State-of-the-Art Analysis of Blockchain Standards for Circular Supply Chains

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Chapter 1: Introduction: The Convergence of Blockchain, Circularity, and Supply Chains

The contemporary global economy operates on intricate networks of supply chains, facilitating the transformation of raw materials into finished goods delivered to consumers worldwide. However, these complex systems face mounting pressures: heightened consumer and regulatory demands for transparency, ethical sourcing, and environmental responsibility; persistent inefficiencies leading to increased costs and waste; and vulnerabilities exposed by disruptions like the COVID-19 pandemic (1). Simultaneously, the imperative to transition from linear 'take-make-waste' economic models to circular ones—emphasizing resource longevity, reuse, and regeneration—is gaining critical momentum, driven by environmental limits and evolving business strategies (2, 3).

In this confluence of challenges and opportunities, Distributed Ledger Technology (DLT), most prominently Blockchain, emerges as a potentially transformative force. It offers foundational capabilities to reshape Supply Chain Management (SCM) towards greater efficiency, resilience, circularity, and trustworthiness. This potential extends to organizations of all sizes, including Small and Medium-sized Enterprises (SMEs), which form the backbone of European supply chains. However, SMEs often face unique challenges in adopting new technologies, including resource constraints and skills gaps, making targeted guidance crucial.

This chapter sets the stage by exploring the evolution of blockchain within SCM, the rise of circular supply chain paradigms, the role of European Union (EU) funding in fostering innovation (including support for SMEs), and the consequent critical need for robust standardization to ensure interoperability, accessibility, and alignment with EU policy objectives like the European Green Deal and the Circular Economy Action Plan.

1.1. The Evolution of Blockchain in Supply Chain Management

Blockchain technology's journey from its conceptual origins (cryptographic hashing, peer-to-peer networks) to its current state as a versatile enterprise solution has been rapid and multifaceted. Initially popularized by Bitcoin (4) as a decentralized ledger for cryptocurrency transactions (often termed Blockchain 1.0), its potential soon expanded with the advent of platforms like Ethereum, which introduced programmable smart contracts (Blockchain 2.0) (5). This programmability unlocked applications beyond mere value transfer, enabling the automation of agreements and complex business logic.

The application of blockchain to SCM stems directly from its inherent characteristics, which address long-standing industry pain points (6, 7, 8):

- **Transparency & Traceability:** Blockchains provide a shared, time-stamped, and immutable record of transactions and events. In SCM, this allows stakeholders (suppliers, manufacturers, logistics providers, retailers, regulators, consumers) to track products from origin to consumption (and potentially beyond), verifying provenance, handling conditions, and compliance claims (9, 10, 11). Early pilots by IBM Food Trust with Walmart demonstrated drastic reductions in trace-back times for food products (12, 13). Projects like Connecting Food (EIC Accelerator), TRACEWINDU (CORDIS, GA: 101007979) for wine, or HASHED BLOCKTAC's olive oil anti-counterfeiting solution (EIC Accelerator) leverage this for end-to-end food traceability using blockchain-secured "digital twins" or seals. Similarly, SeafoodTrace (EIC Accelerator) applied it to the seafood industry.

- **Trust & Security:** By replacing centralized databases with a distributed, cryptographically secured ledger validated by consensus, blockchain minimizes the need for intermediaries and reduces the risk of single points of failure or data tampering (14, 15). This fosters trust among participants who may not have direct relationships or established trust mechanisms (16, 17). This is particularly relevant for SMEs collaborating in complex supply chains. Projects like TNT (EIC Accelerator, GA: 779291) utilize DLT for log security, ensuring data integrity in underlying IT systems.

- **Efficiency & Automation:** Smart contracts can automate various SCM processes, such as triggering payments upon verified delivery, enforcing quality compliance based on sensor data, or managing access rights to shared information (18, 8). This reduces manual paperwork, administrative overhead, and potential disputes (19, 20). Projects like CARECHAIN (ONTOCHAIN Cascade Funding) explored smart contracts for automating parametric microinsurance payouts in agriculture based on sensor data, while Trade on Chain (TrustChain Cascade Funding) aims to automate international trade contracts.

- **Disintermediation:** While not eliminating all intermediaries, blockchain can reduce reliance on certain third parties (e.g., some brokers, escrow services) by enabling direct, secure peer-to-peer interactions and automated verification (21, 7). This can potentially lower transaction costs, benefiting SMEs. The I Go Slow project (EIC Accelerator, GA: 868842) explored connecting gourmet food producers directly with consumers using a blockchain-based token ecosystem.

The evolution has progressed towards "Blockchain 3.0" applications (5) and enterprise-focused solutions. Recognizing the limitations of public permissionless blockchains (like Bitcoin or early Ethereum) regarding scalability, privacy, and governance for business contexts, *permissioned* (private or consortium) blockchains gained prominence (14). Platforms like Hyperledger Fabric (23) (used in i4Q CORDIS GA: 958205 for manufacturing quality) and R3 Corda emerged, offering controlled access, higher transaction throughput, and customizable governance models better suited for enterprise supply chain consortia (22). These platforms are frequently leveraged in the EU projects discussed later (e.g., potentially in PharmaLedger GA: 853992, although it aimed for DLT-agnosticism, and MH-MD CORDIS GA: 732907). However, the choice between permissionless and permissioned systems involves trade-offs, and accessibility for SMEs remains a key consideration in standardization efforts.

1.2. The Imperative of Circular Supply Chains

The traditional linear economic model, characterized by resource extraction, production, consumption, and disposal, is facing increasing scrutiny due to resource depletion, environmental degradation, and volatile commodity prices (2, 3). The Circular Economy offers an alternative paradigm focused on:

- **Designing out Waste and Pollution**: Prioritizing durable design, reuse, and repair.
- **Keeping Products and Materials in Use**: Extending product lifespans through maintenance, refurbishment, remanufacturing, and establishing secondary markets.
- **Regenerating Natural Systems**: Returning biological nutrients safely to the biosphere.

Implementing circularity necessitates a fundamental rethinking of supply chain design and operation. Circular Supply Chains (CSCs) require enhanced capabilities for:

- **Material Traceability**: Knowing the exact composition of products and tracking materials through multiple use cycles (26).

- **Reverse Logistics**: Efficiently collecting, sorting, and processing used products or materials for reuse, repair, or recycling.
- **Data Sharing & Collaboration**: Enabling information flow between diverse actors (designers, manufacturers, users, collectors, recyclers) across the product lifecycle.
- **Verification & Trust**: Providing credible proof of circularity practices (e.g., recycled content, repair history, responsible end-of-life handling) to consumers and regulators (25).

Technology, particularly digital technology, is a critical enabler for managing the complexity of circular systems. Blockchain, with its strengths in traceability, transparency, and secure data sharing, is uniquely positioned to provide the digital infrastructure for trustworthy CSCs (24). It can create immutable records for **Digital Product Passports (DPPs)**, track material flows across lifecycles, verify sustainability claims, and automate incentives for circular behaviors via smart contracts (27, 28, 29). Projects like DigInTraCE (CORDIS, GA: 101091801) explicitly aim to use blockchain for DPPs and traceability of secondary raw materials, while CirculariseSource (EIC Accelerator) focuses on tracking material characteristics like recycled content.

1.3. Blockchain & DLT within the EU Funding Landscape

The European Union has recognized the strategic potential of blockchain and DLT, progressively increasing support through its research and innovation funding programs (e.g., Horizon Europe, Digital Europe Programme). This reflects an alignment with broader EU goals such as achieving digital sovereignty, strengthening the Digital Single Market, realizing the ambitions of the European Green Deal, and ensuring trustworthy digital interactions compliant with regulations like GDPR and eIDAS (30, 31).

Evolution of Funding Focus:

- **FP7 & Early H2020 (approx. 2007-2016):** Funding focused on foundational elements like data security (e.g., KONFIDO GA: 727528), interoperability, and digital identity concepts, creating prerequisites for future DLT adoption.
- **Mid-Late H2020 (approx. 2016-2020):** Emergence of dedicated blockchain topics (e.g., EU Blockchain Observatory & Forum) and application-focused projects exploring use cases in supply chains and healthcare (e.g., MH-MD GA: 732907). The Next Generation Internet (NGI) initiative (36) started funding blockchain-related projects, often via cascade mechanisms targeting SMEs and researchers.
- **Horizon Europe & Digital Europe Programme (2021-Present):** Blockchain is recognized as a key enabling technology. Funding supports large-scale pilots, deployment of infrastructure like the European Blockchain Services Infrastructure (EBSI) (35), and market uptake, particularly through the EIC Accelerator (37) for SMEs and continued NGI calls (e.g., ONTOCHAIN, TrustChain). There's a stronger emphasis on standardization, interoperability (especially with EBSI and eIDAS 2), sustainability, and alignment with data strategies (Data Act, EHDS).

Funding Mechanisms & SME Relevance:

- **CORDIS (RIAs/IAs):** Large consortia tackling complex challenges. Blockchain is often integrated within larger systems (e.g., DEMETER GA: 857202 for agricultural interoperability, PharmaLedger GA: 853992 for the pharma industry). While led by larger entities, SMEs participate as partners, gaining exposure and contributing expertise.
- **EIC Accelerator:** Specifically supports individual, high-potential SMEs/startups developing disruptive innovations. Many funded projects feature blockchain as a core differentiator (e.g.,

Connecting Food, HASHED BLOCKTAC, tilkal). This mechanism is vital for fostering SME leadership in blockchain applications.

- **Cascade Funding (e.g., NGI - ONTOCHAIN, TrustChain, SPADE):** Distributes smaller grants to third parties (often SMEs, startups, or research teams) for developing specific components or applications within a defined framework (e.g., CARECHAIN ONTOCHAIN, Trussihealth ONTOCHAIN, NeWG TrustChain). This fosters agile development and lowers the barrier for SMEs to engage in cutting-edge R&D.

Sector Focus: Agriculture and healthcare serve as crucial testbeds due to their complexity, regulatory requirements (food safety, patient data privacy), and societal impact, driving the need for trustworthy DLT solutions applicable to circular principles (e.g., tracking sustainable farming practices via PestNu GA: 101037128, managing pharmaceutical traceability via PharmaLedger GA: 853992, ensuring food traceability via FAIRCHAIN GA: 101000723 or DiTECT GA: 861915).

1.4. The Critical Need for Standardization in Blockchain for Circular Supply Chain Management

While the potential of blockchain for circular SCM is significant, realizing this potential at scale hinges critically on standardization (14, 11). The current landscape, as evidenced by the diversity of EU projects, is fragmented, with various DLT platforms, protocols, and data models being explored. Without standardization, there is a high risk of creating new digital silos, hindering the very interoperability and data flow that circular economies require (15, 22). This fragmentation poses a particular barrier for SMEs, which lack the resources to navigate multiple incompatible systems.

Standardization is essential across multiple layers:

- **Foundational Concepts:** Establishing common terminology (ISO 22739:2020, FG DLT D1.1) and reference architectures (ISO 23257:2022, DIN SPEC 32790:2022-11) to ensure a shared understanding and consistent design principles, making solutions more accessible.

- **Interoperability:** Defining protocols and APIs for communication between different blockchain systems (cross-chain) and between blockchains and legacy IT systems (e.g., ERP, IoT platforms) (43, ISO/TR 6277:2024). This is crucial for SMEs needing to integrate with larger partners' systems. Projects like Perun-X (ONTOCHAIN) and TokEngine (TrustChain) explicitly target cross-chain interoperability.

- **Data Semantics & Formats:** Agreeing on standardized ways to represent supply chain events (e.g., building on GS1 EPCIS), product attributes (for DPPs, linking to ISO/AWI 59040 PCDS), and sustainability metrics (ISO 59020:2024, EN 45557:2020) to ensure data can be consistently interpreted across systems. The **DEMETER** project (GA: 857202) highlighted the need for common agricultural information models (AIM).

- **Identity Management:** Aligning blockchain-based identity solutions (DIDs/VCs) with regulatory frameworks like eIDAS 2 and common standards (W3C) for secure and recognized identification of actors (including SMEs) and assets (31). Projects like Trussihealth (ONTOCHAIN), Trade on Chain (TrustChain), SSITIZEN (TrustChain), and CHECKS (TrustChain) actively explore this using technologies compatible with EBSI or Alastria ID.

- **Smart Contracts:** Standardizing templates, security best practices, legal validity frameworks (relevant to the EU Data Act), and oracle interactions for reliable automation (49). Secure and standardized contracts lower implementation risks for SMEs.

- **Security & Privacy:** Defining security requirements for DLT platforms and applications, and standards for integrating Privacy-Enhancing Technologies (PETs) to meet GDPR requirements (ISO/TC 307; PANACEA GA: 826293; ASCLEPIOS GA: 826093; LEAP GA: 101071724).

- **Sustainability:** Developing metrics and methodologies for assessing the environmental footprint of DLTs themselves (CEN-CLC/JTC19/WG2; 31 - BlockStand Recommendations) to ensure the enabling technology aligns with circular goals.

EU initiatives like the EU Blockchain Strategy, EBSI, the Rolling Plan for ICT Standardisation, and dedicated coordination actions like BlockStand (31) are actively working to address these needs. They support participation in international standards bodies (ISO/TC 307, ITU-T FG DLT), foster collaboration between projects, and identify priority areas to ensure blockchain deployment aligns with European values, strategic objectives, and the needs of all stakeholders, including SMEs. The following chapters will delve deeper into the specific standards relevant to blockchain in circular supply chains, the technologies enabling their implementation, and examples drawn from the EU-funded project landscape.

Chapter 2: Foundational Concepts: Blockchain and Circular Supply Chains

Before delving into the specifics of standardization, it is crucial to establish a solid understanding of the core technological principles of Blockchain/Distributed Ledger Technology (DLT) and the fundamental requirements of Circular Supply Chains (CSCs). This chapter elucidates these foundational concepts, highlighting the inherent capabilities of DLT that make it particularly suited to address the unique data management, trust, and transparency challenges posed by the transition to circular economic models within complex supply networks, while also considering implications for SMEs.

2.1. Core Blockchain/DLT Principles Relevant to SCM

Blockchain technology, a specific implementation of DLT, is not a monolithic entity but rather a suite of technologies built upon several core principles. Understanding these principles is essential to grasp its potential impact on SCM, particularly in the context of circularity and accessibility for diverse actors.

- **Distributed Ledger & Decentralization:**

  - ***Concept:*** Unlike traditional centralized databases where data resides in a single location under the control of one entity, a DLT distributes identical copies of the ledger across numerous nodes (computers) in a peer-to-peer (P2P) network (4, 5, 14). Decentralization implies that no single entity has authoritative control; network maintenance and validation are shared responsibilities.

  - ***SCM Relevance:*** This architecture inherently enhances resilience, as the failure of one or even multiple nodes does not compromise the entire system (11, 16). It directly combats the issue of data silos prevalent in traditional SCM, where information is fragmented across different participants' systems (22). By providing a shared, single version of the truth accessible to permitted participants, it fosters collaboration and reduces disputes arising from data discrepancies (15). Many EU projects like PharmaLedger (GA: 853992) or MH-MD (GA: 732907) leverage this distributed nature for secure data sharing.

  - ***SME Consideration:*** While offering resilience, participating as a node can have infrastructure costs. Consortium models require governance agreements, which SMEs need resources to negotiate and manage. Cloud-based Blockchain-as-a-Service (BaaS) can lower entry barriers but introduces reliance on the BaaS provider. FOrLedger (EIC Accelerator) aimed to provide a low-code BaaS platform for agri-food traceability.

- **Cryptography (Hashing & Digital Signatures):**
    - ***Concept:*** *Hash functions* create unique digital fingerprints (hashes) for data blocks; any change alters the hash. Blocks link via previous block hashes. *Digital signatures* (using public-private keys) authenticate transaction origins (DIN SPEC 32790, 9, ISO 22739:2020).
    - ***SCM Relevance:*** Hashing ensures data integrity (tamper evidence). Digital signatures provide accountability and non-repudiation for transactions (e.g., transfer of ownership, quality certification) (11, 9, 16). The TNT project (GA: 779291) used hash-based cryptography (KSI) for log security.
    - ***SME Consideration:*** Cryptography provides strong security but requires proper key management practices. Loss of private keys means loss of access/control. Secure key management solutions are essential but add complexity.
- **Immutability and Tamper Evidence:**
    - ***Concept:*** The combination of cryptographic hashing and network distribution makes records practically immutable and inherently tamper-evident (22, 11, 14). Altering historical data without detection is computationally infeasible in robust networks (16).
    - ***SCM Relevance:*** Creates a permanent, reliable audit trail for product journeys, certifications (e.g., organic, recycled content), and transactions (9, 15). Combats counterfeiting and ensures compliance data integrity (11, 50). This is valuable for SMEs needing to prove compliance or provenance to larger partners or regulators, as targeted by projects like HASHED BLOCKTAC or SMark2.0.
- **Transparency and Auditability:**
    - ***Concept:*** Depending on the blockchain type (public vs. permissioned), transaction data can be visible to all or specific authorized parties (22). Even with restricted access, transaction existence/metadata often provides an auditable trail (9).
    - ***SCM Relevance:*** Enhances visibility, breaking down information silos (11, 6). Stakeholders access shared information, improving coordination (15). Simplifies compliance checks and audits (22). Projects like CATTLECHAIN 4.0 (GA: 853864) aimed to provide consumers/authorities with immutable traceability and welfare verification.
    - ***SME Consideration:*** Transparency can be a double-edged sword. While facilitating trust, SMEs may be concerned about exposing sensitive business data (pricing, suppliers) to competitors within a consortium. Permissioned blockchains with granular access controls are often preferred but require careful design (50).
- **Consensus Mechanisms:**
    - ***Concept:*** Protocols nodes use to agree on transaction validity without a central authority (14, DIN SPEC 32790). Common types include the following:
        - **Proof-of-Work (PoW):** (e.g., Bitcoin, Ethereum 1.0) Nodes compete to solve complex computational puzzles ("mining") to validate blocks. Secure but energy-intensive and slow (11)
        - **Proof-of-Stake (PoS):** (e.g., Ethereum 2.0) Validators are chosen based on the amount of cryptocurrency they "stake". More energy-efficient than PoW (DIN SPEC 32790)

    - **Proof-of-Authority (PoA):** Validation is performed by a set of pre-approved, trusted authorities based on their reputation. Faster and efficient, often used in private/consortium chains (DIN SPEC 32790, 16).
    - **Practical Byzantine Fault Tolerance (PBFT):** Consensus achieved through multiple rounds of message exchanges among known validators, tolerating a certain number of faulty/malicious nodes. Efficient for permissioned settings (DIN SPEC 32790, 16).

- ***SCM Relevance:*** Choice impacts performance, energy use (sustainability), security, and governance (14). Permissioned SCM networks often favor PoA or PBFT variants for efficiency and control (15, 9).

- ***SME Consideration:*** Energy-intensive PoW is generally unsuitable due to cost and sustainability concerns. PoS requires staking assets, which might be a barrier. PoA relies on trusted authorities, raising governance questions. The choice impacts operational costs and participation requirements. TokEngine (TrustChain) utilized Convergent Proof of Stake for energy efficiency.

- **Smart Contracts:**

- ***Concept:*** Self-executing contracts with agreement terms written into code (5, 51). Reside on the blockchain and automatically execute actions (e.g., release payment) when predefined conditions (verifiable on-chain or via trusted oracles) are met (18, DIN SPEC 32790, 9).

- ***SCM Relevance:*** Enable automation: payments on proof-of-delivery, compliance rule enforcement, track-and-trace events, automated customs clearance, triggering actions based on IoT data (16, 24, 15, 9, DIN SPEC 32790, 14). Reduce overhead, speed up processes, minimize disputes (52). Examples include BEACON (GA: 821964) for automating insurance payouts, SOLARFARM (GA: 817096) for testing PPA contracts, B-LOCS for GMP compliance, and DigiPharm for value-based healthcare agreements.

- ***SME Consideration:*** Offer significant efficiency gains but require technical expertise to develop, audit, and deploy securely. Bugs can be costly and hard to fix due to immutability. Standardized, audited templates can lower risks and development costs. Legal validity is still evolving (EU Data Act).

- **Permissioned vs. Permissionless Models:**

- ***Concept:*** *Permissionless (Public)* blockchains (e.g., Bitcoin) allow anyone to join/view/participate. *Permissioned (Private/Consortium)* blockchains restrict participation and access to known, authorized entities (9, 14, 22, DIN SPEC 32790).

- ***SCM Relevance:*** Most enterprise SCM applications favor permissioned models for confidentiality, control, regulatory compliance (GDPR), and performance (14, 22). Public chains might be used for consumer-facing transparency or anchoring (24). PharmaLedger (GA: 853992) and MH-MD (GA: 732907) likely used permissioned approaches for healthcare/pharma data.

- ***SME Consideration:*** Permissionless chains offer openness but limited privacy and potentially higher transaction fees. Permissioned consortia offer control but require governance structures and onboarding processes, which can be barriers for SMEs unless facilitated by industry platforms or associations.

2.2. Circular Supply Chain Principles & Requirements

Transitioning to a circular economy demands a shift from linear SCM to one actively managing resources through multiple lifecycles. This imposes specific requirements on information management and collaboration.

Core Circular Economy Principles (aligning with ISO 59004)**:**

- **Design for Durability, Reuse, Repair, Remanufacturing**: Products are designed from the outset for longevity and ease of disassembly/reprocessing.
- **Extended Use Cycles**: Business models shift towards leasing, sharing, or product-as-a-service to keep assets in use longer.
- **Material Passports/Digital Product Passports (DPPs):** Detailed information on material composition, manufacturing processes, repair history, and end-of-life options travels with the product (ISO/AWI 59040, EU ESPR Regulation).
- **Closing Loops:** Establishing efficient systems for collection, sorting, and reprocessing of used products and materials (Reverse Logistics).
- **Value Recovery:** Maximizing the value extracted from returned products through reuse, refurbishment, remanufacturing, or high-quality recycling (cascading).
- **Stakeholder Collaboration:** Increased interaction and data sharing are needed across a wider network, including consumers, recyclers, and remanufacturers (24).

Data and Information Requirements for Circular SCM:

- **Granular Material/Component Information:** Precise data on materials used, including recycled content, hazardous substances, and disassembly instructions (ISO 59040 PCDS, EN 45557:2020).
- **Lifecycle Tracking:** Ability to trace a product's journey through manufacturing, use, repair, collection, and reprocessing stages (26, 25).
- **Condition Monitoring:** Data on product usage, wear, and tear (often via IoT) to inform maintenance, repair, or end-of-life decisions (ISO/IEC TR 30176:2021).
- **Chain of Custody:** Verifiable proof of ownership and handling across multiple lifecycles, crucial for managing liability and ensuring compliance (9).
- **Verification of Claims:** Trustworthy mechanisms to prove recycled content, responsible sourcing, or proper end-of-life treatment (ASTM D8558-2024, CirculariseSource).
- **Data Interoperability:** Need for standardized data formats and exchange protocols to allow seamless information flow between different actors and systems (DIN SPEC 32790; DEMETER AIM).

Why Traditional SCM Falls Short & Blockchain's Role:

Traditional Supply Chain Management systems are often linear, optimized for forward logistics, and suffer from data fragmentation across organizational silos (22, 15). This makes tracking products beyond the initial point of sale, managing reverse logistics effectively, sharing granular lifecycle data, and establishing trust across a broad network of circular economy actors extremely difficult (16). SMEs, in particular, struggle with visibility and data exchange in complex, fragmented chains.

Blockchain directly addresses these shortcomings:

- Its **immutable ledger** provides a reliable platform for recording granular lifecycle data (material passports, repair history) (24).
- Its ***transparency*** (within permissioned settings) facilitates data sharing and collaboration across the extended network needed for circularity (15).
- Its ***traceability*** features enable tracking materials through multiple use cycles and verifying circular claims (9, EN 45557:2020). Projects like FoodRUS (GA: 101000617) explore blockchain for waste prevention certification and traceability, while DigInTraCE (GA: 101091801) targets secondary raw materials.
- ***Smart contracts*** can automate processes like verifying recycling certificates, managing deposit-return schemes, or triggering end-of-life handling (24).
- The ***distributed and secure nature*** builds trust among participants (collectors, recyclers, remanufacturers, SMEs) who might otherwise hesitate to share data (15). Projects like tilkal build B2B data sharing networks on this trust.

Therefore, blockchain provides a foundational digital trust layer, essential for orchestrating the complex data flows and multi-stakeholder interactions inherent in effective Circular Supply Chains, potentially leveling the playing field for SMEs by providing access to trusted data and automated processes if designed accessibly. Standardization is key to realizing this potential inclusively.

Chapter 3: State-of-the-Art Analysis: Blockchain Standards for Circular Supply Chain Management

The transition towards circular supply chains, enabled and accelerated by Distributed Ledger Technologies (DLT), necessitates a robust framework of standards to ensure interoperability, security, trust, and regulatory compliance. While no single, overarching standard currently governs the intersection of blockchain and circular SCM, a growing ecosystem of standards from international bodies like ISO and IEEE, alongside regional and industry-specific specifications, provides essential guidance. This chapter presents a state-of-the-art analysis of these standards, examining their core principles, technical provisions, specific relevance for implementing traceable, transparent, and efficient circular supply chains using blockchain, and considerations for SMEs.

3.1. ISO Standards Landscape: Building Foundational Layers

The International Organization for Standardization (ISO) plays a pivotal role through two key technical committees: ISO/TC 307 (Blockchain and DLT) and ISO/TC 323 (Circular Economy). Their work, along with crucial technical reports, provides foundational layers for terminology, architecture, processes, and measurement.

3.1.1. ISO/TC 307: Blockchain and Distributed Ledger Technologies

Established in 2016, ISO/TC 307 aims to develop international standards addressing the burgeoning need for standardized approaches in blockchain and DLT. Its goal is to provide internationally agreed ways of working to improve security, privacy, scalability, and interoperability. With Standards Australia holding the secretariat, the committee actively develops standards covering (49, 54):

- **Terminology**: Establishing a common vocabulary (e.g., ISO 22739:2020).

- **Reference Architecture**: Defining foundational structures (e.g., ISO 23257:2022).
- **Security & Privacy**: Addressing risks and protection mechanisms.
- **Identity Management**: Standardizing approaches for managing identities on DLTs.
- **Smart Contracts**: Guidance on development, security, and lifecycle.
- **Governance**: Frameworks for managing DLT systems.
- **Interoperability**: Enabling communication between different DLT systems.

As of mid-2024, TC 307 had published 12 standards with 10 more under development (54). Its work directly contributes to achieving several UN Sustainable Development Goals (SDGs), including SDG 12 (Responsible Consumption and Production), highlighting its relevance to circular economy principles (ISO/TC 307 Website).

SME Relevance: ISO/TC 307 standards provide foundational knowledge and best practices, reducing uncertainty for SMEs entering the blockchain space. However, active participation in the standardization process itself can be resource-intensive for smaller organizations. Accessing and implementing published standards requires technical understanding.

3.1.2. ISO 23257:2022 – Blockchain and Distributed Ledger Technologies — Reference Architecture

This standard provides a crucial technical blueprint for designing and implementing DLT systems, including those for circular SCM (ISO 23257:2022).

- ***Core Guidance:*** Defines a modular, layered reference architecture promoting interoperability and flexibility. Key layers typically include Infrastructure, DLT Platform, and Application layers (24). It acknowledges the need for integrating components like IoT devices (potentially certified under standards like TS 17880) and recommends energy-efficient consensus mechanisms (24).
    - **Infrastructure Layer:** Underlying hardware, networking, potentially integrating IoT devices (as needed for physical tracking in Supply Chain Management) certified under standards like TS 17880.
    - **DLT Platform Layer:** Core ledger functionalities, consensus mechanisms (e.g., recommending energy-efficient PoS like Algorand), cryptographic services (Singapore Standards Summary from 24).
    - **Application Layer:** Business logic, smart contracts, user interfaces (e.g., for supply chain tracking applications or DPP interactions) (24).
- ***Relevance to Circular SCM & Blockchain Integration:***
    - **Modularity**: Supports integration of diverse components needed for circularity (IoT sensors, ERPs, sustainability databases) (ISO 23257 Overview).
    - **Interoperability**: Defines interfaces and promotes protocols (like IBC 1.0 for cross-chain communication) essential for connecting diverse stakeholders (suppliers, recyclers, SMEs) and systems across a circular value network (ISO 23257 Technical Scope). Projects like Perun-X (ONTOCHAIN) develop such cross-chain solutions.
    - **Scalability & Customization**: Enables adaptation for complex supply chains. Modules can be tailored for specific circular functions like material passports or reverse logistics tracking (24).

- **Security Foundation**: Provides a structure for implementing security measures, including cryptographic protection (e.g., SHA-3 hashing), consensus, and integration with identity management (W3C DIDs) (55).

- ***SME Relevance:*** The modularity allows SMEs to potentially implement parts of the architecture relevant to their role, rather than needing a full-stack deployment. However, understanding and applying the architecture still requires significant technical expertise. Standardized architectures can reduce development costs compared to fully custom solutions.

- ***Examples/Implementation:*** Underpins platforms like BMW's battery passports (56) and traceability systems like Tilkal (EIC Accelerator) or Connecting Food (EIC Accelerator). Provides the technical foundation for implementing systems aligned with ISO 590xx metrics and EU DPP requirements, addressing data silos through standardized interoperability (24).

3.1.3. ISO/TR 3242:2022 – Blockchain and Distributed Ledger Technologies – Use Cases

This Technical Report serves as a practical guide, documenting implementable DLT patterns and architectures across various industries (PD ISO/TR 3242).

- ***Core Guidance:*** Catalogs 22 international use cases with system architecture diagrams, offering blueprints for applying DLT (PD ISO/TR 3242 Overview, 14).

- ***Relevance to Circular SCM & Blockchain Integration:***

  - **Material Traceability**: Provides patterns for tracking recycled content (e.g., using Hyperledger Fabric), crucial for verifying circular inputs and complying with DPP mandates (PD ISO/TR 3242, UN/CEFACT Blockchain for Circular Textiles). Examples include H&M tracking recycled polyester (58) or projects like CirculariseSource (EIC Accelerator) tracking material characteristics.

  - **Reverse Logistics**: Documents architectures using Ethereum smart contracts to automate returns and remanufacturing workflows (PD ISO/TR 3242).

  - **Waste-to-Resource Systems**: Illustrates tokenizing industrial by-products (e.g., using ERC-1155) for cross-sector exchanges (PD ISO/TR 3242).

  - **Interoperability & Governance**: Describes use of cross-chain protocols (IBC 1.0) and decentralized governance (PBFT) for multi-stakeholder circular systems (PD ISO/TR 3242). Addresses GDPR compliance via hybrid storage.

  - **Standards Alignment**: Guides implementations towards SDG 12, EU DPP requirements, and integration with ISO 59020 metrics (PD ISO/TR 3242, UN/CEFACT Blockchain for Circular Textiles).

- ***SME Relevance:*** Provides concrete examples and architectural patterns that SMEs can adapt, reducing the need to design solutions from scratch. Understanding these use cases can help SMEs identify relevant applications for their business.

3.1.4. ISO/TR 6277:2024 – Blockchain and Distributed Ledger Technologies — Data Flow Models for Blockchain and DLT Use Cases

This technical report focuses specifically on standardizing how data moves within and between DLT systems and connected external systems, critical for ensuring interoperability and process integrity in complex circular SCM (ISO/TR 6277:2024 Scope).

- ***Core Guidance:*** Defines five key data flow models: Model N (Intra-System), Model A (Inter-DLT/Cross-Chain), Model B (DLT ↔ Non-DLT, e.g., IoT/ERP), Model C (Administration/Audit), Model D (User Applications) (ISO/TR 6277:2024).
    - **Model N (Intra-System):** Data flows within a single DLT network (nodes, smart contracts). *Circular Application:* Tracking recycled material batches within one organization's private ledger, enforcing internal KPIs (ISO/TR 6277:2024).
    - **Model A (Inter-DLT):** Flows between distinct DLT systems (cross-chain). *Circular Application:* Exchanging tokenized waste streams (e.g., ERC-1155 recycled steel) between a manufacturer's DLT and a construction firm's DLT via IBC protocols (ISO/TR 6277:2024). Reduces virgin material use.
    - **Model B (DLT ↔ Non-DLT):** Flows between a DLT and external systems like IoT sensors or ERPs. *Circular Application:* IoT RFID tags on reusable packaging feeding location data to the blockchain; ERP systems pushing production data to validate PCDS claims on-chain (ISO/TR 6277:2024). Cuts verification errors.
    - **Model C (Administration Applications):** Flows between DLTs and governance/audit tools. *Circular Application:* Regulators accessing permissioned nodes to audit on-chain CO2 emissions or DPP compliance data (40). Reduces audit costs.
    - **Model D (User Applications):** Flows between DLTs and end-user interfaces (apps, web portals). *Circular Application:* Consumers scanning QR codes linked to blockchain to verify product recyclability; suppliers using dApps to submit sustainability claims (ISO/TR 6277:2024 Use Cases). Increases consumer trust.
- ***Relevance to Circular SCM & Blockchain Integration:*** Provides standardized templates for designing data interactions essential for end-to-end traceability, multi-stakeholder collaboration (SMEs, suppliers, recyclers, regulators), automated compliance checks (DPPs, EN 45557), and secure integration with physical tracking (IoT). Aligns with ISO 23257 architecture (ISO/TR 6277:2024 Scope). Examples include aviation parts tracking and international trade platforms using GS1 standards (EASA Blockchain Use Cases, ANSI Link). Projects like Trade on Chain (TrustChain) implement complex data flows for trade automation.
- ***SME Relevance:*** Standardized data flow models simplify integration for SMEs connecting to larger platforms or consortia. Clear models reduce ambiguity and potential errors in data exchange, lowering integration costs and risks.

3.1.5. ISO/TC 323: Circular Economy Standards

Established to develop standards specifically for the Circular Economy, ISO/TC 323 published three foundational standards in May 2024 (61), providing the conceptual and practical framework that blockchain implementations can support and operationalize.

3.1.6. ISO 59004:2024 – Circular Economy — Vocabulary, Principles and Guidance for Implementation

This standard establishes the common language and core principles for transitioning to circular models (ISO 59004 Overview).

- ***Core Guidance:*** Defines key terms (e.g., *material cascading*, *value retention*) and outlines core principles (systems thinking, value creation/sharing, resilience, resource management, information transparency). Provides an implementation framework.

- ***Relevance to Circular SCM & Blockchain Integration:***
  - **Unified Terminology**: Enables shared understanding across blockchain networks, crucial for standardizing data fields in DPPs or material passports recorded on-chain.
  - **Principle Operationalization**: Blockchain directly enables principles like Resource Tracking/Management (IoT+Blockchain, e.g., **HMCS** GA: 854670 for contaminant tracking), Value Creation/Sharing (Tokenized incentives, e.g., **ReSeed** GA: 101118063 for seed conservation), Systems Thinking/Resilience (Cross-chain protocols, e.g., **Perun-X** ONTOCHAIN), and Information Transparency.
  - **Compliance & Measurement**: Smart contracts can automate compliance checks based on ISO 59004 criteria (e.g., recycling thresholds) and operationalize system dynamics models for real-time circularity scoring.
  - **Technical Requirements:** Implies need for GDPR-compliant data handling (ISO/IEC 20889), energy-efficient consensus (ISO 50001), secure smart contracts (ISO/IEC 15408), and interoperability (ISO/TR 3242) in supporting blockchain systems.
- ***SME Relevance:*** Provides a clear framework and vocabulary for SMEs aiming to adopt circular practices, facilitating communication with partners and customers. Blockchain can help SMEs demonstrate adherence to these principles verifiably.

3.1.7. ISO 59010:2024 – Circular Economy — Guidance on the Transition of Business Models and Value Networks

This standard provides a methodology for organizations redesigning their business models and value networks for circularity (ISO 59010 Link).

- ***Core Guidance:*** Offers structured guidance for remapping value networks, identifying circular opportunities (e.g., product-as-a-service, remanufacturing), setting objectives, and managing the transition.
- ***Relevance to Circular SCM & Blockchain Integration:***
  - **Value Network Redesign**: Blockchain facilitates the complex multi-stakeholder collaboration needed for new circular value networks (e.g., connecting manufacturers, users, collectors, remanufacturers) by providing a trusted platform for secure data sharing (Ellen MacArthur Foundation: Tech Enablers, PA Consulting).
  - **Automated Workflows**: Smart contracts can automate new circular business logic, such as pay-per-use models, automated ordering of refurbishment services, or triggering payments to suppliers when remanufactured components re-enter the market (Schneider Electric Example, PA Consulting).
  - **Transparency**: DLT provides the transparency needed to track materials and value flows across redesigned networks, enabling models like BMW's remanufacturing tracking via Hyperledger Fabric. Addresses trust gaps and data fragmentation barriers identified by ISO 59010 (IEEE Workshop Context, Nandi et al. 2020).
  - **Incentives**: Tokenized systems (ERC-20) can incentivize participation in new circular models (e.g., rewarding returns for refurbishment) (UNECE Case Study).
- ***SME Relevance:*** Provides a structured approach for SMEs considering circular business models. Blockchain can enable SMEs to participate in complex, data-intensive circular networks that might otherwise be inaccessible.

3.1.8. ISO 59020:2024 – Circular Economy — Measuring and Assessing Circularity Performance

This standard focuses on standardizing how circularity is measured, ensuring consistent and verifiable performance assessment (ISO 59020 Overview, ISO 59020 Link).

- ***Core Guidance****:* Defines requirements and guidance for collecting and calculating data using circularity indicators. Specifies 8 mandatory KPIs, including the critical Circular Material Use Rate (CMUR), and optional indicators like water intensity. Provides methodology for assessment at various levels (product, organization, region).
- ***Relevance to Circular SCM & Blockchain Integration:***
  - **Immutable KPI Reporting**: Blockchain provides the ideal infrastructure for recording and reporting ISO 59020 KPIs immutably, preventing data manipulation and ensuring auditability (62, 24). Smart contracts can automate KPI calculation based on validated on-chain data (material inputs, outputs).
  - **Data Integrity & Verification**: Supports the standard's requirement for verifiable data. Cryptographic hashing secures LCA data. Zero-Knowledge Proofs (ZKPs) can privately verify compliance with thresholds (e.g., recycled content for CMUR) (Ellen MacArthur Foundation on Tech Enablers, 67). Enables accurate tracking (Ku H-H et al. Bubble Tea Tracking).
  - **DPP Integration**: Provides the standardized metrics (CMUR, VRS, etc.) needed for the sustainability sections of EU Digital Product Passports, which can be securely stored and managed using blockchain (EU DPP & Blockchain Integration).
  - **Automation & Incentives**: Smart contracts can track KPIs (e.g., GHG emissions using oracles linked to meters compliant with TS 17880) and trigger incentives (UNECE). Projects like **FoodRUS** (GA: 101000617) aim to track waste reduction metrics.
- ***SME Relevance****:* Standardized metrics allow SMEs to measure and credibly communicate their circularity performance. Blockchain provides a cost-effective way (compared to traditional audits) to ensure the integrity of reported data.

3.1.9. ISO/AWI 59040 – Circular Economy – Product Circularity Data Sheet (PCDS)

This standard, currently under development (AWI - Approved Work Item), aims to standardize a format for exchanging product circularity data across supply chains (ISO 59040:2025 Link).

- ***Core Guidance****:* Defines key reporting areas (material inputs, recycled content, durability, reparability, end-of-life options) in a structured template (PCDS) for consistent data sharing (Luxembourg PCDS Framework).
- ***Relevance to Circular SCM & Blockchain Integration:***
  - **Data Backbone for DPPs:** PCDS provides the standardized data structure suited for EU DPPs. Blockchain can store or anchor PCDS data immutably (Cirmar on PCDS Integration, PCDS & DPPs). Projects like DigInTraCE (GA: 101091801) and MultiPass (TrustChain) are directly relevant.
  - **Verifiable Claims**: Storing PCDS data (or hash) on-chain allows tamper-proof verification of claims like recycled content (ISO 59040:2025). ZKPs can enable verification without exposing full PCDS.

- **Interoperability**: Standardized PCDS format simplifies data exchange between different blockchain systems or integration with ERPs (Cirmar on PCDS Integration). Smart contracts can automate checks against PCDS data.

- ***SME Relevance**:* A standard data sheet simplifies data provision for SMEs supplying larger companies requiring circularity information. Blockchain integration can automate reporting and verification, reducing administrative burden.

3.1.10. Inter-Committee Liaison (TC 307 & TC 323)

The formal liaison between ISO/TC 307 and ISO/TC 323 signals a commitment to ensuring standards are complementary, fostering integrated solutions where blockchain supports circular economy practices defined by the ISO 590xx series. This collaboration is crucial for developing targeted standards at the intersection of these fields, benefiting all stakeholders, including SMEs seeking coherent guidance.

3.2. IEEE Standards Landscape: Focusing on Finance and IoT Integration

The Institute of Electrical and Electronics Engineers (IEEE) contributes key standards relevant to blockchain in specific application areas crucial for circular SCM, notably supply chain finance and IoT integration.

3.2.1. IEEE 2418.7-2021 – Standard for the Use of Blockchain in Supply Chain Finance

This standard provides a framework for applying blockchain specifically to financial processes within the supply chain (IEEE 2418.7-2021 Link).

- ***Core Guidance**:* Defines an architectural framework focusing on asset tokenization (representing financial claims or physical goods as digital tokens) and secure transaction processing, potentially using consensus mechanisms like PBFT combined with PoA (EBIN Analysis).

- ***Relevance to Circular SCM & Blockchain Integration:***

- **Financing Circular Models**: Provides standardized approach for financing reverse logistics, secondary markets. Includes **tokenizing waste streams** (Sfridoo example), **automated settlements** (carbon credits - BASF example, payments to farmers - CARECHAIN ONTOCHAIN), and improving access to finance for SMEs involved in circular activities (repair, recycling) by providing transparent track records (75).

- **Secure Onboarding & Compliance**: Facilitates secure supplier onboarding using DIDs to verify sustainability criteria (ISO 59004). Aligns with DPP financial data linkage needs.

- ***SME Relevance**:* Can potentially lower barriers for SMEs to access supply chain finance based on verifiable performance data recorded on the blockchain. Standardized approaches reduce complexity for participating in SCF programs.

3.2.2. IEEE P2418.1 – Standard for the Framework of Blockchain Use in Internet of Things (IoT)

This standard (part of the P2418 series) focuses on establishing a common framework for integrating blockchain and IoT, crucial for linking physical product tracking with immutable digital records in circular SCM (IEEE P2418.1 Link).

- ***Core Guidance:*** Defines reference architectures, interfaces, and data models for interoperability and security when connecting IoT devices (sensors, RFID, GPS) to blockchain networks (IEEE Press Release).

- ***Relevance to Circular SCM & Blockchain Integration:***

  - **Secure IoT Data Integration**: Provides standardized approach for securely feeding real-time IoT data (location, condition, usage) onto the blockchain (IEEE P2418.1). Addresses security risks (Mofatteh's CO2 Tracking Framework). Projects like PestNu (GA: 101037128) and SeafoodTrace (EIC Accelerator) rely on such integration.

  - **Traceability & Provenance**: Enables reliable end-to-end traceability by linking physical events (captured by IoT) to immutable blockchain entries (Wang, Luo ad Zhang Fast Fashion Case Study). Supports tracking of circular KPIs (IEEE Press Release).

  - **Automation & Smart Contracts**: Facilitates triggering smart contracts based on verified IoT data (quality checks, location, environmental thresholds) (Verma et al. Industry 5.0 Integration).

  - **Interoperability**: Promotes unified data formats and protocols allowing diverse IoT devices and blockchain platforms to interact (Herbe et al. 2023).

- ***SME Relevance:*** Standardized integration frameworks reduce the complexity and cost for SMEs wanting to connect IoT devices to blockchain platforms for tracking or monitoring. Ensures compatibility with partners' systems.

3.3. Other Key Standards and Specifications

Beyond ISO and IEEE, several other standards bodies and specific technical specifications contribute important elements.

3.3.1. DIN SPEC 32790:2022-11 – Reference Architecture for Blockchain Applications to Create Transparency in Supply Chains

Developed by the German Institute for Standardization (DIN), this specification provides a reference architecture specifically aimed at enhancing supply chain transparency using blockchain (DIN SPEC 32790:2022-11).

- ***Core Guidance:*** Outlines a modular architecture (similar to ISO 23257), consensus considerations (PoA, PBFT), and features for tamper-proof event logging. Includes use cases like CO2 footprint tracking, conflict minerals, and plastic recycling (DIN SPEC 32790).

- ***Relevance to Circular SCM & Blockchain Integration:*** Directly addresses transparency needs. Complements ISO/TR 6277 data flows. Provides governance frameworks for consortia and emphasizes auditability (DIN SPEC 32790).

- ***SME Relevance:*** Offers a practical architectural blueprint focused on transparency, potentially simpler to adopt than the full ISO 23257 for specific use cases relevant to SMEs proving compliance or origin.

3.3.2. CLC/TS/EN 45557:2020 – General Method for Assessing the Proportion of Recycled Material Content in Energy-related Products

This European standard from CEN-CENELEC provides a standardized methodology for calculating and verifying recycled content claims (EN 45557:2020 Link).

- ***Core Guidance**:* Defines calculation methods (mass balance, chain of custody) and documentation requirements for assessing recycled material proportions (EN 45557).
- ***Relevance to Circular SCM & Blockchain Integration**:* Provides the standardized *methodology* whose *results* can be immutably recorded and verified using blockchain (EN 45557 Scope). Crucial for validating claims underpinning CMUR (ISO 59020) or meeting regulatory mandates. Smart contracts can automate checks against EN 45557 thresholds. Informs DPP data structure (BEAMA). Reduces audit costs (TraceMet Study; Circularise CORDIS Project).
- ***SME Relevance**:* Provides a clear, recognized method for SMEs to calculate and report recycled content, enhancing credibility. Blockchain integration simplifies verification for customers.

3.3.3. ISO/TR 16340:2023 – Application of Blockchain-based Traceability Platform for Cold Chain Food

While focused on cold chain food, this Technical Report offers principles adaptable for tracking other sensitive or high-value materials in circular SCM (e.g., electronics, advanced materials) (ISO/TR 16340:2023 Link).

- ***Core Guidance**:* Provides framework for blockchain traceability, defining minimum data requirements, emphasizing consortium governance, interoperability (GS1 standards), and security. Includes CO2 tracking case study.
- ***Relevance to Circular SCM & Blockchain Integration**:* Methods adaptable for tracking materials through reuse/repair loops. Aligns with material passport data needs (e.g., battery passports). Condition monitoring adaptable for reusable assets. Promotes consortium models suitable for circular networks. Supports compliance verification. Projects like COOL-SENS (EIC Accelerator) address similar needs.
- ***SME Relevance**:* Offers practical guidance adaptable for SMEs handling sensitive or high-value goods requiring careful tracking and condition monitoring within circular flows.

3.3.4. ASTM D8558-2024 – Standard Guide for Verification of a Certificate of Authentication Used to Track Products through Their Supply Chain by Utilizing Blockchain Technology

Developed by ASTM International, this guide focuses on standardizing blockchain-verified Certificates of Authentication (CoA) for product tracking (ASTM D8558-2024 Link).

- ***Core Guidance**:* Defines requirements for blockchain-based CoAs to ensure tamper-proof verification of claims about provenance, lifecycle events (reuse/refurbishment), and authenticity, potentially using hashing and DIDs.
- ***Relevance to Circular SCM & Blockchain Integration**:* Provides standard for verifiable digital credentials traveling with products through circular loops (proving history, certified recycled content, refurbishment cycles). Helps prevent fraud in secondary markets (ASTM D8558, Art Ecosystem Example). Aligns with DPP data needs and supports automated compliance reporting. Integrates with other standards like DIN SPEC 32790 and ISO 59040. Projects like HASHED BLOCKTAC (EIC Accelerator) implement similar digital seal concepts.
- ***SME Relevance**:* Enables SMEs to create standardized, verifiable certificates for their products or processes (e.g., repair services), enhancing trust and market access, particularly in B2B contexts or secondary markets.

3.3.5. ISO/IEC TR 30176:2021 – Internet of Things (IoT) — Integration of IoT and DLT/Blockchain: Use Cases

This joint ISO/IEC Technical Report provides standardized templates and use cases for integrating IoT and DLT, relevant for capturing real-world data in circular systems (ISO/IEC TR 30176:2021 Link).

- ***Core Guidance****:* Outlines integration patterns and use cases (agricultural tracing, waste management - Vottun example). Addresses security (ZKPs, DIDs) and interoperability.
- ***Relevance to Circular SCM & Blockchain Integration****:* Provides standardized ways to link IoT sensor data (material flows, conditions, usage) to immutable blockchain records for lifecycle tracking and DPP population. Offers blueprints applicable to circularity (e.g., tracking organic waste). Shows integration of PETs and identity management. Enables smart contracts to react reliably to verified IoT events.
- ***SME Relevance****:* Offers practical integration patterns, reducing complexity for SMEs implementing IoT-blockchain solutions. Facilitates connection to standardized platforms.

3.3.6. CEN/CLC/TS 17880:2022 – Protection Profile for Smart Meter to build trusted blockchain data

This Technical Specification from CEN-CENELEC, critical for enabling trusted data input, defines security requirements for smart meters measuring resources (electricity, gas, water, heat) (TS 17880 Link).

- ***Core Guidance****:* Based on Common Criteria EAL3+, specifies minimum security requirements (data integrity via crypto signing (FCS_COP.1), authenticity, confidentiality, availability, auditability, secure time, secure firmware management, access control, interface security).
- ***Relevance & Implications for Circular SCM & Blockchain Integration:***
  - **Solving the Oracle Problem for Resource Tracking**: Ensures trustworthiness of meter data *before* it reaches the blockchain, crucial for circular KPIs (resource efficiency, LCAs, Scope 3 emissions) and sustainability reporting (ISO 59020). Addresses "Garbage-In, Garbage-Out".
  - **Enabling Verifiable Sustainability Metrics**: Provides verifiable input for calculating KPIs like resource intensity or carbon footprint, recorded on blockchain aligned with ISO 59020.
  - **Foundation for Automated Compliance & Smart Contracts**: Ensures reliable event logging and data integrity for smart contracts verifying energy efficiency, triggering carbon credits (e.g., based on savings tracked by SOLARFARM GA: 817096), or automating billing in pay-per-use models. Tamper-evident logs support execution verification.
  - **Cyber-Physical Security Link**: Protects the link between physical resource flow and digital representation from manipulation.
  - **Interoperability & Ecosystem Integration**: Facilitates integration with IoT platforms (IEEE P2418.1) and blockchain networks (ISO 23257).
- ***SME Relevance****:* While crucial for data trust, deploying TS 17880-compliant meters involves costs. SMEs relying on utility-provided meters may depend on the utility's compliance. For SMEs installing their own sub-metering, choosing compliant devices ensures data credibility for reporting or participating in blockchain-based schemes.

3.3.7. GS1 Standards (e.g., Global Traceability Standard, EPCIS, Digital Link)

GS1 provides foundational standards for identification (GTINs, GLNs, SSCCs), data capture (barcodes, RFID), and data sharing (EPCIS) essential for supply chain visibility (GS1 Global Traceability Standard, ISO/TR 16340, ISO 59004).

- ***Core Guidance:*** Provides globally unique identifiers and standardized event data structures (EPCIS) to track products/assets and share "what, where, when, why" information. GS1 Digital Link connects physical products to online information.
- ***Relevance to Circular SCM & Blockchain Integration:***
  - **Unique Identification**: Crucial for linking physical items to blockchain records throughout circular loops.
  - **Standardized Event Data**: EPCIS provides standard format for events (commissioning, shipping, recycling) recorded immutably on blockchain, ensuring interoperability.
  - **Physical-Digital Link**: Digital Link provides standardized way (QR/NFC) to access product info (potentially DPP data on blockchain).
  - **Complementarity**: GS1 provides identification/event structure; blockchain provides secure, decentralized infrastructure for recording/sharing that data. Mentioned in ISO/TR 6277 use cases.
- ***SME Relevance:*** GS1 standards are widely adopted, providing a familiar framework. Using GS1 identifiers allows SMEs to easily integrate their products into larger blockchain-based traceability systems that leverage these standards.

3.3.8. UNECE Standards (Traceability for Sustainable Garments and Footwear)

The United Nations Economic Commission for Europe (UNECE) has developed specific traceability standards targeting the textile and footwear industry, focusing on sustainability and circularity (UNECE 2017).

- ***Core Guidance:*** Establishes requirements/recommendations for data sharing along the textile value chain (social/environmental compliance, material composition, processing steps) for transparency and due diligence (OECD 2018, UNECE 2017).
- ***Relevance to Circular SCM & Blockchain Integration:*** Provides sector-specific policy/data framework blockchain can implement. Defines sustainability data types (certifications, chemical usage) trackable on blockchain. Supports OECD due diligence via transparent, immutable record-keeping (OECD 2018).
- ***SME Relevance:*** Offers guidance for SMEs in the complex textile sector. Blockchain implementation can help smaller players meet traceability and sustainability demands from larger brands or regulators.

3.4. Comparative Analysis and Interrelations

The landscape of standards relevant to blockchain in circular SCM is multifaceted, operating at different levels and often complementing each other:

- **Foundational Layers:** ISO/TC 307 (Blockchain) & ISO/TC 323 (Circular Economy) provide principles, vocabulary (ISO 59004), process guidance (ISO 59010, ISO 59020). ISO 23257 & DIN SPEC 32790 offer structural blueprints.

- **Data & Integration:** ISO/TR 6277 (Data Flows), ISO/AWI 59040 (PCDS), EN 45557 (Recycled Content), ASTM D8558 (CoA), and GS1 standards focus on the *data* and its movement (including IoT via IEEE P2418.1, ISO/IEC TR 30176).
- **Domain Specificity:** UNECE (Textiles), ISO/TR 16340 (adaptable from Cold Chain), use cases in PD ISO/TR 3242 provide sector context.
- **Finance & Automation:** IEEE 2418.7 addresses finance; smart contract standardization (ISO/TC 307, ETSI ISG PDL) underpins automation.
- **Trust & Security:** Identity standards (W3C DID/VC, eIDAS alignment) & security specs (TS 17880 for meters) provide trust infrastructure.

Key Interrelations & Synergies:

- **ISO 590xx + Blockchain Standards:** Circular economy standards define *what* (principles, measurement); blockchain standards provide *how* DLT enables it.
- **PCDS (ISO 59040) + DPP + Blockchain:** PCDS defines data, DPP is the application context (e.g., ESPR), blockchain provides secure backbone. ASTM D8558 provides CoA element.
- **IoT Standards + Traceability Standards + Blockchain:** IoT captures physical data, traceability standards structure it, blockchain records it securely. TS 17880 ensures trusted input for specific resources.
- **Reference Architectures + Data Flows:** Architectures (ISO 23257, DIN SPEC 32790) define structure; data flow models (ISO/TR 6277) define interactions.

Successfully implementing blockchain for circular SCM requires navigating and integrating relevant standards from these different layers and domains to build robust, interoperable, and trustworthy solutions meeting business and regulatory requirements, accessible also to SMEs. Ongoing work within SDOs, informed by practical implementations (like EU projects) and coordination (like BlockStand), is crucial for maturing this ecosystem.

Chapter 4: Key Enabling Technologies & Integration for Blockchain-Based Circular Supply Chains

The successful implementation of blockchain technology to support circular Supply Chain Management (SCM) rarely occurs in isolation. It relies heavily on integration with a suite of complementary digital and physical technologies that bridge the gap between real-world assets/processes and the digital ledger. These enabling technologies provide essential data inputs, facilitate automation, enhance analytical capabilities, and ensure seamless information flow across the circular value network. This chapter explores the core blockchain components relevant to circular SCM and delves into the critical enabling technologies – including IoT sensors, smart meters, digital twins, AI, and Digital Product Passports (DPPs) – examining their roles, technical underpinnings, integration patterns within a blockchain framework, and relevance for SMEs.

4.1. Core Blockchain Components for Circular SCM

As established in Chapter 2, specific blockchain capabilities are fundamental to enabling circularity:

- **Immutable Ledger:** Provides a permanent, tamper-evident record essential for tracking product lifecycles, material provenance, repair histories, and compliance data across multiple use phases and stakeholder transitions (9, 24). Offers SMEs a reliable way to document their processes and product history.

- **Transparency & Auditability:** Offers (permissioned) visibility into material flows and process histories, supporting verification of circularity claims (e.g., recycled content) and simplifying audits (15, 11). Reduces information asymmetry that can disadvantage SMEs.

- **Smart Contracts:** Automate critical circular processes such as validating certificates (EN 45557), executing take-back agreements, managing deposit-return schemes, triggering end-of-life sorting, or distributing incentives (24, 14). Can reduce administrative burden and transaction costs for SMEs.

- **Decentralization:** Fosters trust and collaboration among diverse actors (manufacturers, consumers, collectors, recyclers, remanufacturers, SMEs) without reliance on a single central intermediary (16, 15). Enables SMEs to participate in networks on a more level playing field.

- **Tokenization:** Can represent physical assets, track fractional ownership during recycling/remanufacturing, or create incentive tokens (plastic credits, repair rewards) to encourage participation (IEEE 2418.7-2021). Projects like ReSeed (GA: 101118063) and Value4All (TrustChain) explore token-based incentives, while EKOFOLIO (GA: 876676) proposed tokenizing forestry assets.

These core components form the digital trust infrastructure, but their effectiveness depends on reliable integration with technologies interacting with the physical world and processing complex information.

4.2. Integration with Foundational & Emerging Technologies

4.2.1. Internet of Things (IoT) & Sensors (RFID/NFC)

- ***Role in Circular SCM:*** IoT devices are the sensory interface connecting physical products/processes to the blockchain ledger. They capture real-time data crucial for tracking assets, monitoring conditions, and understanding usage patterns – vital for circularity.

  - **Tracking**: RFID/NFC tags provide unique identification for tracking through supply/recycling chains (22, 16). GPS tracks location (14).

  - **Condition Monitoring**: Sensors monitor environment (temperature, humidity) or operation (usage cycles, stress) (14). Informs maintenance, repair, or recycling decisions (24). Relevant for projects like COOL-SENS (EIC Accelerator) or SeafoodTrace (EIC Accelerator).

  - **Usage Data**: Embedded sensors track usage for pay-per-use models or predictive maintenance (24).

- ***Blockchain Integration:*** IoT sensor data (hashed) recorded on blockchain as immutable, time-stamped events (14, 16). Creates verifiable physical-digital link. Smart contracts triggered by verified IoT data (14, Verma et al. Industry 5.0 Integration). Projects like PestNu (GA: 101037128) and TAC! (TrustChain) integrate sensor data with blockchain.

- ***Standards Link:*** IEEE P2418.1 provides framework for secure Blockchain-IoT integration (IEEE P2418.1 Link). ISO/IEC TR 30176 outlines use cases (ISO/IEC TR 30176 Link). GS1 standards provide identifiers. Secure tagging technologies (Waltonchain) address vulnerabilities.

- ***SME Relevance:*** IoT allows SMEs to gather valuable data about their products in use or materials in process. Standardized integration lowers the barrier to connecting this data to blockchain platforms for enhanced traceability or service offerings. Cost of sensors and integration remains a factor.

4.2.2. Smart Meters & CEN/CLC/TS 17880: A Foundation for Trusted Resource Data

While general IoT sensors track products, smart meters specifically measure resource flows (energy, water, gas) – data fundamental for quantifying environmental footprint and resource efficiency central to circular economy assessments. Ensuring the trustworthiness of this data *before* it enters the blockchain is paramount.

- ***Role as Enabling Technology for Circular SCM on Blockchain:***
  - **Trusted Data Source ("Oracle"):** Circularity requires accurate measurement of resource consumption for LCAs, sustainability reports (CSRD), and KPIs ([ISO 59020]) ([24]). Smart meters provide this data. [TS 17880] ensures this input data is trustworthy *before* reaching the blockchain, addressing the "Garbage-In, Garbage-Out" problem ([DIN SPEC 32790]).
  - **Verifiable Input for KPIs & Compliance**: TS 17880 mandates integrity features (crypto signing, tamper-evident logs). Secure data used as input for [ISO 59020] KPIs (resource intensity) or verifying Ecodesign compliance, with results recorded on blockchain.
  - **Enabling Automated Circular Processes**: Smart contracts automate actions based on *verified* meter data: calculating carbon credits ([BMW example]), implementing pay-per-use, automating resource allocation. TS 17880 provides trust in triggering data. Projects like [SOLARFARM] (GA: 817096) tested smart contracts based on PVI asset data.
- ***Technical Foundation via TS 17880:*** Ensures Data Integrity (crypto signing), Tamper-Evident Logging, Secure Time Synchronization, Cyber-Physical Security (protecting meter hardware/interfaces).
- ***Interrelation with Other Standards:*** Specific device security standard within broader IoT ecosystem ([IEEE P2418.1], [ISO/IEC TR 30176]). Provides trusted input for measurement standards ([ISO 59020]) using architectures ([ISO 23257]). Relies on Common Criteria ([ISO/IEC 15408]).
- ***SME Relevance:*** Secure, compliant meters provide SMEs with credible data for sustainability reporting or participating in energy efficiency schemes. Cost of certified meters is a consideration, but ensures data validity required by partners or regulations. Standard ensures interoperability if SMEs need to integrate meter data into shared platforms.

4.2.3. Digital Twins

- ***Role in Circular SCM:*** Dynamic virtual representation of a physical asset/process, continuously updated with real-world data ([24]). Models product lifecycle, tracking condition, usage, maintenance, composition. Enables:
  - **Predictive Maintenance**: Extending product life.
  - **Optimized Remanufacturing/Recycling**: Determining best end-of-life pathway.
  - **Simulation**: Modeling impact of circular strategies.

- ***Blockchain Integration:*** Blockchain provides secure, shared, immutable ledger for digital twin data throughout circular lifecycle (24). Ensures data integrity and controlled access for multiple stakeholders (manufacturer, user, repairer, recycler). Smart contracts automate updates based on IoT/meter inputs or trigger actions based on twin's state (Hasan et al. 2020). Projects like Connecting Food (EIC Accelerator) use blockchain-secured digital twins for traceability.
- ***Standards Link & Examples:*** ISO 23247 series provides framework for digital twins in manufacturing. Projects like BBTWINS (GA: 101023334) use digital twins for agri-food value chains, potentially integrating blockchain (87).
- ***SME Relevance:*** Digital twins can help SMEs optimize product design for circularity, manage assets more effectively (e.g., leased equipment), and offer enhanced services. Blockchain integration adds trust and facilitates data sharing with partners, but implementation complexity and cost are significant.

4.2.4. Artificial Intelligence (AI) & Predictive Analytics

- ***Role in Circular SCM:*** AI leverages data for insights, process optimization, and intelligent decision-making. Applications include:
  - **Demand Forecasting**: New vs. refurbished products/parts.
  - **Reverse Logistics Optimization**: Collection routes, sorting strategies.
  - **Quality Assessment**: Analyzing sensor data for reuse/remanufacturing potential.
  - **Anomaly Detection**: Identifying fraud or deviations (24). Projects like PestNu (GA: 101037128) use AI for optimizing inputs based on verified data.
- ***Blockchain Integration:*** Blockchain provides high-quality, reliable, comprehensive dataset for training/running AI models (14). Immutability ensures input integrity. Smart contracts can automate actions based on AI predictions recorded on ledger (Herbe et al. 2023). Integration with PETs allows AI analysis while preserving privacy (14). Projects like AI-MetaBloQ (TrustChain) combine AI quality assessment with a DLT marketplace.
- ***Standards Link & Examples:*** Projects like i4Q (GA: 958205) use AI for quality control based on reliable data (potentially DLT-stored). Standardization emerging around AI ethics, trustworthiness, data governance (ISO/IEC JTC 1/SC 42).
- ***SME Relevance:*** AI can provide SMEs with valuable insights previously only accessible to larger firms. Blockchain ensures the data used for AI is trustworthy. However, AI implementation requires data science expertise and computational resources, which can be barriers. AI-as-a-Service platforms integrated with blockchain could lower entry costs.

4.2.5. Digital Product Passports (DPPs)

- *Concept & Role in Circular SCM:* Digital records with dynamic lifecycle info (provenance, materials, manufacturing, usage, repair, sustainability, end-of-life) (Herbe et al. 2023). Cornerstone for circular economy, providing data for informed decisions supporting reuse, repair, recycling (BlockStand Reports, ISO/AWI 59040).
- ***Blockchain Integration:*** Ideal underlying infrastructure for DPPs, ensuring data is:
  - **Secure & Tamper-Proof**: Guaranteeing integrity of claims/history (24).
  - **Accessible & Interoperable**: Standardized access for authorized stakeholders (ISO 59004, Cirmar Analysis).

- **Dynamically Updated**: Securely adding new info (repair events, IoT data) (DigInTraCE).
- **Managed with Granular Permissions**: Data owner control over visibility (24).

- ***Standards & Regulatory Context:***
  - **Data Structure**: ISO/AWI 59040 (PCDS) developing standard format.
  - **Identification**: GS1 standards.
  - **Architecture**: ISO 23257, DIN SPEC 32790.
  - **Regulatory Drivers**: EU regulations (ESPR, Battery Regulation, CSRD) mandating/encouraging DPPs (BlockStand Reports).
- ***Examples:*** DigInTraCE (GA: 101091801), MultiPass (TrustChain) project explores multi-ledger DPPs. Battery passports are prime example.
- ***SME Relevance:*** DPPs will become increasingly mandatory. Blockchain offers SMEs a standardized and secure way to manage DPP data and comply with regulations. Participation in industry platforms leveraging blockchain for DPPs will be crucial. Cost and complexity of managing DPP data need accessible solutions.

4.3. Interoperability Mechanisms

Effective blockchain-based circular SCM across diverse ecosystems requires robust interoperability.

- ***The Challenge:*** Different organizations may use different blockchain platforms (e.g., Hyperledger Fabric, Ethereum, IOTA) or need to connect blockchain data with existing ERP, MES, or IoT platforms. Lack of interoperability creates new silos and prevents end-to-end visibility and data flow needed for circularity (16, 14, BlockStand Reports).
- ***Mechanisms & Solutions:***
  - **Cross-Chain Protocols**: Standards like IBC enable communication/asset transfer between blockchains (mentioned in ISO 23257, PD ISO/TR 3242, ISO/TR 6277, IEEE 2418.7). Projects like Perun-X (ONTOCHAIN) develop frameworks.
  - **Standardized APIs:** Allow different applications (blockchain/legacy) to exchange data (DIN SPEC 32790). Platforms like DEMETER (GA: 857202) focus on standardized agricultural data models (AIM) via APIs.
  - **Oracles**: Secure bridges providing external data (sensors, prices) to smart contracts or relaying on-chain events (ISO 59020). Projects like DESMO-LD (ONTOCHAIN) and ADOS (ONTOCHAIN) develop decentralized oracles.
  - **Data Standards**: Common data formats (PCDS via ISO 59040, EPCIS via GS1) ensure consistent interpretation (Cirmar Analysis, 9).
- ***Standards Link:*** ISO 23257 (architecture), ISO/TC 307 work on interoperability, PD ISO/TR 3242 & ISO/TR 6277 (use cases/data flows), IEEE P2418.1 (IoT-Blockchain), data format standards (GS1, ISO 59040) contribute.
- ***SME Relevance:*** Interoperability standards are crucial for SMEs to participate in larger ecosystems without being locked into single platforms or facing prohibitive integration costs. Standardized APIs and data formats lower barriers to entry.

Effectively integrating these enabling technologies with blockchain, guided by relevant standards and considering the specific needs and capacities of SMEs, is key to unlocking the full potential for transparent, efficient, and trustworthy circular supply chains.

Chapter 5: Synthesis of EU Project Implementations: Patterns, Gaps, and Standards Application

The analysis of EU-funded projects (detailed in the RZ02 Research Documentation Report and referenced throughout this document) reveals key patterns in how blockchain technology is being applied to circular supply chain challenges in agriculture and healthcare, alongside significant gaps where standardization and implementation maturity are lacking. This chapter synthesizes these findings, highlighting common approaches, challenges encountered in practice, and the relationship between project implementations and the standards landscape discussed in Chapter 3.

For a detailed list of Case Studies and Examples related to the observed sectors, refer to **Annex I.**

5.1. Dominant Application Patterns

- **Traceability and Provenance:** The most prevalent use case leverages blockchain's immutability for tracking products and materials from origin to consumption (and sometimes beyond).
  - ***Agriculture/Food:*** Projects like Connecting Food (EIC Accelerator), HASHED BLOCKTAC (EIC Accelerator), SeafoodTrace (EIC Accelerator), DiTECT (CORDIS), mEATquality (CORDIS), FAIRCHAIN (CORDIS), TAC! (TrustChain), and TRACEWINDU (CORDIS) focus on food safety, anti-counterfeiting, and verifying origin claims. These often integrate IoT sensors (e.g., SeafoodTrace) and rely implicitly or explicitly on unique identification (GS1) and secure physical-digital links (relevant to ASTM D8558). SPACE4GREEN (CORDIS) specifically integrated Galileo signals for trusted location proofs.
  - ***Healthcare:*** PharmaLedger (CORDIS) addresses pharmaceutical supply chain integrity (finished goods, clinical trials), aligning with regulatory needs (e.g., FMD) and GS1 serialization. ChemChain (EIC Accelerator) proposed tracking chemical ingredients. Preemie (EIC Accelerator) uses blockchain to trace donor milk.
  - ***Standard Relevance:*** These applications directly benefit from foundational standards like ISO 23257 (architecture), PD ISO/TR 3242 (use cases), ISO/TR 6277 (data flows), and identification standards (GS1).
- **Verification of Sustainability/Circularity Claims:** Blockchain is used to provide verifiable proof for environmental or circular practices.
  - ***Agriculture:*** PestNu (CORDIS) uses DLT for data evidence supporting reduced pesticide use. FoodRUS (CORDIS) implements blockchain for FLW prevention certification. DigInTraCE (CORDIS) focuses on traceability for secondary raw materials. CATTLECHAIN 4.0 (CORDIS) aimed to verify animal welfare standards.
  - ***Cross-Sector:*** CirculariseSource (EIC Accelerator) tracks material characteristics like recycled content.
  - ***Standard Relevance:*** These applications connect strongly with the emerging circular economy standards (ISO 59004, ISO 59020, ISO 59040) and specific claim verification methods (EN

45557). The need for trusted data input (TS 17880 for meters, secure IoT via IEEE P2418.1) is paramount.

- **Secure Data Sharing and Access Control:** Particularly prominent in healthcare, blockchain facilitates controlled and auditable sharing of sensitive data.

  - ***Healthcare:*** MH-MD (CORDIS), PatientDataChain (EIC Accelerator), Trussihealth (ONTOCHAIN), PS-SDA (ONTOCHAIN), GUEDHS (TrustChain), and Aria (WOMEN TECHEU) focus on patient-centric data control, consent management, and secure sharing for research, often integrating PETs and SSI/VC frameworks (W3C DID/VC, eIDAS alignment). PANACEA (CORDIS) used DLT for secure threat intelligence sharing. AI-MetaBloQ (TrustChain) created a DLT marketplace for biosample data.

  - ***Standard Relevance:*** These projects highlight the critical importance of identity management standards (ISO/TC 307, W3C DID/VC), alignment with regulations (GDPR, eIDAS 2), data format standards (e.g., FHIR in healthcare), and emerging standards for integrating PETs with DLT governance.

- **Automation via Smart Contracts:** Used across sectors to automate agreements, payments, and compliance checks.

  - ***Agriculture:*** CARECHAIN (ONTOCHAIN) for parametric insurance. SOLARFARM (EIC Accelerator) for PPA validation. Trade on Chain (TrustChain) for international trade contracts. BEACON (CORDIS) for agricultural insurance payouts.

  - ***Healthcare:*** DigiPharm (EIC Accelerator) for value-based payment agreements. B-LOCS (EIC Accelerator) for GMP compliance monitoring.

  - ***Standard Relevance:*** Underscores the need for mature smart contract standards covering security, legal validity, oracle integration, and standardized templates (ISO/TC 307, ETSI ISG PDL, EU Data Act).

5.2. Identified Gaps and Challenges in Implementation

The project analysis also reveals recurring challenges and gaps where standardization and practical solutions are needed:

- **Interoperability:** Despite standardization efforts (ISO 23257, ISO/TR 6277), achieving seamless data exchange between different blockchain platforms and legacy systems remains a major practical hurdle, as seen in complex multi-partner projects like DEMETER (GA: 857202) or the goals of PharmaLedger (GA: 853992). The need for robust cross-chain solutions (Perun-X, TokEngine) and standardized APIs is consistently highlighted. NeWG (TrustChain) aimed to bridge FIWARE/Gaia-X data spaces with blockchain networks.

- **Data Quality and the Oracle Problem:** Ensuring the trustworthiness of data inputted from the physical world (via IoT, sensors, meters, manual entry) remains a critical challenge. While projects like ADOS (ONTOCHAIN) and DESMO-LD (ONTOCHAIN) develop oracle solutions and standards like TS 17880 address meter security, reliable and standardized mechanisms for verifying diverse real-world data inputs are still evolving. Projects like INSPECTO (EIC Accelerator) explored linking portable testing devices to blockchain.

- **Scalability and Cost:** While permissioned blockchains offer better performance than early public chains, scaling solutions to handle high volumes of transactions (e.g., item-level tracking in FMCG) efficiently and cost-effectively remains a concern, particularly for SMEs. Storage costs associated with immutable ledgers also need consideration.

- **SME Adoption Barriers:** While funding mechanisms like EIC Accelerator and Cascade Funding target SMEs, broader adoption faces challenges related to cost, technical complexity, lack of awareness, and difficulties integrating into existing consortia or platforms governed by larger players. Standardized, user-friendly solutions like the low-code platform proposed by FOrLedger (EIC Accelerator) and clear ROI demonstrations are needed.

- **Governance Models:** Establishing effective, fair, and adaptable governance frameworks for consortium blockchains involving multiple competing or collaborating organizations (including SMEs) is complex and often project-specific, lacking standardized best practices.

- **Integration with Circular Economy Standards:** While many projects *support* circularity goals (e.g., traceability enables reuse), the explicit integration and automated verification against the newer, specific circular economy standards (ISO 590xx series) and DPP data requirements (ISO 59040) appears less mature in implemented projects. This represents a key area for future development and standardization focus.

- **Sustainability of DLT:** The environmental footprint of the blockchain technology itself, particularly energy consumption, is a concern that needs addressing through wider adoption of efficient consensus mechanisms (PoS, PoA) and standardized measurement methodologies (CEN-CLC/JTC19/WG2).

5.3. Synthesis: Aligning Practice with Standards

EU projects serve as vital innovation engines, pushing the boundaries of blockchain application in circular SCM. They demonstrate the practical relevance of existing standards (e.g., for identity, architecture, data flows) while simultaneously exposing critical gaps where further standardization is urgently required (interoperability, circularity metrics integration, SME accessibility, governance, DLT sustainability). A feedback loop between practical implementation experiences (from projects like those funded by the EU) and formal standardization processes (within bodies like ISO, CEN-CENELEC, IEEE) is essential for developing standards that are both technically robust and practically relevant, ultimately enabling the scalable and inclusive adoption of blockchain for a truly circular European economy.

Chapter 6: Guidelines for SMEs: Navigating Blockchain for Circular Supply Chains

SMEs are the engine of the European economy and play a critical role in supply chains across all sectors, including agriculture and healthcare. As the transition towards a circular economy accelerates, driven by policy (EU Green Deal, Circular Economy Action Plan) and market demands, blockchain technology emerges as a key enabler for the necessary transparency, traceability, and collaboration. However, adopting new and complex technologies like blockchain presents unique challenges for SMEs due to resource constraints (financial, human, technical).

This chapter provides practical guidelines specifically tailored for SMEs seeking to understand and potentially leverage blockchain technology to enhance their participation in, and benefit from, circular supply chains. It synthesizes insights from the standards landscape, EU project implementations, and identified challenges discussed in previous chapters.

6.1. Understanding the Value Proposition for SMEs

Before diving into implementation, SMEs should clearly assess how blockchain can add value to their specific circular economy activities. Potential benefits include:

- **Enhanced Traceability & Provenance:** Providing verifiable proof of origin, sustainable practices (e.g., organic farming, use of recycled materials), or product handling history. This can increase trust with customers and partners, potentially opening access to premium markets or simplifying compliance. *(Example: An SME food producer could explore solutions similar to those developed by Connecting Food or HASHED BLOCKTAC to provide verifiable origin or quality data to consumers/retailers).*

- **Improved Compliance & Reporting:** Streamlining the process of meeting regulatory requirements (e.g., DPPs, waste tracking, sustainability reporting) by providing immutable, auditable records. This can reduce administrative burden and audit costs. *(Relevant Standards: ISO 59020, EN 45557, ISO 59040)*

- **Increased Efficiency:** Automating processes like compliance checks, certifications, or payments via smart contracts, reducing manual effort and potential disputes. *(Example: An SME involved in international trade could investigate platforms like Trade on Chain to automate contract execution).*

- **Access to New Markets/Finance:** Participating in blockchain-based platforms can provide access to wider networks of suppliers or buyers. Verifiable performance data can potentially improve access to supply chain finance or green finance. *(Relevant Standard: IEEE 2418.7) (Example: An SME implementing sustainable practices could potentially leverage blockchain data to access green financing schemes, similar to the concept explored in SOLARFARM).*

- **Stronger Collaboration:** Building trust within consortia or partnerships through shared, transparent (permissioned) data, facilitating participation in complex circular value chains. *(Example: SMEs could join industry platforms like Catena-X (automotive) or participate in data spaces facilitated by projects like NeWG (fresh food logistics)).*

SMEs should conduct a cost-benefit analysis, considering not only potential gains but also implementation costs and risks (see Section 6.4).

6.2. Navigating the Standards Landscape

The evolving standards landscape can seem daunting. SMEs should focus on standards most relevant to their specific application and industry:

- **Foundational Knowledge:** Understand basic terminology (ISO 22739) and architectural concepts (ISO 23257, DIN SPEC 32790) to engage effectively with technology providers or partners.

- **Identification:** If tracking physical items, understand and utilize GS1 standards (GTINs, barcodes, potentially EPCIS for event data) as these are widely adopted and integrate well with blockchain solutions.

- **Circularity Data:** Be aware of the emerging ISO 590xx series, particularly ISO 59020 (measurement) and the upcoming ISO 59040 (PCDS) if involved in products requiring DPPs or detailed circularity reporting. Understand methods for specific claims, like recycled content (EN 45557).

- **Interoperability:** When joining platforms or consortia, inquire about adherence to interoperability standards (ISO/TR 6277 data flows, cross-chain protocols like IBC) to avoid vendor lock-in.
- **Identity:** Understand the move towards decentralized identity (W3C DID/VC) and its alignment with eIDAS 2, especially if dealing with sensitive data or needing strong authentication. Projects like CHECKS show how VCs can be used for business verification.
- **Sector-Specific:** Look for relevant sector guidance (e.g., UNECE for textiles, pharma guidelines potentially referenced by PharmaLedger).

SMEs don't need to be standards experts but should be aware of key frameworks relevant to their use case to ask informed questions of partners and providers. Resources like BlockStand (31) can provide valuable summaries and guidance.

6.3. Addressing Implementation Challenges: Practical Steps

SMEs face specific hurdles when implementing blockchain:

- **Cost:**

  - ***Explore BaaS****:* Cloud-based Blockchain-as-a-Service can significantly reduce upfront infrastructure investment.
  - ***Leverage Open Source****:* Utilize open-source platforms (Hyperledger Fabric) and tools where possible.
  - ***Start Small****:* Begin with a focused pilot project addressing a clear pain point with measurable ROI before scaling.
  - ***Seek Funding****:* Explore EU funding (EIC Accelerator, Cascade Funding via NGI) and national/regional grants supporting digitalization and circular economy transitions. *(Example: Many projects listed in RZ02, like tilkal, CirculariseSource, or Connecting Food, received EIC Accelerator funding).*

- **Skills Gap:**

  - ***Partner Strategically****:* Collaborate with technology providers, universities, or research institutions with blockchain expertise.
  - ***Utilize Low-Code Platforms****:* Explore emerging platforms aiming to simplify blockchain application development *(Example: FOrLedger explored this concept for agri-food traceability).*
  - ***Focus on User Interface****:* Ensure the solution interacting with the blockchain has a user-friendly interface requiring minimal technical knowledge for staff.
  - ***Invest in Training****:* Provide targeted training for key personnel involved in managing or using the blockchain application.

- **Interoperability & Integration:**

  - ***Prioritize Standards****:* Choose solutions and partners committed to using recognized interoperability standards (APIs, data formats like EPCIS/PCDS).
  - ***Phased Integration****:* Integrate blockchain with existing systems (ERP, etc.) gradually, starting with essential data flows.

- ***Join Industry Platforms****:* Participate in sector-specific platforms that handle much of the underlying complexity and ensure interoperability among members. *(Example: SMEs in agriculture might explore platforms aligned with DEMETER's AIM or FIWARE standards used in projects like CATTLECHAIN 4.0).*

- **Governance:**

- ***Understand the Rules****:* If joining a consortium, clearly understand the governance rules, data ownership policies, cost-sharing model, and dispute resolution mechanisms *before* committing.

- ***Seek Representation****:* Ensure SME interests are considered in consortium governance structures, potentially through industry associations.

6.4. Leveraging Enabling Technologies

Blockchain rarely works in isolation. SMEs should consider how it integrates with other technologies relevant to circularity:

- **IoT:** Use sensors (RFID, NFC, environmental sensors) to capture real-time data for tracking, condition monitoring, or usage patterns. Ensure secure integration (IEEE P2418.1). *(Example: SMEs could replicate the approach of SeafoodTrace using smart labels with sensors linked to a blockchain).*

- **Smart Meters:** If resource consumption (energy, water) is critical for reporting or efficiency, use compliant smart meters (TS 17880) to ensure trustworthy data input to the blockchain.

- **DPPs:** Prepare for DPP requirements by structuring product data according to emerging standards (ISO 59040 PCDS). Consider blockchain as the infrastructure to manage and share this data securely. *(Example: SMEs needing DPPs could look at solutions being developed in projects like DigInTraCE or the interoperability concepts from MultiPass).*

- **AI**: Explore how AI can leverage the trusted data stored on the blockchain for optimizing processes, predicting maintenance needs, or assessing quality. *(Example: SMEs could explore AI tools for quality control based on blockchain-verified data, similar to the goals of i4Q).*

6.5. Getting Started: A Phased Approach

1. **Educate & Assess:** Understand blockchain basics and identify specific circular SCM challenges where it offers a clear advantage over traditional solutions. Assess potential ROI.

2. **Identify Use Case:** Start with a well-defined, manageable pilot project (e.g., tracking a specific high-value product, verifying a key sustainability claim, automating a simple payment process).

3. **Explore Solutions & Partners:** Research available platforms (BaaS, open-source), industry consortia, and potential technology partners. Prioritize solutions adhering to relevant standards. *(Example: SMEs could investigate providers mentioned in successful EIC Accelerator projects or partners involved in relevant CORDIS/NGI projects).*

4. **Pilot & Evaluate:** Implement the pilot project, carefully measuring costs, benefits, and challenges. Gather feedback from staff and partners.

5. **Scale & Integrate:** If the pilot is successful, gradually scale the solution and integrate it more deeply with existing business processes and IT systems, continuously monitoring performance and adapting as needed.

6. **Stay Informed:** Keep abreast of evolving standards, regulations (DPPs, eIDAS 2), and technological developments. Participate in industry networks or initiatives like BlockStand.

By taking a strategic, informed, and phased approach, SMEs can navigate the complexities of blockchain technology and harness its potential to thrive in the emerging circular economy, enhancing transparency, efficiency, and trust within their supply chains.

Chapter 7: Challenges, Limitations, and Future Directions

Despite the significant potential and ongoing innovation surrounding blockchain technology for circular supply chains, its widespread adoption faces considerable technical, organizational, and regulatory hurdles. Understanding these challenges, particularly from an SME perspective, is crucial for navigating the implementation path, guiding future research, and prioritizing standardization efforts. This chapter details the key limitations and adoption barriers, followed by an outline of future directions and critical standardization needs identified through the analysis.

7.1. Technical Challenges

While blockchain technology offers unique advantages, inherent technical limitations currently constrain its application in demanding, large-scale circular SCM scenarios.

- **Scalability and Performance:**

  - ***Throughput & Latency****:* Many platforms struggle with low transaction throughput (TPS) and high latency, insufficient for high-volume SCM environments (14, 16). This hinders real-time tracking required for dynamic circular loops. While permissioned chains are generally faster, scaling remains a challenge (24).

  - ***Data Storage Burden****:* Continuously growing ledgers place significant storage demands on participants, especially resource-constrained SMEs or IoT devices (16, 8). Off-chain storage solutions (used by PharmaLedger's OpenDSU, OriginTrail) mitigate this but add complexity (16).

  - ***Potential Solutions****:* Layer 1 improvements (efficient consensus like PoS/PoA, DAGs like IOTA used in PestNu), Layer 2 solutions (state channels - Perun-X), and off-chain storage are key areas of development.

- **Interoperability:**

  - ***Platform Fragmentation****:* Numerous incompatible DLT platforms create digital silos, hindering data exchange (14, ITU-T FG DLT D2.1, 16). This forces SMEs to potentially support multiple systems if partners use different platforms.

  - ***Legacy System Integration****:* Connecting blockchain with existing ERP, MES, etc., is complex and requires custom integration efforts (15, DIN SPEC 32790).

  - ***Data Semantics****:* Ensuring consistent interpretation of shared data requires standardized models (e.g., DEMETER AIM, ISO 59040 PCDS).

  - ***Need for Standards****:* Overcoming these requires standards for cross-chain communication (ISO 23257), APIs (DIN SPEC 32790), data formats (GS1, ISO 59040), and reference architectures (ISO

23257) (31, 11). Projects like MultiPass (TrustChain) directly tackle multi-ledger interoperability for DPPs.

- **The Oracle Problem:**
  - ***Concept:*** Guaranteeing the accuracy of data inputted from the physical world remains a fundamental challenge (DIN SPEC 32790). "Garbage-In, Garbage-Out".
  - ***Circular SCM Impact:*** Critical for verifying claims about recycled content, resource consumption, or product conditions.
  - ***Mitigation Approaches:*** Requires trusted data sources: secure IoT devices (IEEE P2418.1), secure smart meters (TS 17880), reliable decentralized oracles (DESMO-LD, ADOS), and process verification.
- **Energy Consumption:**
  - ***PoW Impact:*** Traditional PoW consensus is energy-intensive, conflicting with circular economy goals (22, ITU-T FG DLT D2.1). Unsuitable for most SMEs.
  - ***Shift to Alternatives:*** Industry moving towards energy-efficient PoS, PoA, or DAGs (31, 14). Projects like TokEngine use PoS.
  - ***Standardization Need:*** Standardized methodologies for measuring DLT environmental footprint are crucial (31, CEN-CLC/JTC19/WG2).
- **Security Vulnerabilities:**
  - ***Smart Contract Bugs:*** Flaws can lead to loss or incorrect execution (14). Formal verification and secure coding standards (ISO/TC 307) are vital, especially for SMEs lacking extensive auditing resources.
  - ***Network Attacks:*** Theoretical risks exist for consensus mechanisms (14).
  - ***Private Key Management:*** Secure key management is critical but challenging for non-experts (14). Solutions like hardware security modules or advanced wallets (PRIVÈ) are needed but add cost/complexity.
  - ***Integration Risks:*** Vulnerabilities often arise at interfaces with external systems.

7.2. Adoption & Implementation Barriers (Including SME Perspective)

Beyond technical hurdles, several factors impede adoption:

- **Cost and Return on Investment (ROI):**
  - ***High Initial Costs:*** Significant investment needed for technology, integration, process changes, onboarding, training (ITU-T FG DLT D2.1). Often prohibitive for SMEs.
  - ***Uncertain ROI:*** Benefits can be hard to quantify upfront, making business case difficult, especially for SMEs needing faster returns (15, ITU-T FG DLT D2.1).
  - ***SME Exclusion Risk:*** High costs can exclude SMEs from participating in blockchain-based ecosystems unless accessible solutions (BaaS, industry platforms) are available.
- **Complexity and Skills Gap:**
  - ***Technical Complexity:*** DLT requires specialized expertise (14, ITU-T FG DLT D2.1), often lacking in SMEs.

- *Integration Challenges:* Integrating with diverse legacy systems is demanding (15).
- *Knowledge Gap:* Lack of understanding among managers, policymakers, and users hinders adoption (ITU-T FG DLT D2.1, 50). Need for clear communication beyond crypto hype.

- **Regulatory and Legal Uncertainty:**
  - *Evolving Frameworks:* Legal status of blockchain records, smart contracts, tokens still evolving. Impact of GDPR, eIDAS 2, Data Act, MiCA, DORA needs clarification (31). Creates uncertainty for businesses, especially SMEs lacking legal resources. Projects like **PS-SDA** and **DOOF** aim to address GDPR/Data Act compliance.
  - *Cross-Border Issues:* Lack of harmonized regulations complicates international supply chains (50).
  - *Smart Contract Enforceability:* Legal standing requires clarification (ITU-T FG DLT D2.1).
- **Standardization Gaps:**
  - *Lack of Maturity:* Absence of mature, widely adopted standards for interoperability, data formats (especially for circularity), security, identity, and sustainability metrics is a major barrier (14, ITU-T FG DLT D2.1, 31).
  - *Vendor Lock-in Risk:* Lack of standards increases risk of being locked into proprietary platforms (11).
- **Governance and Collaboration Challenges:**
  - *Consortium Governance:* Establishing effective, fair governance for multi-stakeholder consortia is complex (24, ITU-T FG DLT D2.1). SMEs may lack bargaining power.
  - *Stakeholder Alignment:* Achieving buy-in from all partners requires trust, clear value propositions, and addressing data sharing concerns (15, 50, 24). SMEs may hesitate to share data with larger players.

7.3. Future Directions & Standardization Needs

Addressing challenges and unlocking blockchain's potential for circular SCM requires concerted efforts:

- **Prioritizing Interoperability Standards:** Standardizing APIs, maturing cross-chain protocols (IBC), defining standard data models/semantics (GS1 EPCIS, ISO 59040 PCDS).
- **Maturing Identity Management Standards:** Finalizing/promoting W3C DID/VC adoption, ensuring alignment with EUDIW/eIDAS 2, standardizing linking mechanisms.
- **Strengthening Smart Contract Standardization:** Secure coding standards, audited templates for circular processes, standardized oracle interfaces, legal validity frameworks (EU Data Act).
- **Developing Robust Sustainability & Circularity Standards:** Standardized DLT footprint measurement (CEN-CLC/JTC19/WG2), standard formats/verification for circularity metrics (ISO 59020), standardized DPP data requirements (ISO 59040, ESPR).
- **Enhancing Security & Privacy Standards:** DLT-specific security assessment methods, standards for integrating PETs, secure DLT-IoT integration (IEEE P2418.1, TS 17880 principles).
- **Fostering Ecosystem Collaboration & Governance:** Standardized governance templates for consortia, promoting collaborative platforms (BlockStand), focusing on education and capacity building, especially for SMEs.

- **Continued Technological Innovation:** Improving DLT scalability/efficiency, trustworthy oracles, user experience (wallets, dApps for SCM/circularity).

Addressing these requires ongoing collaboration between industry, researchers, policymakers, and SDOs (ISO, IEEE, CEN-CENELEC, ETSI, GS1), coordinated by initiatives like BlockStand (31).

Chapter 8: Conclusion

The convergence of the imperative for a circular economy and the maturation of blockchain/DLT presents a transformative opportunity for European supply chains. This report confirms that blockchain offers a powerful technological foundation for building the transparent, trustworthy, and collaborative ecosystems essential for managing resources effectively through multiple lifecycles, benefiting businesses of all sizes, including SMEs. Its core principles – immutability, transparency (permissioned), decentralization, and automation via smart contracts – directly address key challenges in tracking materials, verifying claims (including sustainability and circularity), managing complex multi-stakeholder interactions, and ensuring data integrity across circular value networks in sectors like agriculture and healthcare.

The analysis of the current standards landscape reveals significant progress. International and European bodies (ISO, IEEE, CEN-CENELEC, DIN, ASTM, GS1, UNECE) are developing crucial building blocks: foundational architectures (ISO 23257, DIN SPEC 32790), data flow models (ISO/TR 6277), specific circular economy frameworks (ISO 590xx series), data formats (ISO 59040 PCDS), claim verification methods (EN 45557, ASTM D8558), IoT integration guides (IEEE P2418.1), and secure data input mechanisms (TS 17880). EU-funded projects (CORDIS, EIC Accelerator, NGI Cascade Funding) provide vital practical validation, demonstrating applications in traceability (Connecting Food), sustainability verification (PestNu), secure data sharing (PharmaLedger, Trussihealth), and automation (CARECHAIN).

However, realizing the full potential requires overcoming substantial challenges. Technical hurdles persist in scalability, practical interoperability between diverse systems, and ensuring the trustworthiness of real-world data feeding the blockchain (the oracle problem). Furthermore, significant adoption barriers remain, particularly for SMEs, related to implementation costs, the need for specialized skills, navigating regulatory uncertainty (GDPR, eIDAS 2, Data Act, DPP mandates), establishing effective multi-stakeholder governance, and demonstrating clear ROI.

The path forward necessitates a dual focus on continued technological innovation (e.g., efficient consensus, user-friendly interfaces, robust oracles) and, critically, accelerated standardization efforts. Priority areas identified include maturing interoperability protocols and APIs, finalizing identity management frameworks aligned with EUDIW, strengthening smart contract security and legal clarity, developing robust standards for integrating circularity metrics (ISO 590xx) and DPP data (ISO 59040) with blockchain verification, and establishing methodologies for assessing the sustainability of DLT itself.

Crucially, specific attention must be paid to SME needs, ensuring standards and solutions are accessible, affordable, and provide tangible benefits. The dedicated guidelines provided in Chapter 6 aim to support SMEs in navigating this complex landscape. Initiatives like BlockStand (31) are indispensable for coordinating these efforts, bridging the gap between research, industry (including SMEs), policymakers, and SDOs.

In conclusion, while the journey towards fully realizing blockchain's potential for circular supply chains is ongoing, the foundational standards, enabling technologies, and demonstrable use cases provide a strong starting point. By addressing the identified challenges through collaborative innovation and targeted standardization, Europe can leverage blockchain as a key enabler for a more transparent, efficient, sustainable, and truly circular economy.

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- **P8: HASHED BLOCKTAC** (EIC Accelerator Phase 1, GA: H2020-SMEInst-2018-2020-1). Link
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Annex I: Implementation in EU Projects: Case Studies / Examples from Agriculture & Healthcare

The theoretical potential and standardized frameworks for blockchain in circular supply chains (as discussed in Chapters 2, 3, and 4) gain practical relevance through their implementation in real-world projects. The European Union's funding mechanisms (CORDIS, EIC Accelerator, Cascade Funding) provide a fertile ground for exploring, developing, and validating these applications.

This Annex provides a list of Case Studies and Examples that examine a selection of EU-funded projects, primarily focusing on the agriculture/food and healthcare sectors, to illustrate how blockchain technologies and associated standards are being applied to address specific circularity-related challenges, such as traceability, resource management, compliance, and secure data sharing.

Analysis Approach

The following case study and example list draws upon the project repositories and analyses presented in the complentary Research Documentation Report, supplemented by project details mentioned elsewhere in the provided source materials. The analysis focuses on:

1. **Identifying Relevant Projects:** Selecting projects from CORDIS (RIA/IA), EIC Accelerator, and Cascade Funding (NGI) streams that explicitly utilize blockchain/DLT or closely related principles (e.g., secure distributed data sharing, verifiable credentials) to address challenges in agriculture, food systems, or healthcare relevant to circularity.

2. **Analyzing Blockchain Use:** Examining the specific role and technical implementation of blockchain within each project (e.g., platform used, data stored, consensus if known, integration with IoT/AI).

3. **Mapping to Circularity Goals:** Understanding how the blockchain application contributes to circular economy objectives, such as enhancing traceability for reuse/recycling, verifying sustainable practices, managing resource lifecycles, or enabling new circular business models.

4. **Linking to Standards:** Evaluating how these practical implementations align with, apply, or highlight the need for the standards discussed in Chapter 3 (e.g., ISO 590xx series, ISO/TC 307 standards, IEEE standards, GS1, sector-specific regulations). Identifying both successful applications and potential gaps where standards are lacking or not yet fully leveraged.

Annex I / 1. Case Studies/Examples: Agricultural Sector

The agricultural and food sector, with its complex value chains, critical safety requirements, and growing emphasis on sustainability, presents numerous opportunities for blockchain applications, as reflected in EU funding priorities.

1A. Enhancing Traceability & Food Safety

Ensuring the provenance and safety of food products is paramount. Blockchain provides an immutable record to track goods from farm to fork, combat fraud, and facilitate rapid response in case of contamination.

- **Technical Approaches:** Projects often combine blockchain with IoT (RFID, sensors) for real-time tracking and unique identification (GS1 standards). Permissioned ledgers (like Hyperledger Fabric, as used in IBM Food Trust pilots mentioned by DiTECT) are common for B2B data sharing. Smart contracts can automate checks or alerts based on traceability data.

- **Examples & Standards Links:**
    - **Connecting Food (EIC Accelerator Link):** Creates blockchain-secured "digital twins" for end-to-end traceability, allowing real-time auditing of product claims. *Standards Link:* Leverages concepts from ISO traceability standards, potentially aligns with data structures like PCDS (ISO 59040) for the digital twin, and requires robust identity management (ISO/TC 307, W3C DID/VC) for participants.
    - **HASHED BLOCKTAC (EIC Accelerator - Olive Oil Link):** Uses blockchain as a "digital seal" linked to physical products to prevent counterfeiting. *Standards Link:* Relies on secure physical-digital linking (a challenge mentioned in Chapter 4) and standards for verifiable claims, potentially ASTM D8558 for CoA.
    - **SeafoodTrace (EIC Accelerator Link):** Combines anti-tamper smart labels (with sensors) and a DLT-enabled IoT platform for seafood traceability. *Standards Link:* Requires IoT-DLT integration standards (IEEE P2418.1, ISO/IEC TR 30176) and standards for secure data logging from sensors (concepts similar to TS 17880).
    - **DiTECT (CORDIS Link):** Integrated blockchain for traceability and integrity within a broader EU-China food safety framework using Big Data and sensor fingerprinting. *Standards Link:* Highlights the need for cross-border data interoperability standards and secure data management frameworks (ISO/TC 307).
    - **mEATquality (CORDIS Link):** Evaluated blockchain alongside other techniques for meat authentication and linking quality to production systems. *Standards Link:* Requires standards for verifiable claims about production methods and quality attributes, potentially linking to ISO 59004 (provenance) and ISO 59020 (if specific metrics measured).
    - **TAC! (TrustChain – Cascade Link):** Provides end-to-end food production traceability using blockchain and IoT, with smart contracts enforcing transparency. *Standards Link:* Needs clear smart contract standards (ISO/TC 307) and IoT integration standards (IEEE P2418.1).

Project Name	**Funding Type**	**Goal**	**Blockchain Use**	**Standards Alignment/Gap Example**
Connecting Food Link	EIC Accelerator	End-to-end food traceability & auditing via Digital Twins	Secure backbone for Digital Twin data, real-time auditing	Needs DPP data standards (ISO 59040/PCDS), reliable IoT integration (IEEE P2418.1)
HASHED BLOCKTAC Link	EIC Accelerator	Anti-counterfeiting for Olive Oil	"Digital Seal" linking physical product to immutable blockchain record	Requires secure physical-digital link; potentially ASTM D8558 (CoA).
SeafoodTrace Link	EIC Accelerator	Intelligent Traceability for Seafood	Secure ledger for anti-tamper smart label/sensor data (IoT)	Needs robust IoT-DLT integration (IEEE P2418.1) & secure sensor data standards.

DiTECT Link	CORDIS (RIA)	EU-China integrated food safety monitoring	Traceability, transparency, data integrity within Big Data platform	Highlights need for international data format/interoperability standards.
mEATquality Link	CORDIS (IA)	Link husbandry practices to meat quality, product authentication	Evaluated as tool for immutable record linking production system & quality data	Needs standards for verifiable claims on production methods/quality; links to ISO provenance concepts.
TAC! Link	TrustChain (Casc.)	End-to-end food production traceability	Ledger for IoT sensor data, Smart Contracts for transparency enforcement	Requires clear Smart Contract standards & reliable IoT data integration (IEEE P2418.1).

Table 1A: Example EU Projects - Agricultural Traceability & Safety

1B. Supporting Sustainable Practices & Resource Management

Blockchain enables verifiable tracking of resource inputs, certifications for sustainable practices (organic, fair trade), and management of environmental data, supporting the EU Green Deal and Farm to Fork strategies.

- **Technical Approaches:** Integration with farm management systems (FMS), IoT sensors (soil moisture, water meters, energy meters), satellite data (Earth Observation - EO), and potentially smart meters compliant with TS 17880. Smart contracts automate verification or trigger incentives.
- **Examples & Standards Links:**
  - **PestNu (CORDIS Link):** Uses IOTA DLT and smart contracts within its DSS/FMS to provide data evidence and verify AI models aimed at reducing pesticide/fertiliser use. *Standards Link:* Relies on secure IoT data integration (IEEE P2418.1) and potentially verifiable AI model standards (emerging field). Data integrity supports claims related to sustainable inputs (ISO 59004).
  - **ReSeed (CORDIS – ERC Link):** Employs blockchain to create a digital market incentivizing on-farm conservation of indigenous seeds (ISK), tracking their flow and use. *Standards Link:* Explores tokenization (ISO/TC 307 work) for incentive mechanisms and needs standards for tracking genetic resource provenance. Relates to SDG 15.
  - **SOLARFARM (EIC Accelerator Link):** Tested blockchain-based smart contracts for validating solar irrigation (PVI) assets as collateral in green financing PPAs. *Standards Link:* Requires standards for smart contracts in finance (linking to IEEE 2418.7) and trusted data input (potentially from TS 17880-compliant meters measuring energy production/water use).
  - **FoodRUS (CORDIS Link):** Implements blockchain for FLW prevention certification and potentially for the PAYT waste tracking scheme. *Standards Link*: Needs standards for verifiable certifications (linking to CoA concepts like ASTM D8558) and secure tracking

of waste flows (potentially using GS1 identifiers). Aligns with ISO 59020 (waste reduction metrics) and SDG 12.

- **DigInTraCE (CORDIS Link):** Uses blockchain, DPPs, and AI for traceability of secondary raw materials (relevant if agricultural biomass is used). *Standards Link:* Directly addresses DPP standards (ISO 59040 PCDS) and circularity metrics (ISO 59020).

Project Name	Funding Type	Goal	Blockchain Use	Standards Alignment/Gap Example
PestNu Link	CORDIS (IA)	Reduce pesticide/nutrient use via digital tools	Data evidence, AI model verification via IOTA DLT & Smart Contracts	Requires secure IoT/AI integration standards. Supports verifiable claims (ISO 59004).
ReSeed Link	CORDIS (ERC)	Incentivize conservation of indigenous seeds (ISK)	Digital market tracking ISK flow & use, managing incentives	Explores tokenization standards (ISO/TC 307), needs genetic resource provenance standards. Aligns with SDG 15.
SOLARFARM Link	EIC Accelerator	Facilitate solar irrigation financing	Tested Smart Contracts for PPA validation using blockchain	Needs smart contract standards (finance - IEEE 2418.7) & trusted data input (e.g., TS 17880 meters).
FoodRUS Link	CORDIS (IA)	Reduce food loss/waste	FLW prevention certification, traceability, potential PAYT waste tracking	Needs verifiable certificate standards (ASTM D8558); links to ISO 59020 (waste metrics), SDG 12.
DigInTraCE Link	CORDIS (IA)	Traceability for secondary raw materials (incl. biomass valorisation)	Decentralized platform using blockchain, DPPs, AI contracts	Directly applies DPP concepts (ISO 59040 PCDS), circularity measurement (ISO 59020). Requires interoperability standards (ISO 23257).

Table 1B: Example EU Projects - Agricultural Sustainability & Resource Management

1C. Enabling Fair Value Chains & Market Access

Blockchain's potential for disintermediation and transparency can empower smaller producers, enable direct trade, and facilitate novel financial instruments like microinsurance.

- **Technical Approaches:** Utilizing public or consortium blockchains for marketplaces, tokenization for direct payments or alternative financing, and smart contracts for automating agreements and payouts.
- **Examples & Standards Links:**
  - **I Go Slow (EIC Accelerator Link):** Explored a blockchain token platform to connect gourmet food producers directly with consumers, enhancing trust and bypassing intermediaries. *Standards Link:* Requires token standards (e.g., ERC-20 like) and identity management for producers/consumers (W3C DID/VC).
  - **FAIRCHAIN (CORDIS Link):** Uses blockchain as part of its solution set to improve information flow and management capacity, aiming to strengthen the position of small/mid-sized actors in dairy and fruit/vegetable chains. *Standards Link:* Needs data sharing standards and potentially links to fair trade certification verification on-chain. Addresses SDG 10 (Reduced Inequalities).
  - **CARECHAIN (ONTOCHAIN – Cascade Link):** Developed blockchain smart contracts and oracles for parametric microinsurance triggered by agricultural sensor data. *Standards Link:* Requires secure oracle standards (linking real-world data to smart contracts), smart contract standards for insurance, and potentially links to IEEE 2418.7 for financial aspects.
  - **Trade on Chain (TrustChain – Cascade Link):** Built an open-source blockchain platform using SSI/VCs and smart contracts to digitize and automate international trade contracts, reducing barriers for SMEs trading agricultural commodities. *Standards Link:* Directly implements identity standards (W3C DID/VC, potentially eIDAS aligned) and needs robust smart contract standards.

Project Name	Funding Type	Goal	Blockchain Use	Standards Alignment/Gap Example
I Go Slow Link	EIC Accelerator	Direct producer-consumer links for gourmet food	Explored blockchain token ecosystem for interactions & trust	Needs token standards & identity management standards.
FAIRCHAIN Link	CORDIS (RIA)	Fairer intermediate food value chains (dairy, fruit/veg)	Improve information flow & management capacity via blockchain solution	Requires data sharing standards, potentially links to fair trade verification. Addresses SDG 10.
CARECHAIN Link	ONTOCHAIN (Casc.)	Parametric microinsurance for agriculture	Smart contracts triggered by oracles/sensor data	Needs secure oracle standards, smart contract standards for insurance.
Trade on Chain Link	TrustChain (Casc.)	Digitize international trade contracts, reduce SME barriers	Open-source platform using SSI/VCs & smart contracts	Implements W3C DID/VC identity standards, needs robust smart contract standards.

Table 1C: Example EU Projects - Agricultural Fair Value Chains & Market Access

Annex I / 2. Case Studies/Examples: Healthcare Sector

The healthcare sector, characterized by highly sensitive data, complex regulations, and multi-stakeholder processes, is another key area where blockchain's ability to enhance security, privacy, traceability, and interoperability is being actively explored through EU funding.

2A. Pharmaceutical Supply Chain Integrity

Ensuring the authenticity and safe handling of medicines is critical. Blockchain provides immutable traceability to combat counterfeiting and manage recalls effectively.

- **Technical Approaches:** Utilizing permissioned blockchains (like Hyperledger Fabric or agnostic platforms like OpenDSU) to record serialization data (often linked to GS1 standards), track custody changes, monitor environmental conditions (cold chain), and manage clinical trial logistics.
- **Examples & Standards Links:**
    - **PharmaLedger (CORDIS – IMI Link):** Developed a versatile blockchain platform (using OpenDSU architecture, platform-agnostic) for pharma use cases including supply chain traceability (finished goods, clinical trial materials), anti-counterfeiting, and eLeaflet management. *Standards Link:* Addresses GS1 standards for serialization, regulatory compliance (e.g., FMD in Europe), and potentially data formats for ePI (Electronic Product Information). Needs robust interoperability standards.
    - **ChemChain (EIC Accelerator Link):** Proposed blockchain infrastructure for tracking chemical information through supply chains, relevant for ensuring the safety and compliance of pharmaceutical ingredients. *Standards Link:* Needs chemical data standards (e.g., REACH compliance verification) integrated with blockchain traceability.
    - **COOL-SENS (EIC Accelerator Link):** Focused on cold chain monitoring using IoT, AI, and DLT. *Standards Link:* The DLT component ensures immutable recording of temperature data, requiring IoT-DLT integration standards (IEEE P2418.1) and potentially aligning with principles from ISO/TR 16340 (Cold Chain).

Project Name	Funding Type	Goal	Blockchain Use	Standards Alignment/Gap Example
PharmaLedger Link	CORDIS (IMI)	Trusted platform for pharma use cases (SC, trials, ePI)	OpenDSU architecture anchoring data off-chain, DLT-agnostic	Addresses GS1 serialization, regulatory compliance (FMD); highlights need for interoperability, ePI data standards.
ChemChain Link	EIC Accelerator	Trace chemical information in supply chains	Proposed open-source blockchain infrastructure for tracking chemical data	Needs chemical data standards (REACH) integration with blockchain traceability frameworks (e.g., ISO/TC 307 architecture/data flow).
COOL-SENS Link	EIC Accelerator	Advanced cold chain monitoring	DLT for immutable, transparent recording of real-	Requires IoT-DLT integration standards (IEEE P2418.1), aligns with cold

			time IoT sensor data	chain traceability principles (ISO/TR 16340).

Table 2A: Example EU Projects - Pharmaceutical Supply Chain Integrity

2B. Medical Device Lifecycle Management & Security

Blockchain can track medical devices from manufacturing through use to end-of-life, supporting maintenance, compliance, reuse/recycling (circularity), and cybersecurity.

- **Technical Approaches:** Using blockchain to create DPPs for devices, storing maintenance logs immutably, managing firmware updates securely, and potentially linking to IoT sensor data for usage monitoring.
- **Examples & Standards Links:**
  - **MultiPass (TrustChain – Cascade** Link**):** Enables verifiable DPP data for products (including medical devices) to be managed across multiple, potentially incompatible ledgers using a trust delegation framework. *Standards Link:* Directly addresses DPP concepts (ISO 59040 PCDS) and interoperability challenges (ISO 23257).
  - **ENTRUST (CORDIS** Link**):** Uses DLT as the foundation for issuing and managing real-time, dynamic Conformity Certificates for Connected Medical Devices (CMDs) based on runtime attestation and trust assessments. *Standards Link:* Addresses cybersecurity certification needs (potentially linking to ISO/IEC standards) using a novel DLT-based approach. Requires standards for DLT-based certificates and secure device attestation.
  - **PANACEA (CORDIS** Link**):** Utilized blockchain (in its SISP component) for secure sharing of threat intelligence between healthcare organizations, indirectly contributing to medical device security. *Standards Link:* Relates to cybersecurity information sharing standards (e.g., STIX/TAXII potentially recorded on DLT).

Project Name	Funding Type	Goal	Blockchain Use	Standards Alignment/Gap Example
MultiPass Link	TrustChain (Casc.)	Multi-ledger bridge for verifiable DPP data	Managing custody & data pointers for DPPs across different ledgers	Addresses DPP (ISO 59040) & interoperability (ISO 23257) needs for complex lifecycles.
ENTRUST Link	CORDIS (IA)	Enhance CMD security using Zero Trust & DLT	DLT for issuing/managing real-time, dynamic Conformity Certificates	Needs standards for DLT-based certification & secure device attestation.
PANACEA Link	CORDIS (RIA)	Cybersecurity toolkit for healthcare, including secure info share	SISP component used blockchain for secure P2P threat info sharing	Relates to cybersecurity standards (ISO 27001), needs standards for secure DLT-based information sharing protocols.

Table 2B: Example EU Projects - Medical Device Lifecycle & Security

2C. Secure & Patient-Centric Health Data Management

Empowering patients with control over their health data while enabling secure sharing for research and care is a major driver for blockchain in healthcare.

- **Technical Approaches:** Employing permissioned or P2P blockchain architectures, smart contracts for consent and access control, integration with SSI/VC identity frameworks (W3C DID/VC, eIDAS), and combining blockchain with PETs (FL, MPC, HE) for privacy-preserving analysis.
- **Examples & Standards Links:**
  - **MH-MD (CORDIS Link):** Pioneered a P2P, blockchain-based network for patient-controlled data exchange, using smart contracts and integrating PETs (HE, SMPC). *Standards Link:* Addresses GDPR principles, needs robust identity (DID/VC) and data format (FHIR) integration standards.
  - **PatientDataChain (EIC Accelerator Link):** Explicitly uses blockchain and smart contracts to give patients control over medical record access. *Standards Link:* Needs alignment with identity (eIDAS, DID/VC) and health data standards (FHIR).
  - **Trussihealth (ONTOCHAIN – Cascade Link):** Bridges HL7 FHIR health data into W3C VCs signed with eIDAS-compliant signatures, stored in SSI wallets. *Standards Link:* Directly implements and links key standards (FHIR, W3C VC/DID, eIDAS), showing a path to interoperable, patient-controlled health credentials.
  - **PS-SDA (ONTOCHAIN – Cascade Link):** Uses blockchain and smart contracts to manage GDPR-compliant Data Agreements with immutable provenance trails. *Standards Link:* Addresses GDPR Article requirements via DLT, needs standardization for Data Agreement formats on-chain.
  - **GUEDHS (TrustChain – Cascade Link):** Combines Federated Learning (privacy-preserving AI) with DLT for auditing consent and data usage in secondary health data analysis. *Standards Link:* Highlights need for standards governing DLT use with PETs like FL for auditable, privacy-preserving research.

Project Name	**Funding Type**	**Goal**	**Blockchain Use**	**Standards Alignment/Gap Example**
MH-MD Link	CORDIS (RIA)	P2P network for patient-controlled health data exchange	Blockchain (Fabric likely) for access control, consent, audit; integrated PETs	Addresses GDPR; needs identity (DID/VC), data format (FHIR), PET integration standards.
PatientDataChain Link	EIC Accelerator	Patient control over medical record sharing	Blockchain ledger for immutable records, Smart Contracts for access rules	Needs identity (eIDAS, DID/VC) & health data (FHIR) standards alignment.
Trussihealth Link	ONTOCHAIN (Casc.)	Bridge FHIR health data to legally valid VCs in SSI wallets	Uses DLT implicitly via SSI framework; focus on VC conversion	Directly implements & links FHIR, W3C DID/VC, eIDAS standards.

			& eIDAS signatures	
PS-SDA Link	ONTOCHAIN (Casc.)	GDPR-compliant data sharing with provenance via Data Agreements	Blockchain stores immutable Data Agreements & provenance; Smart Contracts enforce rules	Addresses GDPR via DLT; needs standardized Data Agreement formats.
GUEDHS Link	TrustChain (Casc.)	Privacy-preserving secondary use of health data via FL	DLT provides auditable governance layer for consent/access in FL framework	Highlights need for standards governing DLT+PET (FL) integration for research.

Table 2C: Example EU Projects - Secure & Patient-Centric Health Data Management