]. Integration of the DPP with IoT sensors and blockchain is

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considered a technological coupling capable of reducing the stated losses by 40% through automated monitoring of storage and transportation parameters [13]. The present work aims to systematize DPP technical standards, analyze data verification mechanisms grounded in self-sovereign identity (SSI), and assess how increased transparency is reflected in consumer behavior and business economic performance.

The purpose of the study is to develop theoretical, methodological, and architectural foundations for applying the digital product passport as an instrument of verifiable traceability, enhanced consumer trust, and data monetization within a circular economy, with a special emphasis on Fresh supply chains.

Scientific novelty is expressed through the integration of ESPR regulatory requirements, GS1 standards, and decentralized verification mechanisms (DID, VC, blockchain) into a unified DPP architectural model, supplemented by an authorial rationale for shifting from customer lifetime value (CLV) to product lifetime value (PLV) in relation to perishable products.

The author's hypothesis is based on the assumption that deploying a decentralized digital product passport containing dynamic quality parameters and verifiable provenance information will simultaneously reduce losses in Fresh chains, increase transparency and consumer trust, and form new sources of economic value throughout the product lifecycle.

Materials and Methods

The methodological foundation of the study was formed through a synthesis of European Union regulatory acts, technical specifications issued by international standardization organizations, and an academic corpus of publications indexed in Scopus and Web of Science for 2020-2023. The applied analytical toolkit relies on methods of systems analysis, classificatory ordering, and comparative assessment of technological solutions, ensuring comparability of heterogeneous approaches and identifying their functional limitations [15].

The technical dimension of the study builds on standards for identification and machine-readable data linkage: ISO/IEC 15459 as a basis for unique identification, and the GS1 Digital Link standard as a mechanism for linking a physical object to digital resources in a web environment. The cryptographic layer is examined through the lens of the W3C recommendations Decentralized Identifiers (DIDs) v1.0 and Verifiable Credentials Data Model v1.1, which define a baseline architecture for verifiable attribution of subjects, claims, and digital proofs, as well as the GS1 Digital Link architecture that provides linkage between the physical object and digital resources in a distributed information environment [13]. The cryptographic layer is further considered through W3C standards governing decentralized identifiers (DID) and verifiable credentials (VC), enabling the description of formal mechanisms for authentication of data provenance, provability of claims, and their verifiable transfer among supply chain participants [19, 39].

The economic contour of the study includes analytical indicators extracted from reports by Deloitte, PwC, and Bain & Company reflecting consumer trends and market valuation of DPP solutions, enabling alignment of technological capabilities with observed demand dynamics and the investment attractiveness of relevant platforms [20, 21]. A separate emphasis is placed on the adaptation of international financial

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reporting standards to the conditions of the digital economy: provisions of IAS 41 "Agriculture" are interpreted in the context of tokenization of biological assets as an instrument for formalized accounting and improved traceability of value characteristics within digital ecosystems [12, 24].

Results and Discussion

As of December 2023, the Digital Product Passport had already moved beyond the boundaries of purely voluntary initiatives; however, at an economy-wide level it still remained at the stage of legislative formalization within the European Commission's ESPR proposal. At the same time, in the battery sector the regulatory model had already been concretized by Regulation (EU) 2023/1542, which established an electronic battery passport accessible via a QR code and established that the information contained therein must be based on open standards, presented in an interoperable format, and maintain data accuracy, completeness, and timeliness [1]. The regulatory design further specifies that the DPP must contain a formalized and structured set of information delivered through a machine-readable carrier-a QR code or an NFC tag-placed directly on the product or its packaging [1]. In practical terms, this creates a unified data access interface oriented toward automated processing and integration into digital traceability loops [14, 16].

A central innovation is the imperative of interoperability: data exchange and portability must be ensured without technological dependence on a specific software supplier, thereby avoiding "vendor lock-in" effects and lowering barriers to cross-system compatibility [1]. Such framing shifts attention away from local corporate solutions toward an economy-wide data architecture, where standardized formats, protocols, and identifiers become a necessary condition for scaling DPPs across cross-border supply chains.

Regulatory specification is expected to be implemented through specialized delegated acts for individual product categories; these acts are intended to define an exhaustive list of parameters subject to disclosure as well as the rules governing their representation. Batteries are designated as a priority direction, for which mandatory application of the product passport is established from February 2027 [8].

Table 1 describes the key data groups and parameters of the digital product passport under Battery Regulation 2023/1542.

Table 1. Key data groups and parameters of the digital product passport under Battery Regulation 2023/1542 (compiled by the author based on [1])

Data group	Core parameters	Role in the circular economy
Identification	GTIN, serial number, batch number, operator UID	Ensuring traceability from farm to shelf
Material composition	Chemical profile, substances of concern (SoC)	Safe recycling and waste management

Technical characteristics	Durability, repairability, energy efficiency	Extending the product lifecycle
Environmental footprint	Carbon footprint (GWP), water consumption, biodiversity	Verification of environmental claims (anti-greenwashing)
Instructions	User manuals for operation, repair, and disassembly	Enabling service-based maintenance models
Secondary use	Share of recycled content, disposal instructions	Closing loops of material flows

System-level analysis of regulatory and technological preconditions demonstrates that the DPP cannot be reduced conceptually to a static "product card." The product passport should be treated as a dynamically maintained dataset subject to updates throughout the lifecycle-from release and market placement to servicing, secondary use, and disposal [8]. In particular, when repair is performed or a component is replaced, updates to the DPP are required by an authorized participant (for example, an authorized service center), ensuring reproducibility of intervention history and increasing the reliability of subsequent conformity assessments [8, 17].

To enable scalable exchange of data about millions of individual trade items, a unified identification mechanism is required-one capable of linking a physical object to digital resources in a global environment. In this logic, the GS1 Digital Link standard is interpreted as a transition from isolated identifiers to a "web-native" model that combines traditional keys (including GTIN) with web-technology infrastructure and URI-based addressability [28, 29]. Such a construct makes it possible to use the same machine-readable carrier in a multifunctional mode: within the retail perimeter, operational identification is supported at the point of sale, while the informational perimeter provides access to provenance information, product attributes, and accompanying materials, including usage recommendations [13, 18].

The syntactic model of GS1 Digital Link allows addressability to be specified down to the batch level or even an individual unit, which is illustrated by adding parameters to the URI (for example, a batch identifier and an expiry date): https://id.brand.com/01/GTIN/10/BATCH123?17=EXPIRY. This degree of granularity is of fundamental importance for Fresh supply chains, where responses to contamination incidents or nonconformities must enable targeted product withdrawal with batch-level precision within minimal time windows measured in minutes rather than days [13]. Use of GS1 Digital Link makes it possible to connect traditional GS1 identifiers to web resources and to supplement them with attributes such as batch number, serial number, and expiry date. As a result, the same machine-readable carrier can simultaneously perform an identification function in the operational perimeter and provide access to extended digital information about the product.

A critical technological node for DPP deployment remains the provision of provable reliability of the data being entered. Centralized databases increase vulnerability to unauthorized modifications and create dependence on a single point of failure, which reduces the trust potential of the entire system [30, 32]. In this context, blockchain technologies are considered as a mechanism for building an immutable event registry that records actions and states as a verifiable chronology, increasing resistance to tampering and simplifying traceability audits [15].

The architecture of a trusted DPP conceptually relies on a linkage of several technological layers. Decentralized identifiers (DIDs) provide an object with unique digital addressability in a distributed environment, oriented toward cryptographic protection and resistance to forgery [19]. Verifiable Credentials (VCs) form a class of digital attestation artifacts signed with the issuer's key (for example, a quality-control laboratory or a certification body) and enable confirmation of specific attributes-including absence of pesticides or adherence to environmental production practices-in a form suitable for independent verification [19, 31]. Smart contracts extend this construct through automation of controls and responses: when telemetry from IoT sensors indicates a temperature excursion in a Fresh chain, a smart contract can trigger the prescribed rule for status change, including automatic invalidation of a freshness indicator in the DPP, thereby ensuring not only fact recording but also machine-executable compliance logic [10] (see Fig. 1).

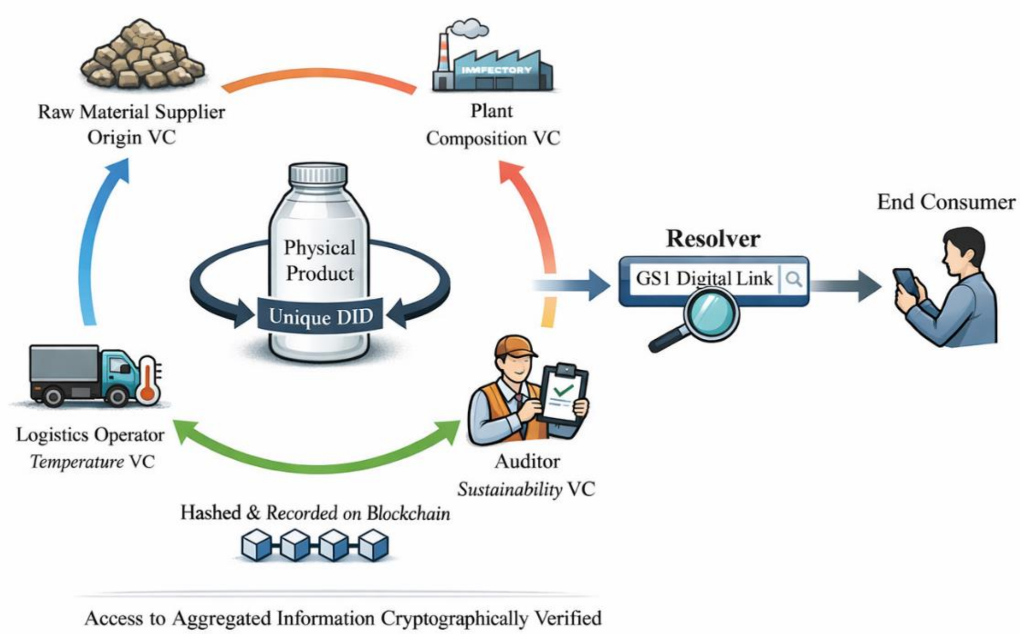

Figure 1. Architectural model of a decentralized Digital Product Passport (author's design).

The Fresh segment is characterized by a specific set of constraints shaped by rapid degradation of consumer properties, heterogeneity of quality-control procedures across operational stages, and pronounced price volatility. Under these conditions, digital modernization of supply chains implies a shift in emphasis from retrospective accounting toward predictive analytics capable of forecasting product condition and managing the risk of quality loss. As the informational core of such solutions, the DPP serves as a carrier of "dynamic shelf-life" data, where remaining usability is calculated not from nominal regulatory norms but from empirically recorded transportation and storage conditions, thereby forming a more accurate model of residual fitness [10].

Within the agricultural contour, tokenization increasingly functions as a verification-oriented financial instrument. IAS 41 requirements imply valuation of biological assets at fair value less costs to sell [24]; however, where production sites are remote and active markets are underdeveloped, such valuations often incorporate a heightened share of expert subjectivity. Translating biological assets (crop yield, livestock herds) into a tokenized representation on blockchain enables formalization of their physical and biological characteristics-mass, age, genetic parameters, and other attributes-into digital tokens, creating conditions for their use as collateral instruments in lending and other financial operations [25, 33].

Empirical findings reported in the literature suggest that use of blockchain platforms for tokenization of agricultural assets correlates with noticeable improvements in operational and institutional indicators: a 31.3% reduction in credit decision time, a 37.3% decrease in transaction costs, a 40% increase in financial transparency, and a 15% reduction in fraudulent practices across supply chains [38]. In the context of Fresh supply chains, tokenization additionally reveals potential for implementing "smart pricing" (Dynamic Pricing), where the retail price is automatically adjusted to the remaining shelf life recorded in the DPP [13]. Such a model strengthens incentives for accelerated sale of products as critical thresholds approach, reducing the probability of their transition into waste by aligning consumer demand more precisely with actual product quality [34, 35].

From an economic standpoint, DPP adoption in corporate practice is frequently interpreted as a predominantly cost-driven contour induced by compliance requirements. Yet, evidence presented by leading analytical agencies indicates that the product passport can function as a generator of new value, serving as a basis for data monetization, process efficiency gains, and the formation of additional service models that go beyond minimal regulatory conformity [22, 23]. To describe monetization models and value sources of the digital product passport, Table 2 is presented below.

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Table 2. Monetization models and sources of value of the Digital Product Passport (compiled by the author based on [22, 23, 26, 27]).

Monetization model	Implementation mechanism	Economic effect
Secondary-market activation	Verification of authenticity and ownership history in the DPP	Increase in resale value (brand halo effect)
Product-as-a-Service	Collection of usage data for subscription models	Shift from one-time sales to recurring revenue
Service leverage	Automated reminders for repair and parts replacement	Increased after-sales service revenue
Logistics optimization	Precise batch tracking and inventory management	Reduction in write-off and recall costs by 20-40%
Access to capital	Asset tokenization (IAS 41) and ESG financing	Lower cost of borrowed capital

According to Bain & Company forecast estimates, DPP implementation can deliver a twofold increase in product lifetime value; at the same time, up to 65% of the additional value generated is potentially redistributed in favor of consumers through expanded access to high-quality secondary-market goods and associated service offerings [22]. Figure 2 below presents a model of value transformation across the product lifecycle.

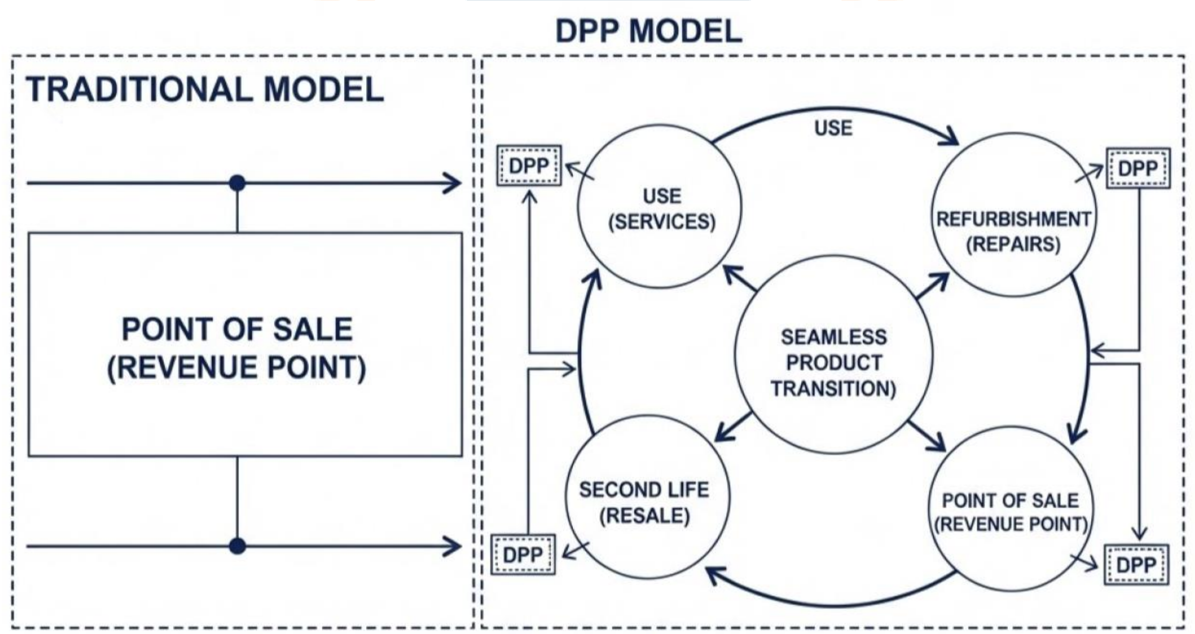

Figure 2. Model of value transformation across the product lifecycle (author's design).

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The effectiveness of DPP implementation is determined by the degree of trust in the digital information accompanying the product, because it is precisely the trust contour that shapes willingness to rely on declared characteristics during product selection and subsequent use. According to Deloitte, grocery retail demonstrates the highest level of consumer trust, reflected in an HX TrustID™ value of 40; this figure exceeds corresponding assessments for apparel and home-goods segments [42, 44]. At the same time, the trust component associated with transparency retains clear room for development: only 27% of consumers agree that retailers are honest about environmental impact, indicating a gap between general institutional trust in the sales channel and perceived credibility of "green" claims [44].

Table 3 describes the specific features of consumer willingness to pay for transparency and sustainability.

Table 3. Consumer willingness to pay for transparency and sustainability (compiled by the author based on [41, 44]).

Consumer category	Object of assessment	Willingness to Pay (WTP)
Overall Fresh market	"Better fresh products"	+28% vs. alternative prices
Eco-conscious consumers	Sustainable products	+30% vs. baseline price
Mass segment	Verified carbon footprint	+9.7% (average across 31 countries)
Generation Z	Brands with clear values and DPP	2.7× higher loyalty

A pronounced perception gap is observed between managerial expectations and the potential consumer readiness to reward sustainable product characteristics with a price premium. Deloitte data indicate that only 19% of retail executives consider it likely that customers will pay more for sustainability, while the expected premium size is estimated by them at approximately 12% [44]. Such a configuration can be interpreted as an indicator of systematic underestimation of the commercial potential of the DPP: where verifiable and comparable information is available, the product passport can function as a mechanism of market differentiation, strengthen trust in declared attributes, and thereby support margin growth by increasing perceived value and reducing price competition [45] (see Fig. 3).

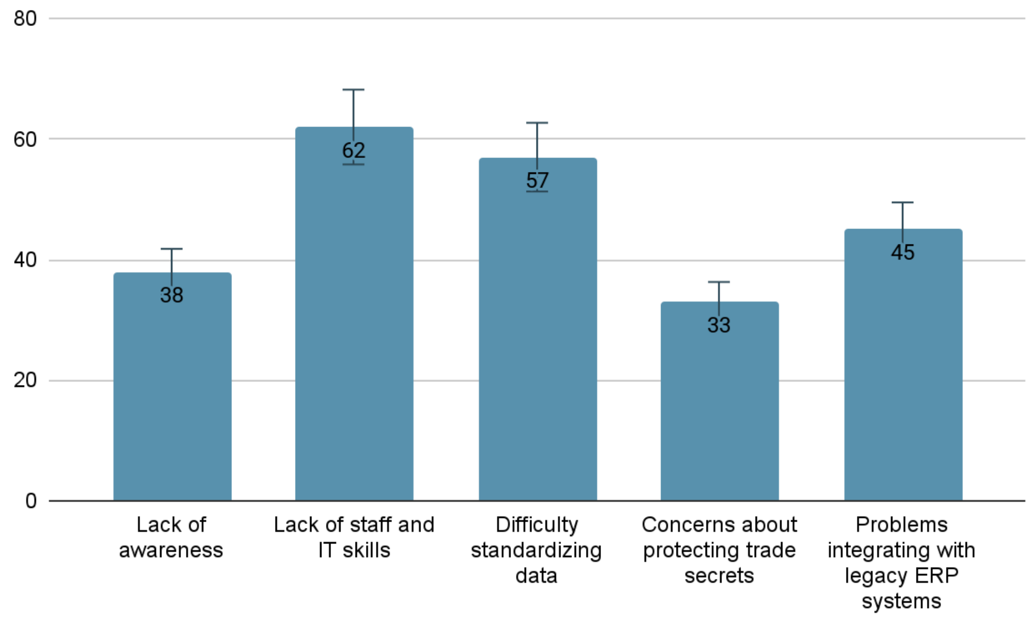

Figure 3. Barriers to DPP implementation in companies (compiled by the author based on [43, 45]).

Despite the emergence of a regulatory and standardization foundation, practical deployment of the DPP is often constrained by data fragmentation: product information is distributed across isolated corporate contours and maintained by disjoint information systems (PIM, ERP, PLM). This reproduces a "silo" effect and complicates end-to-end traceability, attribute comparability, and rapid record updates [2]. A technological response increasingly discussed in this context involves the use of Asset Administration Shells (AAS), which enable the formation of digital representations and digital twins suitable for integration into shared data spaces and compatible with exchange architectures being developed in GAIA-X-class ecosystems [32]. Such an approach supports a transition from point-to-point integrations toward a unified interoperability model in which the product is described as an object with an agreed set of attributes and access interfaces [36, 37].

For Fresh supply chains, an additional critical condition is the use of low-power IoT sensors, because telemetry on temperature, humidity, and other quality parameters must enter the digital contour with minimal latency and remain suitable for subsequent verification. At the same time, direct anchoring of all events in the base blockchain layer encounters scalability constraints (TPS) and transaction-cost pressure, which raises requirements for architectural optimization [40]. These constraints are mitigated through the use of Layer 2 solutions, sharding mechanisms, and off-chain placement of large datasets in decentralized file storage systems, including IPFS, while recording on-chain only control hashes and metadata required for provable integrity and verifiable referentiality [11].

Conclusion

The Digital Product Passport is consistently shifting from the role of a compliance instrument to the status of a strategic corporate asset capable of shaping new contours of value creation. In Fresh supply chains, within the logic of transformation, the DPP becomes a supporting structure of a "smart food" ecosystem in which quality confirmation relies not on declarative labeling but on an immutable digital trace that records provenance, handling conditions, and lifecycle events of perishable products.

Analytical results indicate the need for technological consolidation around interoperable identification standards. Migration to GS1 Digital Link and the use of two-dimensional data carriers (QR, DataMatrix) function as a mandatory preparatory stage for Sunrise 2027, providing multifunctional identification and a unified mechanism for linking the physical product to digital resources. The trust resilience of the DPP in cross-border and multi-actor chains is strengthened through decentralized verification mechanisms: application of DIDs and VCs forms a verifiable environment without dependence on a central intermediary, which is especially significant for ecosystems involving thousands of participants and heterogeneous responsibility contours.

The economic dimension of the DPP extends beyond meeting regulatory requirements: the product passport creates prerequisites for data monetization through secondary markets, service models, and extended lifecycle scenarios, including repair, reuse, and resale, thereby potentially enabling a multiple increase in total product value. The consumer contour also becomes decisive, since verifiable transparency translates into measurable "trust capital": willingness to pay a premium of up to 30% for verified freshness and sustainability forms a substantial financial incentive to invest in data reliability and traceability. At the same time, a need is observed to overcome institutional and technological barriers to scaling: development of "DPP-as-a-Service" providers is considered a practical mechanism for reducing the digital gap and accelerating adoption for small and medium-sized businesses constrained by resources and competencies required for independent integration.

A forward-looking research agenda concentrates on embedding generative artificial intelligence into DPP platforms to automate sustainability reporting and improve the accuracy of dynamic shelf-life forecasting based on large-scale supply-chain datasets. By the horizon of 2030, the digital product passport may become as standard an attribute of a trade item as the barcode is in contemporary retail infrastructure-shifting traditionally passive objects into the mode of "active" participants in the digital economy through continuous addressability, verifiability, and data connectedness.

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