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TRACE: Digital Product Passports for Kenyan Agricultural Exports

A research project submitted in partial fulfillment of the requirements of the Bachelor of Science in Software Engineering in the school of Pure and Applied Sciences

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DECLARATION

We declare that this proposal is our original work and has not been submitted for academic evaluation in any other institution. Information borrowed from other sources has been acknowledged accordingly through proper citations. Examples of personal details used in the text such as names, items, or scenarios, are fictional and used only for academic illustration

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DEDICATION

This work is dedicated to our family and friends whose unwavering support, encouragement and sacrifice have made the pursuit of this degree possible.

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ABSTRACT

This study addressed the critical compliance gap facing Kenyan agricultural exporters, who were challenged by the European Union's emerging Digital Product Passport (DPP) framework and increasingly stringent Environmental, Social, and Governance (ESG) regulations. The central problem involved the heavy reliance of high-value agricultural exporters, particularly in the tea, coffee, and avocado sectors, on fragmented, paper-based, or rudimentary semi-digital systems that were fundamentally incapable of meeting the complex requirements for continuous, machine-readable, and verifiable sustainability disclosures mandated by the new EU regime. These outdated documentation practices exposed Kenyan producers to significant risk of market exclusion and higher due diligence costs. The general objective of this research was to develop and rigorously evaluate a functional prototype of a decentralized multi-agent system (MAS) leveraging IOTA's Directed Acyclic Graph (DAG)-based distributed ledger technology to automate and secure ESG compliance workflows from farm to export. To achieve this general goal, the study pursued four specific, interlocking objectives: first, designing a decentralized system architecture specifically engineered for anchoring high-frequency farm and supply-chain IoT data to a feeless ledger; second, developing autonomous software agents capable of ingesting that data, evaluating it against detailed EU criteria, and autonomously determining shipment-level compliance status; third, implementing a robust mechanism for generating cryptographically linked, DPP-compatible digital identifiers that functioned as verifiable compliance records; and fourth, prototyping a smart-contract-driven workflow for conditional trade events, such as automated payment release or customs clearance upon successful digital passport validation. The primary significance of this study lay in providing a pragmatic and open-source implementation pathway for Kenyan exporters to maintain premium market access while simultaneously demonstrating the critical technical feasibility and economic viability of utilizing feeless DLT in complex, data-intensive agricultural value chains, particularly for smallholder operations. Adopting the systematic framework of the Design Science Research Methodology (DSRM), the study constructed a layered architectural model composed of an IoT data ingestion layer, a tamper-evident IOTA integrity layer for immutable anchoring, and a sophisticated autonomous decision layer for MAS orchestration and rule enforcement. Results indicated that the system successfully anchored time-stamped data on the IOTA Tangle, providing an auditable, tamper-evident record that detected unauthorized modifications through cryptographic hash mismatches. Furthermore, the autonomous compliance agents demonstrated 100% accuracy in classifying consignments based on predefined compliance rules, effectively issuing a DPP only to compliant goods and automatically withholding passports in cases of critical data gaps or cold-chain breaches. The study concluded that the combination of feeless DAG-based distributed ledgers with decentralized multi-agent systems established a robust, scalable, and auditable architectural blueprint for automated ESG compliance, effectively reducing technical trade barriers for emerging economies.

Keywords: Digital Product Passport, ESG compliance, IOTA, distributed ledger, multi-agent systems, agrifood traceability, Kenyan exports.

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Abbreviations

API – Application Programming Interface
IOTA – Internet of Things Application
DAG – Directed Acyclic Graph
DLT – Distributed Ledger Technology
DPP – Digital Product Passport

DBMS – Database Management System
ESG – Environmental, Social and Governance
EU – European Union
IoT – Internet of Things
MAS – Multi-Agent System
TxID – Transaction Identifier

CHAPTER ONE: INTRODUCTION

1.0 Introduction

The convergence of stringent environmental, social and governance (ESG) regulations and digitalization of trade documentation is reshaping how agricultural exports access premium markets such as the European Union (EU). In this context, the EU's emerging Digital Product Passport (DPP) framework is positioned as a cornerstone instrument to enhance traceability, sustainability and circularity across supply chains by mandating product-level, machine-readable information on origin, composition and environmental performance (Heeß et al., 2024; European Commission, 2022). For Kenyan tea, coffee and avocado exporters whose competitiveness depends heavily on access to EU buyers this evolving regime exposes a critical “compliance gap”, as many value-chain actors still rely on fragmented, paper-based or semi-digital systems that are not designed for continuous, verifiable ESG data reporting (Heeß et al., 2024; Xia et al., 2025).

1.1 Background

The Digital Product Passport is an EU policy innovation under the Circular Economy Action Plan and the Ecodesign for Sustainable Products Regulation, intended to embed standardized sustainability information into a persistent digital record attached to a product or batch (European Commission, 2022; Heeß et al., 2024). Structured reviews of DPP initiatives show that passports are envisioned to store data on materials, emissions, chemical substances, repairability, recyclability and end-of-life options, as well as due-diligence information concerning social and human-rights risks in global supply chains (Heeß et al., 2024; Xia et al., 2025). Although early DPP pilots have focused on batteries, textiles and electronics, policy roadmaps explicitly anticipate expansion to other high-impact sectors including agri-food where deforestation, pesticide use and carbon intensity are central sustainability concerns (Heeß et al., 2024; European Commission, 2020).

At the same time, research on digital traceability in agri-food systems highlights that traditional documentation practices and siloed information systems limit the ability of producers to meet advanced transparency and data-sharing requirements. Systematic reviews and empirical studies show that integrating Internet of Things (IoT) sensors with distributed ledger technologies (DLTs) can generate tamper-evident records of product movement and condition, thereby enhancing trust among supply-chain stakeholders and regulators (Zhao et al., 2025; Kechagias et al., 2024). In particular, directed acyclic graph (DAG)-based ledgers such as IOTA’s Tangle have been proposed as a scalable, feeless alternative to conventional blockchains for high-frequency agricultural and logistics data, given their ability to handle micro-transactions and dense IoT telemetry (Piantadosi et al., 2024; Monrat et al., 2025).

1.2 Current/Existing System

Kenya’s tea, coffee and avocado exports are governed by a mix of national quality standards, phytosanitary regulations and voluntary sustainability certifications, which are typically documented through physical certificates, PDFs and spreadsheet-based records. Studies on African agricultural supply chains note that such arrangements often suffer from data fragmentation, manual data entry, and limited interoperability between exporters, regulators, customs authorities and overseas buyers (Kamble et al., 2024; Nyalala et al., 2024). These documentation practices are adequate for traditional audit regimes that rely on periodic inspections and sample-based verification but are poorly suited to DPP-style requirements that expect continuous, product-level, machine-readable evidence of compliance (Heeß et al., 2024; Zhao et al., 2025).

Furthermore, existing systems rarely integrate sensor-level data from farms or transport environments, such as soil moisture, pesticide applications, cold-chain conditions or transport time-temperature profiles, despite growing recognition that such granular data are critical for robust ESG claims (Piantadosi et al., 2024; Kechagias et al., 2025). Interoperability issues between farm management systems, exporter ERPs and customs platforms also hinder the creation of a single, verifiable "source of truth" for each shipment, increasing the risk of conflicting records, fraud and disputes (Zhao et al., 2025; Kamble et al., 2024). As EU instruments such as the Deforestation Regulation and DPP-related rules tighten, these structural weaknesses can translate into shipment delays, additional due-diligence costs or outright loss of market access for exporters unable to provide trusted digital evidence.

1.3 Problem Statement

The core problem addressed in this study is the absence of a scalable, tamper-evident and automated compliance infrastructure that can connect farm-level ESG data and supply-chain events to DPP-compatible digital passports for Kenyan tea, coffee and avocado exports to the EU. Evidence from the emerging DPP literature underscores that passports must be underpinned by data that are collected comprehensively and automatically, processed in a decentralized and tamper-proof manner, and made interoperable across stakeholders (Heeß et al., 2024; European Blockchain Observatory & Forum, 2023). However, Kenyan exporters currently rely on manual certification workflows and siloed databases that not only inflate transaction costs but also fail to satisfy regulators' expectations for near real-time verification, longitudinal traceability and machine-readable ESG disclosures (Kamble et al., 2024; Nyalala et al., 2024).

Without targeted technical innovation, this compliance gap risks marginalizing small and medium-sized exporters, who may lack the resources to implement proprietary compliance platforms yet are most exposed to trade disruptions. Recent agrifood studies show that integrating IoT sensors with DLT can significantly improve traceability, integrity and auditability of agricultural data, but most prototypes rely on fee-based blockchains and have not been tailored to the specific regulatory demands of DPP-style instruments (Piantadosi et al., 2024; Zhao et al., 2025). In parallel, advances in multi-agent systems and autonomous supply chains indicate that autonomous agents can orchestrate complex logistics and compliance processes, but their application to ESG verification and DPP issuance for African agricultural exports remains under-explored (Cano et al., 2025; Kouhizadeh et al., 2023). This study therefore seeks to design and prototype a decentralized multi-agent system that leverages IOTA's feeless, DAG-based ledger and Fetch.ai-style autonomous agents to close this compliance gap.

1.4 Proposed System

The proposed system is a decentralized multi-agent architecture that integrates three main components: (i) an IoT-enabled data acquisition layer at farm and logistics stages, (ii) a DAG-based distributed ledger using IOTA's Tangle for immutable data anchoring, and (iii) a layer of autonomous software agents responsible for ESG compliance verification and Digital Product Passport generation. Building on proof-of-concept work showing that IOTA can securely handle high-frequency sensor data in agricultural settings, the system hashes and anchors critical ESG-related data such as geolocation, soil parameters, pesticide application records and cold-chain telemetry onto the Tangle, preserving data integrity while storing detailed payloads in off-chain databases or IOTA Streams (Piantadosi et al., 2024; Monrat et al., 2025). This design exploits IOTA's feeless transaction model and scalability to accommodate micro-data submissions from many smallholders and supply-chain actors (Piantadosi et al., 2024).

On top of this ledger layer, specialized autonomous agents form a decentralized multi-agent system responsible for monitoring data streams, evaluating compliance and orchestrating DPP issuance. Drawing on methodologies for autonomous supply chains, agents are modeled as digital representatives of farms, cooperatives, exporters, logistics providers and regulators, each with specific objectives and access rights (Cano et al., 2025; IfM & Fetch.ai, 2022). Compliance agents use parameterized rule sets derived from EU DPP and related ESG regulations to automatically assess whether a given consignment satisfies requirements such as non-deforestation, traceable pesticide use and verifiable origin coordinates (Heeß et al., 2024; European Blockchain Observatory & Forum, 2023). Once all relevant conditions are met, a passport-issuing agent mints a unique Digital Product Passport represented as a non-fungible token or similar digital identifier cryptographically linked to the underlying IOTA-anchored evidence and usable by customs and buyers for automated verification (Heeß et al., 2024; Xia et al., 2025). A smart-contract-driven payments module can then trigger disbursement of funds or trade-finance instruments upon successful passport validation, aligning incentives between compliance and liquidity (Piantadosi et al., 2024; Zhao et al., 2025).

1.5 Purpose of the Study

The purpose of this study is to design and implement a decentralized multi-agent architecture that autonomously verifies ESG compliance for Kenyan tea, coffee and avocado export consignments and generates DPP-compatible digital product passports by anchoring cryptographically verifiable data on a feeless DAG-based distributed ledger.

1.6 General Objective

The general objective of this project is to develop and evaluate a functional prototype of a decentralized multi-agent system that integrates IoT data sources, the IOTA Tangle and autonomous agents to deliver secure, automated ESG compliance auditing and Digital Product Passport issuance for Kenyan agricultural exports to the EU.

1.7 Specific Objectives

The study is guided by the following specific objectives:

I. To design a decentralized system architecture for anchoring ESG-relevant farm and supply-chain data to a feeless, DAG-based distributed ledger suitable for high-frequency IoT streams.
II. To develop autonomous agents capable of ingesting on-chain and off-chain ESG data, evaluating it against EU DPP and related ESG criteria, and autonomously determining shipment-level compliance status.
III. To implement a mechanism for generating DPP-compatible Digital Product Passports as unique digital identifiers linked to underlying IOTA-anchored evidence.
IV. To prototype a smart-contract-driven workflow that conditionally triggered exporter payments and trade events upon successful digital passport validation.

The relationship between the specific objectives and the expected outcomes is summarized in Table 1.1

Table 1.1: Research Objectives and Expected Outcomes

Objective	**Expected Outcome**
Design a decentralized architecture for anchoring ESG data on IOTA	Documented system architecture with layers for data ingestion, IOTA anchoring, agents and access
Develop autonomous agents for real-time ESG compliance auditing	Implemented compliance agents that classify consignments as compliant or non-compliant
Implement a mechanism for generating DPP-compatible digital passports	Prototype DPP module producing passports linked to IOTA transaction references
Prototype a trigger mechanism for payment/clearance events	Prototype component that can notify or simulate payment/clearance when DPP is valid

1.8 Justification

From a policy and trade perspective, the proposed system addresses an urgent need to operationalize compliance with EU sustainability regulations for African agricultural exporters. Literature on DPPs emphasizes that their effectiveness depends on comprehensive, trustworthy and interoperable data flows, which many firms particularly in emerging economies are not yet equipped to provide (Heeß et al., 2024; European Blockchain Observatory & Forum, 2023). By offering a blueprint that combines IoT-enabled data collection, tamper-evident data anchoring and autonomous compliance agents, the project directly contributes to practical implementation pathways that can help Kenyan exporters remain competitive in tightening regulatory environments. In doing so, it supports broader development objectives related to rural livelihoods, value-addition and climate-smart agriculture (Kechagias et al., 2025; Nyalala et al., 2024).

From a technological and academic standpoint, this study advances the state of the art in three ways. First, it applies DAG-based DLT, and specifically the IOTA Tangle, to the concrete challenge of ESG compliance in agricultural export supply chains, extending existing work that has thus far focused on proof-of-concept monitoring in rice cultivation and other crops (Piantadosi et al., 2024; Monrat et al., 2025). Second, it operationalizes multi-agent system concepts for autonomous supply chains in a new domain ESG compliance and DPP issuance for perishable commodities building on emerging methodologies for agent-based coordination in logistics (Cano et al., 2025; IfM & Fetch.ai, 2022). Third, by tightly coupling compliance verification with smart-contract-based payment triggers, it contributes to research on incentive-compatible architectures that reward verifiable sustainability performance in global trade (Zhao et al., 2025; Kamble et al., 2024).

1.9 Scope

This study is deliberately constrained to ensure depth of analysis within the available time and resources. On the sectoral side, the prototype focuses on Kenyan tea, coffee and avocado supply chains, which represent high-value horticultural and cash crops with significant exposure to EU sustainability requirements (Nyalala et al., 2024). The system models selected ESG dimensions that are both technically measurable via IoT and salient in EU regulation such as geolocation for deforestation risk, pesticide application records and basic environmental indicators rather than attempting full coverage of all DPP attributes envisaged for all product categories (Heeß et al., 2024; European Commission, 2020).

On the technological side, the study limits itself to integrating IOTA as the primary DLT for data anchoring, a representative but non-exhaustive set of autonomous agents for compliance checking and passport issuance, and a proof-of-concept smart-contract-driven payment mechanism in a controlled environment. Large-scale deployment, integration with national customs or EU systems, detailed user-interface design for all actors and exhaustive cybersecurity hardening are beyond the current scope and are instead treated as directions for subsequent work. Evaluation relies on simulated or limited real-world data streams and scenario-based testing rather than nationwide field trials (Piantadosi et al., 2024; Zhao et al., 2025).

1.10 Limitations

Several limitations are inherent to this research design. First, the regulatory environment for DPPs remains dynamic, with key technical specifications and sector-specific requirements for agri-food products still being refined at EU level. Conceptual work on DPPs stresses that many design principles are still emerging, which implies that any rule sets implemented in this project may need future adaptation to align with finalized regulations (Heeß et al., 2024; European Blockchain Observatory & Forum, 2023). Second, given constraints on time, funding and data access, the prototype cannot incorporate the full heterogeneity of smallholder production systems, cooperative structures and exporter practices in Kenya; instead, it abstracts typical processes derived from literature and stakeholder reports (Kamble et al., 2024; Nyalala et al., 2024).

Third, DAG-based DLTs and autonomous multi-agent systems themselves remain active on research topics, and their long-term performance, security and governance implications in large-scale production environments are not yet fully understood. Comparative studies indicate that while DAG-based ledgers can outperform traditional blockchains in throughput and transaction costs for smart agriculture applications, they introduce new attack surfaces and protocol design challenges that must be carefully managed (Monrat et al., 2025; Zhao et al., 2025). Similarly, research on autonomous supply chains emphasizes both the transformative potential and the operational risks of delegating critical decisions to autonomous agents, including susceptibility to adversarial data, coordination failures and unintended behaviors (Cano et al., 2025; Kouhizadeh et al., 2023). These factors mean that the findings of this study should be interpreted as evidence of feasibility and design patterns rather than as a fully validated blueprint for national-scale deployment.

1.11 Significance of the Study

The proposed system has practical, policy, and academic significance. Practically, it provides a structured pathway for Kenyan tea, coffee and avocado exporters to transition from paper-based compliance to DPP-ready, digitally verifiable ESG reporting, thereby reducing the risk of trade disruption and enabling participation in premium, sustainability-sensitive segments of the EU market (Heeß et al., 2024; Kamble et al., 2024). For regulators and development partners, the architecture illustrates how open, decentralized infrastructures can be leveraged to support inclusive compliance solutions that accommodate smallholders and cooperatives rather than locking them into proprietary platforms.

Academically, the study contributes to emerging literature at the intersection of DPPs, DLT-enabled agri-food traceability, and autonomous supply chains. By integrating IOTA's Tangle and autonomous agents into a single architecture for ESG compliance and DPP issuance, it operationalizes design principles that have so far been largely discussed at a conceptual level (Heeß et al., 2024; Piantadosi et al., 2024). The prototype and accompanying evaluation can inform future research on topics such as interoperability with data spaces, privacy-preserving analytics, incentive mechanisms for data sharing and resilience of multi-agent compliance systems under real-world constraints (Zhao et al., 2025; Kechagias et al., 2025).

1.12 Operational Definition of Terms

- Agrifood Supply Chain: The network of activities and stakeholders involved in the production, processing, distribution and retail of agricultural food products, from farm inputs through logistics to final consumers (Kechagias et al., 2025).
- Autonomous Agent: A software entity capable of perceiving its environment, making decisions and acting without continuous human intervention to achieve defined objectives; in supply chains, autonomous agents can represent organizations, assets or services that negotiate, monitor and execute tasks (Cano et al., 2025).
- Decentralized Multi-Agent System: A system composed of multiple interacting autonomous agents operating on decentralized digital infrastructures, where coordination emerges from agent interactions rather than centralized control, enabling scalable and fault-tolerant decision-making (Cano et al., 2025; Kouhizadeh et al., 2023).
- Digital Product Passport (DPP): A structured, machine-readable digital record attached to a product or batch that stores standardized information on origin, composition, environmental and social performance, and lifecycle management options, mandated or promoted under EU circular-economy policy instruments (Heeß et al., 2024; European Commission, 2022).
- Directed Acyclic Graph (DAG)-Based Distributed Ledger: A category of distributed ledger technologies that replace linear blockchain chains with directed acyclic graphs of transactions, enabling parallel validation and high throughput; in IOTA's design, this supports feeless micro-transactions and scalable IoT data anchoring (Piantadosi et al., 2024; Monrat et al., 2025).
- Environmental, Social and Governance (ESG) Compliance: Conformance with environmental, social and governance standards, regulations or voluntary schemes that evaluate the sustainability and ethical impacts of an organization's operations and products, including aspects such as deforestation risk, pesticide use, labor conditions and governance practices (Kechagias et al., 2025).
- IOTA Tangle: A DAG-based distributed ledger protocol developed by the IOTA Foundation, characterized by feeless transactions, user-validated transaction confirmation and support for IoT-oriented data streaming and anchoring solutions (Piantadosi et al., 2024; Monrat et al., 2025).
- Internet of Things (IoT): A network of interconnected physical devices equipped with sensors, actuators and communication capabilities that can collect and exchange data over the internet, widely applied in agriculture for monitoring environmental conditions, resource use and logistics (Zhao et al., 2025).

- Non-Fungible Token (NFT): A unique, non-interchangeable digital token representing ownership or authenticity of a specific digital or physical asset on a distributed ledger, often used to encode provenance and rights associated with that asset in supply-chain contexts (European Blockchain Observatory & Forum, 2023).
- Smart Contract: A self-executing program stored on a distributed ledger that automatically enforces predefined rules and conditions, enabling automated settlement of payments, compliance checks and other transactional logic without centralized intermediaries (Monrat et al., 2025).
- Traceability: The ability to track and trace the history, application and location of a product or batch through specified stages of production, processing and distribution, typically using recorded identifiers and increasingly supported by digital and ledger-based systems (Zhao et al., 2025).

1.13 Expected Outcomes

This study is expected to produce the following key outcomes:

- A documented decentralized system architecture that specifies how IoT-enabled ESG and logistics data from Kenyan tea, coffee and avocado supply chains are ingested, validated, anchored on the IOTA Tangle and exposed to autonomous agents and external stakeholders.
- A functional prototype of a decentralized multi-agent system that integrates IOTA-anchored data with autonomous compliance agents capable of classifying export consignments as compliant or non-compliant with selected EU ESG and DPP-related criteria.
- A prototype Digital Product Passport module that generates unique, machine-readable passports linked to underlying IOTA transaction references and suitable for automated verification by EU customs authorities and buyers.
- A smart-contract-driven or rule-based trigger mechanism that demonstrates how successful passport validation can conditionally initiate payment notifications or trade events, illustrating incentive-compatible alignment between ESG compliance and liquidity for exporters.
- An evaluation report based on scenario-driven tests using simulated ESG and logistics data, providing empirical evidence on the feasibility, benefits and limitations of DAG-based ledgers and autonomous agents for ESG compliance and DPP issuance in Kenyan agricultural exports.

These outcomes collectively provide both a practical blueprint and empirical insights for stakeholders interested in implementing DPP-ready ESG compliance infrastructures in agrifood export contexts

1.14 Conclusion

This chapter introduced the problem context, defined the research problem and objectives, and outlined the proposed system concept. The next chapter reviews relevant literature on Digital Product Passports, distributed ledger technologies and multi-agent systems, and develops a conceptual framework that guides the system design.

CHAPTER TWO: LITERATURE REVIEW

2.0 Introduction

This chapter comprehensively reviews scholarly and policy literature relevant to a decentralized multi-agent system that uses IOTA and autonomous agents to support ESG compliance and Digital Product Passports (DPPs) for agricultural exports. The review is structured around four themes aligned with the project problem: (i) DPPs and sustainable supply chain management, (ii) distributed ledger technologies especially IOTA in agrifood traceability, (iii) autonomous and multi-agent systems for supply chains and ESG, and (iv) identified gaps that justify the proposed framework. The chapter concludes with a conceptual framework that synthesizes insights from the literature and directly informs the subsequent system design.

2.1 Related literature review

2.1.1 Digital Product Passports and Sustainable Supply Chains

Digital Product Passports have been introduced in EU policy as digital records that accompany products along their life cycle, containing standardized information on origin, material composition, environmental performance and circularity attributes (European Commission, 2020, 2022). Structured reviews show that DPPs are expected to serve multiple functions, including enabling traceability, demonstrating regulatory compliance, supporting circular business models and improving information for downstream users (Heeß et al., 2024; Lazarevic et al., 2024). Heeß et al. (2024) identify key design dimensions such as data scope, granularity, governance and interoperability that determine whether DPP systems can effectively enhance trust in global supply chains.

Lazarevic et al. (2024) further argue that DPPs should move beyond static manufacturing data to incorporate dynamic use-phase and end-of-use information, which is crucial for meaningful circularity assessments. Sector-specific analyses, such as the European Parliament's study on DPPs for the textile sector, demonstrate how DPPs can be operationalized through technical architectures, data models and governance arrangements tailored to particular industries (European Parliament, 2024). For food and agricultural products, emerging work suggests that DPPs can integrate analytical indicators (e.g., quality and safety parameters) and origin data to strengthen authenticity and reduce fraud, particularly in high-value or geographically indicated categories (Vlachos et al., 2024). However, most DPP literature remains conceptual or focused on EU manufacturing sectors, with limited attention to agrifood exports from low- and middle-income countries

Table 2.1: Selected Digital Product Passport Literature and Contributions

Author(s), Year	**Focus Area**	**Key Contribution**
Heeß et al., 2024	DPPs for sustainable/circular supply chains	Structured review of DPP use cases and value propositions
European Commission, 2020	Circular Economy Action Plan	Policy context and strategic objectives for DPP adoption
European Commission, 2022	ESPR proposal	Legal proposal defining DPP requirements and scope
European Parliament, 2024	DPP in textile sector	Sector-specific DPP data model and governance insights

2.1.2 Distributed Ledger Technologies and IOTA in Agrifood Traceability

Distributed ledger technologies are widely proposed as infrastructural supports for reliable, tamper-evident traceability in supply chains, including agriculture. Reviews of IoT-blockchain integration in agrifood systems conclude that combining sensor networks with ledgers can improve data integrity, transparency and trust among dispersed actors, but they also highlight constraints related to scalability, transaction fees and interoperability when conventional blockchains are used (Kechagias et al., 2025; Zhao et al., 2025). These limitations become particularly salient in IoT-intensive scenarios that generate high-frequency, low-value data, such as continuous monitoring of environmental and logistics conditions.

To address these constraints, DAG-based DLTs such as the IOTA Tangle have been investigated for smart agriculture and logistics. A comparative study by Monrat et al. (2025) finds that DAG-based approaches can offer higher throughput and feeless transactions, making them more suitable than traditional blockchains for granular IoT data in smart agriculture. Piantadosi et al. (2024) present a proof-of-concept that integrates IOTA's Tangle with IoT sensors in sustainable rice cultivation, demonstrating that the Tangle can securely anchor continuous agronomic data while supporting efficient visualization and decision support. Similarly, Rodríguez et al. (2025) design an IoT node for monitoring live plants in maritime transport, using IOTA to store sensor readings and ensure tamper-proof traceability of conditions throughout the journey. Applications in other sectors, such as mining, confirm that IOTA-based ledgers can support end-to-end traceability of materials and environmental parameters across complex value chains (Stăncescu et al., 2024). Nevertheless, these studies primarily evaluate technical feasibility and do not fully embed regulatory or DPP-specific compliance logic.

Table 2.2: Selected DLT/IOTA Applications in Agrifood Traceability

Author(s), Year	**Technology**	**Domain / Use Case**	**Relevance to This Study**
Piantadosi et al., 2024	IOTA (DAG)	Rice cultivation traceability	Demonstrates IOTA feasibility for sustainable agriculture
Rodríguez et al., 2025	IOTA + IoT	Live plant maritime transport monitoring	Shows IOTA use for cold-chain and transport traceability
Ferrández-Pastor et al., 2022	Blockchain + IoT	General agrifood traceability	Illustrates hybrid IoT–DLT architectures
Monrat et al., 2025	Blockchain vs DAG	Smart agriculture traceability comparison	Compares blockchain and DAG for performance and scalability

2.1.3 Autonomous and Multi-Agent Systems in Supply Chains and ESG

Multi-agent systems and autonomous supply chains are gaining prominence as approaches to managing complexity and uncertainty in modern logistics networks. Cano et al. (2025) propose a multi-agent system architecture in which autonomous agents represent supply-chain entities and collaboratively make decisions on ordering, routing and disruption management, showing that such systems can enhance responsiveness and resilience. Their work demonstrates how agent communication protocols and shared state information can support decentralized decision-making without centralized control.

Beyond logistics, “agentic AI” approaches are increasingly explored for continuous ESG monitoring and reporting. Industry and early academic contributions argue that autonomous agents can aggregate ESG-relevant data from IoT sensors and enterprise systems, standardize this information according to reporting frameworks and generate near real-time analytics for compliance and risk management (Alternates AI, 2025; Nayak et al., 2025). Kouhizadeh et al. (2023) outline a research agenda on autonomous supply chains and sustainability, noting both the potential of agents to support complex decision-making and the need for robust governance mechanisms to address risks such as opacity, data quality issues and unintended behaviors. To date, however, most multi-agent implementations focus on operational efficiency rather than formal regulatory compliance or DPP issuance.

Table 2.3: Selected Multi-Agent System Studies in Supply Chains

Author(s), Year	**Application Focus**	**MAS Role**	**ESG/DPP Focus?**
Cano et al., 2025	Autonomous supply chain coordination	Agents for planning and execution	Limited
Kouhizadeh et al., 2023	Autonomous supply chains & sustainability	Conceptual agenda for autonomous, sustainable SCs	High-level only
Other MAS paper(s) you cite	Inventory/logistics optimization	Agents for negotiation/coordination	None or limited

2.1.4 ESG Regulations, DPPs and Agrifood Supply Chains

ESG regulations are tightening globally, with the EU’s Corporate Sustainability Reporting Directive, Deforestation Regulation and related policies imposing more stringent due-diligence and disclosure requirements on supply chains (Log-Hub, 2025; Resilinc, 2025). For agrifood exports, this often translates into demands for geolocation-based proof of origin, evidence of deforestation-free production, documentation of pesticide use and broader environmental performance indicators (Kechagias et al., 2025; Zhao et al., 2025). Within this context, DPPs are increasingly framed as tools for consolidating and communicating ESG-relevant information along supply chains, thereby supporting both regulatory compliance and market differentiation (Heeß et al., 2024; Gieß et al., 2025).

At the same time, work focusing on African agrifood supply chains reveals structural challenges that complicate compliance with such regimes. Nyalala et al. (2024) review blockchain and IoT applications in African agricultural food chains and find that while pilot projects demonstrate technical feasibility, they are often constrained by fragmented data systems, limited digital infrastructure and capacity constraints among smallholders and cooperatives. As a result, there is a risk that sophisticated ESG and DPP requirements designed in the EU may disproportionately burden exporters in the Global South unless enabling digital infrastructures are co-developed (Nyalala et al., 2024; Kechagias et al., 2025).

2.2 Summary of Gaps and Research Justification

The literature reviewed in this chapter reveals several gaps that motivate the present study.

- Digital Product Passport implementation gap: Existing DPP research and policy documents provide detailed concepts, objectives and high-level architectures, but there is limited evidence of practical DPP implementations for smallholder-dominated agrifood exports from developing countries, particularly in the Kenyan context (Heeß et al., 2024; European Parliament, 2024).
- DLT and IOTA gap in ESG compliance: Many studies explore blockchain-based traceability in agrifood supply chains, but there are comparatively few applications of DAG-based distributed ledgers such as IOTA for ESG-oriented compliance and DPP generation, despite their advantages for high-frequency IoT data and feeless transactions (Piantadosi et al., 2024; Monrat et al., 2025).
- Multi-agent system gap in ESG and DPPs: Research on autonomous and multi-agent systems in supply chains focuses mainly on logistics optimization and coordination, with limited emphasis on formal ESG compliance auditing and digital passport issuance as primary objectives (Cano et al., 2025; Kouhizadeh et al., 2023).
- Integration gap across domains: There is a lack of integrated architectures that combine DPP concepts, IoT-enabled ESG data collection, DAG-based DLT for tamper-evident anchoring and multi-agent decision-making into a single system tailored to the needs and constraints of Kenyan agricultural exporters (Kechagias et al., 2025; Nyalala et al., 2024).

This project addresses these gaps by designing and evaluating a decentralized multi-agent system that leverages IOTA for immutable anchoring of ESG and logistics data and autonomous agents for real-time compliance auditing and DPP generation for Kenyan tea, coffee and avocado exports.

2.3 Conceptual Framework

The conceptual framework derived from the literature links four main constructs: regulatory/DPP requirements, IoT-enabled data collection, DAG-based distributed ledger infrastructure and decentralized multi-agent compliance and passport issuance.

At the top level, ESG regulations and EU DPP requirements define what information must be captured, how it must be structured and what conditions must be satisfied for a consignment to be considered compliant

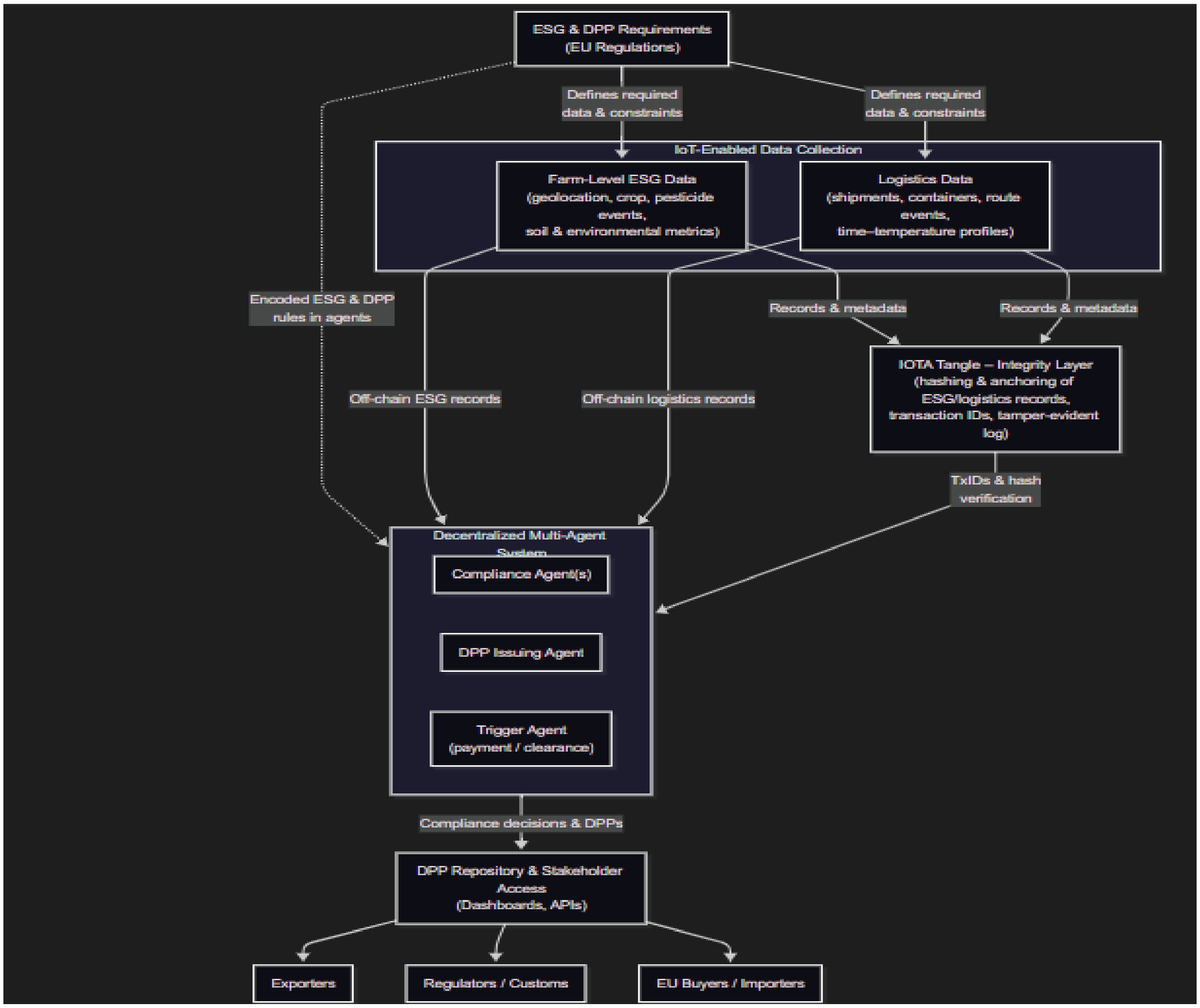
(European Commission, 2022; Heeß et al., 2024). These requirements are operationalized as formal rule sets that specify necessary data elements (e.g., geolocation, pesticide use records, environmental indicators) and threshold conditions.

At the data layer, IoT devices deployed on farms and along logistics routes collect primary data relevant to these rules, such as soil parameters, pesticide application events, GPS coordinates for deforestation checks and cold-chain temperatures (Kechagias et al., 2025; Zhao et al., 2025). These data are pre-processed and transmitted to the integrity layer.

The integrity layer is implemented using the IOTA Tangle, which anchors cryptographic hashes of ESG-relevant data and, where appropriate, selected payloads, thereby providing tamper-evident, time-stamped records resilient to unilateral manipulation (Monrat et al., 2025; Piantadosi et al., 2024). Off-chain storage mechanisms retain full data payloads, but the ledger serves as an immutable index and verification backbone.

On top of this, a decentralized multi-agent system operates as the decision and orchestration layer. Autonomous agents representing farms, cooperatives, exporters, logistics providers and regulators access anchored and off-chain data, interpret them through the encoded ESG and DPP rules, and determine the compliance status of individual consignments (Cano et al., 2025; Kouhizadeh et al., 2023). When all requirements are met, a passport-issuing agent generates a DPP for the consignment modeled as a unique digital identifier or token that references the underlying ledger evidence and can be presented to EU for customs and buyers. Smart-contract-based mechanisms can be linked to the passport, enabling conditional payment release, financing or customs clearance once passport validity is verified (Monrat et al., 2025; Zhao et al., 2025). This framework provides the conceptual basis for the system architecture detailed in later chapters.

Figure 2.1: Conceptual Framework for IOTA-Enabled Multi-Agent DPP System



2.4 Conclusion

This chapter has reviewed key strands of literature on Digital Product Passports, distributed ledger technologies particularly IOTA in agrifood traceability, and autonomous multi-agent systems for supply chains and ESG. The review shows that DPPs are evolving as central tools for implementing EU circular economy and ESG policies, but practical implementations in agrifood exports from developing regions remain rare (Heeß et al., 2024; European Parliament, 2024). At the same time, DAG-based DLTs such as IOTA have demonstrated technical advantages for IoT-intensive traceability applications, yet their integration with regulatory logic and DPP generation has not been fully realized (Piantadosi et al., 2024; Rodríguez et al., 2025).

The literature on autonomous and multi-agent supply chains indicates significant potential for decentralized decision-making and continuous monitoring, but has so far largely neglected formal ESG compliance and digital passport issuance as primary objectives (Cano et al., 2025; Kouhizadeh et al., 2023). Collectively, these gaps justify the proposed project: a decentralized multi-agent system that leverages IOTA for immutable ESG data anchoring and autonomous agents for real-time compliance auditing and DPP generation tailored to Kenyan tea, coffee and avocado exports. The conceptual framework articulated in this chapter will guide the methodological choices and system design presented in the subsequent chapters.

CHAPTER THREE: METHODOLOGY

3.0 Introduction

This chapter presents the methodology used to design, implement and evaluate the decentralized multi-agent system for autonomous ESG compliance and Digital Product Passports (DPPs) in Kenyan agricultural export supply chains. The project is primarily artifact-oriented: its central contribution is a working prototype that integrates IoT-like data streams, a DAG-based distributed ledger (IOTA) and autonomous software agents to address a documented compliance and traceability gap under emerging EU regulatory requirements (European Commission, 2020, 2022; Heeß et al., 2024). In such contexts, where the aim is to create and assess an innovative information system rather than merely describe existing practices, design science research offers a suitable methodological foundation because it explicitly focuses on the systematic construction and rigorous evaluation of IT artifacts that solve real-world problems (Hevner et al., 2004; Peffers et al., 2007).

Building on this foundation, the chapter adopts the Design Science Research Methodology (DSRM) as the overarching research process and complements it with an iterative, incremental software development approach tailored to emerging technologies (Peffers et al., 2007; Wang et al., 2021). The subsequent sections describe how the development methodology is operationalized, justify the choice of methods, and detail the data collection and evaluation strategies used to configure and assess the system. Particular attention is given to the derivation of ESG and DPP rules from regulatory and scholarly sources, the generation of synthetic ESG and logistics datasets for testing and demonstration, and the combination of functional testing, scenario-based demonstrations and basic non-functional assessment to evaluate the artifact’s performance against its objectives.

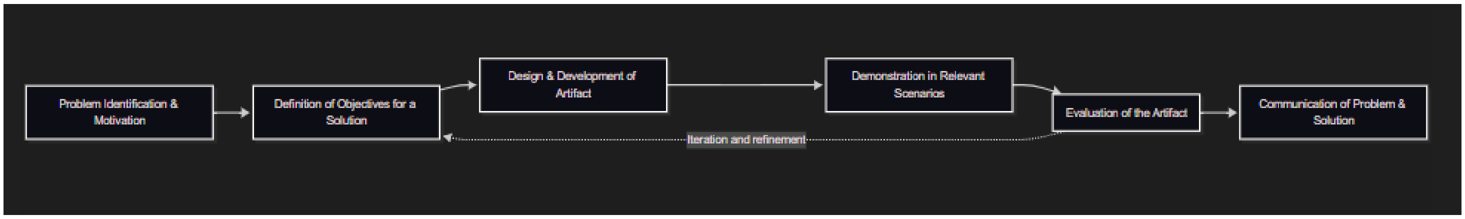
3.1 Development Methodology

3.1.1 Design Science Research Methodology

Design science research focuses on creating and rigorously evaluating innovative IT artifacts such as models, methods, and software systems that address relevant organizational or societal problems (Hevner et al., 2004). In information systems, it complements behavioral research by emphasizing the utility of artifacts, that is, whether they effectively solve the targeted problem, while still maintaining rigor in their construction and evaluation (Hevner et al., 2004; Okoli, 2010). This study fits the design science paradigm because it seeks to design and evaluate a decentralized architecture that uses IOTA and autonomous agents to reduce the ESG compliance and traceability gap identified in earlier chapters.

To structure the research, the study follows the Design Science Research Methodology (DSRM) developed by Peffers et al. (2007). DSRM specifies a six-step nominal process: (1) problem identification and motivation, (2) definition of objectives for a solution, (3) design and development of the artifact, (4) demonstration of the artifact in relevant scenarios, (5) evaluation of the artifact, and (6) communication of the problem and its solution (Peffers et al., 2007; Peffers et al., 2020). In this project, the problem and solution objectives are established in Chapters One and Two using regulatory and academic literature on DPPs, distributed ledgers and multi-agent systems. Chapter Three addressed steps three to five by describing how the architecture is designed and implemented with IOTA and autonomous agents, and how it is demonstrated and evaluated using realistic agrifood scenarios, while the dissertation as a whole fulfills the communication step.

Figure 3.1: Design Science Research Methodology Applied in the Study



3.1.2 Interactive and Incremental Software Development Process

Within the DSRM framework, an iterative and incremental software development approach is adopted to implement the system’s components. Iterative methods are recommended for complex information systems that combine emerging technologies, because they support early prototyping, learning and progressive refinement of requirements and designs (Rivera, 2013; Wang et al., 2021). In this project, development is organized into three main increments:

- Increment 1: Implementation of the IOTA-based data anchoring and retrieval layer, including data ingestion interfaces and hashing mechanisms.
- Increment 2: Development of core autonomous agents responsible for ESG rule evaluation and DPP issuance.
- Increment 3: Integration of an end-to-end workflow, including a simple smart-contract-like mechanism for conditional payment or clearance triggers.

Each increment follows a mini-cycle of requirement refinement, high-level and low-level design, implementation, unit testing and integration testing. This structure is consistent with prior blockchain- and DLT-enabled supply chain projects, where iterative prototyping is used to balance technical feasibility, performance and stakeholder requirements (Babaei et al., 2023; Wang et al., 2021). By adopting this incremental approach, each core subsystem the IOTA anchoring layer, the agent layer and the overall workflow can be validated and refined before additional complexity is introduced, reducing the risk of late-stage architectural flaws and aligning with design science guidance that emphasizes cycles of building and evaluation in realistic contexts (Hevner et al., 2004; Peffers et al., 2007).

3.2 Justification of Methodology

3.2.1 Rationale for Design Science in Information Systems

Design science is widely accepted as an appropriate paradigm when the primary contribution of a study is an artifact that addresses a complex real-world problem (Hevner et al., 2004; Gregor & Hevner, 2013). The compliance gap created by EU DPP and ESG requirements, combined with fragmented digital infrastructures in agricultural export chains, exhibits features such as evolving requirements, multiple stakeholders and tightly coupled technical and regulatory constraints that design science is particularly suited to address (Hevner et al., 2004).

Peffers et al. (2007) argue that DSRM provides both a process for conducting design science research and a mental model for presenting it, which supports transparency and comparability across projects. Applying DSRM in this study clarifies how insights from the literature are translated into solution objectives, how these objectives drive architectural and implementation choices, and how evaluation results feed back into design. This level of methodological clarity is important for subsequent researchers who may seek to replicate or extend the work in other sectors or jurisdictions.

3.2.2 Suitability of Iterative Development for Emerging Technologies

The integration of IoT-like data streams, a DAG-based ledger and a decentralized multi-agent system introduces technical and design uncertainties that are difficult to resolve with a single, linear development cycle. Literature on blockchain-enabled and blockchain-inspired supply chain systems shows that iterative development and evaluation cycles are commonly used to refine requirements, test performance and adjust design choices in response to empirical findings (Wang et al., 2021; Kumar et al., 2023). Rivera (2013) similarly advocates iterative approaches for projects in emerging domains, emphasizing that such methods allow a minimum viable artifact to be delivered early and improved as understanding deepens.

In this project, the incremental structure ensures that foundational capabilities such as secure data anchoring on IOTA and correct rule evaluation by autonomous agents are established and tested before additional features, such as smart-contract-like payment triggers, are introduced. This staged approach reduces implementation risk and supports a clear mapping between design decisions and observed behaviour, in line with design science recommendations that artifacts be developed and refined through iterative cycles of building and evaluation in realistic or realistic-enough contexts (Hevner et al., 2004; Peffers et al., 2007)..

3.3 Data Collection

Although the primary output of this study is a software artifact, data are essential for configuring the compliance logic and for demonstrating and evaluating system behaviour. Data collection therefore covers two main categories: (i) regulatory and scholarly documentary sources used to derive ESG and DPP rules and design constraints, and (ii) synthetic and simulated operational data used as input to the prototype for testing and demonstration.

3.3.1 Regulatory and Scholarly Documentary Sources

Regulatory texts and policy analyses provide the primary basis for the ESG and DPP rule sets encoded in the autonomous agents. EU documents such as the Circular Economy Action Plan and the proposal for the Ecodesign for Sustainable Products Regulation articulate the overarching objectives and structural requirements of DPPs, including expected data categories, transparency goals and traceability expectations (European Commission, 2020, 2022). The European Parliament's study on digital product passports for the textile sector further illustrates how passport data models, governance structures and implementation options can be specified at sectoral level, offering transferable design insights for other value chains (European Parliament, 2024).

Scholarly work on DPPs and their value ecosystems identifies common data elements, lifecycle stages and governance challenges, which informs the design of data schemas and rule sets in the prototype (Heeß et al., 2024; Gieß et al., 2025). Literature on agrifood IoT and traceability is used to determine which ESG-relevant variables should be represented in the system, such as farm geolocation for deforestation checks, pesticide application records, soil and environmental conditions, and logistics parameters including time–temperature profiles (Kechagias et al., 2025; Zhao et al., 2025; Nyalala et al., 2024). These documentary sources are reviewed and synthesized to produce a set of implementable rules and data attributes that approximate regulatory expectations while remaining tractable for a prototype system. The resulting rules may, for example, require that each consignment be linked to farm geocoordinates, that pesticide events remain within defined thresholds, or that temperature readings stay within acceptable ranges throughout transport, without attempting to reproduce full legal texts verbatim.

3.3.2 Synthetic and Simulated ESG Data

Access to comprehensive, real-world ESG and logistics datasets from Kenyan exporters is constrained by confidentiality, heterogeneity and time limitations. For this reason, the study uses synthetic and simulated data streams for demonstration and evaluation, an approach commonly adopted in design science and supply chain technology research when real data are difficult to obtain or share (Babaei et al., 2023; Nyalala et al., 2024).

Synthetic datasets are generated to represent three main categories of information. First, farm-level ESG data include farm and cooperative identifiers, crop types (tea, coffee, avocado), geocoordinates, soil parameters and time-stamped pesticide application events, with parameter ranges and basic correlations informed by agrifood and environmental studies on traceability and sustainable agriculture (Kechagias et al., 2025; Piantadosi et al., 2024). Second, logistics data include shipment IDs, container identifiers, route segments, port or checkpoint events and time-temperature profiles for cold-chain monitoring, reflecting data structures proposed in IoT-based plant transport and traceability solutions (Rodríguez et al., 2025; Zhao et al., 2025). Third, compliance labels and thresholds are defined to distinguish rule-consistent examples (for instance, pesticide use within an acceptable range and non-deforestation geolocation) from rule-violating examples (such as missing coordinates or excessive pesticide events), providing “ground truth” for unit tests and scenario-based evaluations.

Data generation scripts and configuration files are designed so they can be re-used and adapted in future work, supporting reproducibility and extension. Parameter choices are documented and linked back to the relevant literature wherever possible, ensuring that the simulated datasets reasonably reflect expected conditions in export-oriented agricultural supply chains while avoiding the use of confidential or proprietary information.

3.4 Data Analysis and System Evaluation

In design science research, data analysis focuses on evaluating the artifact against the objectives defined during problem formulation rather than on drawing statistical inferences about populations (Hevner et al., 2004; Peffers et al., 2007). In this study, the evaluation strategy examines whether the developed system satisfies its design goals of secure ESG data anchoring, correct compliance decision making and consistent Digital Product Passport (DPP) issuance. To achieve this, the evaluation combines design-science-oriented assessment, functional testing, scenario-based demonstration and basic non-functional analysis.

3.4.1 Evaluation in Design Science

Evaluation in design science is concerned with determining how well an artifact meets the objectives derived from the problem context and the literature, using methods appropriate to the artifact type and application domain (Hevner et al., 2004; Peffers et al., 2007). For the proposed system, evaluation focuses on whether the architecture and implementation:

- Correctly anchor and retrieve ESG-related data using the IOTA-based layer.
- Correctly apply the encoded compliance rules within the autonomous agents and produce appropriate decisions.
- Consistently support the generation or rejection of DPPs based on those decisions.

To address these questions, the evaluation strategy integrates systematic functional testing, scenario-based demonstrations and a limited non-functional assessment. Together, these methods provide a qualitative and technical assessment of how well the artifact fulfils its intended role in supporting ESG compliance and traceability

3.4.2 Functional Testing of Components

Functional testing verifies that individual components and the integrated workflow behave according to their specifications. For the IOTA-based layer, tests confirm that input data items are correctly hashed and that the resulting hashes are properly linked to Tangle transactions so that each ESG or logistics record has an immutable reference. In addition, transaction references are used to recompute hashes and compare them with the values stored on the ledger, ensuring that any subsequent modification of the underlying data would be detectable through a hash mismatch (Piantadosi et al., 2024; Rodríguez et al., 2025).

For the autonomous agents, unit tests supply controlled ESG and logistics input data and verify that rule evaluation and resulting decisions match expectations. For example, if a test dataset includes pesticide use above the configured threshold or missing mandatory geolocation attributes, the agent should classify the consignment as non-compliant and refrain from issuing a DPP, whereas compliant input patterns should lead to a positive decision and passport generation. Integration tests then validate the complete pipeline: synthetic ESG and logistics data are generated, anchored on IOTA, retrieved by agents, evaluated against the rule set and translated into DPP issuance or rejection. This functional evaluation approach is consistent with prior blockchain and DLT-enabled supply chain design studies, where the central question is whether the digital infrastructure reliably implements the intended business logic (Wang et al., 2021; Kumar et al., 2023).

3.4.3 Scenario-Based Demonstration

Beyond component testing, scenario-based demonstration is used to evaluate the artifact under realistic usage conditions, in line with design science guidance that emphasizes demonstration in relevant scenarios as a core element of evaluation (Hevner et al., 2004; Peffers et al., 2007). In this project, a set of representative scenarios is defined, each specifying the input ESG and logistics data, the expected compliance interpretation and the corresponding DPP outcome.

Illustrative scenarios include:

- Scenario A: A consignment with complete ESG and logistics data where all parameters (such as farm geolocation, pesticide application records and cold-chain temperature profiles) fall within acceptable ranges, leading to a compliant decision and successful DPP issuance.
- Scenario B: A consignment with missing or inconsistent critical attributes, for example incomplete geolocation or pesticide records, resulting in a non-compliant decision and no DPP being generated.
- Scenario C: A consignment with acceptable farm-level data but a cold-chain failure or similar logistics anomaly during transport, causing the system to classify the shipment as non-compliant and withhold the DPP.

For each scenario, the system's actual behaviour is recorded and compared with predefined expected outcomes derived from the encoded rule set and criteria informed by literature on DPPs and traceability. Deviations between expected and observed behaviour are analysed and, where necessary, used to refine the compliance rules or implementation logic. This qualitative evaluation provides evidence that the artifact behaves as intended under realistic conditions and offers insight into its practical usefulness for stakeholders concerned with ESG compliance and end-to-end traceability (Hevner et al., 2004; Peffers et al., 2007; Babaei et al., 2023).

3.4.4 Basic Non-Functional Assessment

Comprehensive performance and security evaluations are beyond the scope of this study; however, basic non-functional properties are examined to verify technical plausibility. In line with prior DLT-enabled supply chain research, simple measurements are taken of approximate latency for anchoring data to the IOTA network and retrieving verification references, as well as system behaviour under moderate increases in data volume to observe whether processing remains stable (Monrat et al., 2025; Kumar et al., 2023). Additionally, data integrity tests attempt to modify historical records and confirm that such modifications are detectable because the corresponding hashes no longer match the values recorded on the ledger. These checks illustrate the tamper-evident properties of the IOTA-based design, which is a critical requirement for trustworthy ESG reporting and auditable Digital Product Passports.

3.5 Conclusion

This chapter has set out the methodological framework underpinning the design, implementation and evaluation of a decentralized multi-agent system for ESG-compliant Digital Product Passports in Kenyan agricultural export supply chains. The study adopts design science research as its overarching paradigm, following theDSRM process to move from problem identification and objective definition to artifact design, demonstration and evaluation in a structured and transparent manner (Hevner et al., 2004; Peffers et al., 2007). Within this framework, an iterative and incremental software development approach is employed to implement the IOTA-based anchoring layer, the autonomous compliance agents and the integrated workflow, reflecting best practices in blockchain and DLT-enabled supply chain systems where requirements and technologies co-evolve (Wang et al., 2021; Kumar et al., 2023).

Data collection combines regulatory and scholarly documentary sources to derive realistic ESG and DPP rule sets with synthetic and simulated ESG and logistics data streams that exercise the system under plausible conditions, consistent with approaches used when real-world data are sensitive or difficult to obtain (Babaei et al., 2023; Nyalala et al., 2024). Evaluation integrates design science-oriented assessment, functional testing of components and end-to-end pipelines, scenario-based demonstrations in representative export situations, and basic non-functional checks on latency and data integrity (Piantadosi et al., 2024; Monrat et al., 2025). Together, these methodological choices provide a rigorous and reproducible basis for judging whether the artifact meets its design objectives and for informing future extensions or adaptations. The next chapter builds on this methodological foundation to present the detailed system design, including architectural diagrams, data models and component specifications.

Table 3.1: Mapping of Research Objectives to Evaluation Methods

Objective	**Evaluation Method(s)**	**Evidence Generated**
Architecture for IOTA-based ESG anchoring	Integration tests; scenario-based runs	Successful end-to-end data flow; hashes anchored and retrievable
Autonomous agents for real-time compliance auditing	Unit tests of rule evaluation; scenarios	Correct compliant / non-compliant classifications; decision logs
Mechanism for DPP-compatible passport generation	System tests; scenario outputs	DPP records generated only for compliant consignments

Prototype trigger mechanism linked to DPP status	Integration tests of trigger workflows	Trigger events fired when DPP is valid; no triggers otherwise

This mapping ensures that each objective is explicitly linked to one or more evaluation techniques and observable outcomes

CHAPTER FOUR: SYSTEM ANALYSIS, DESIGN AND IMPLEMENTATION

4.0 Introduction

This chapter presents the analysis, design and high-level implementation blueprint for the decentralized multi-agent system that supports ESG-compliant Digital Product Passports (DPPs) for Kenyan agricultural exports. Building on the conceptual framework in Chapter Two and the design science methodology in Chapter Three, the chapter translates the abstract constructs regulatory/DPP requirements, IoT-enabled data collection, DAG-based distributed ledger, and multi-agent compliance and passport issuance into a concrete technical architecture, data structures, user interfaces and process flows (Kechagias et al., 2025; Piantadosi et al., 2024). The design is informed by existing traceability architectures that combine distributed ledgers with conventional databases and interfaces, as well as by multi-agent system patterns used in supply chain management (Li et al., 2024; Fierro et al., 2020).

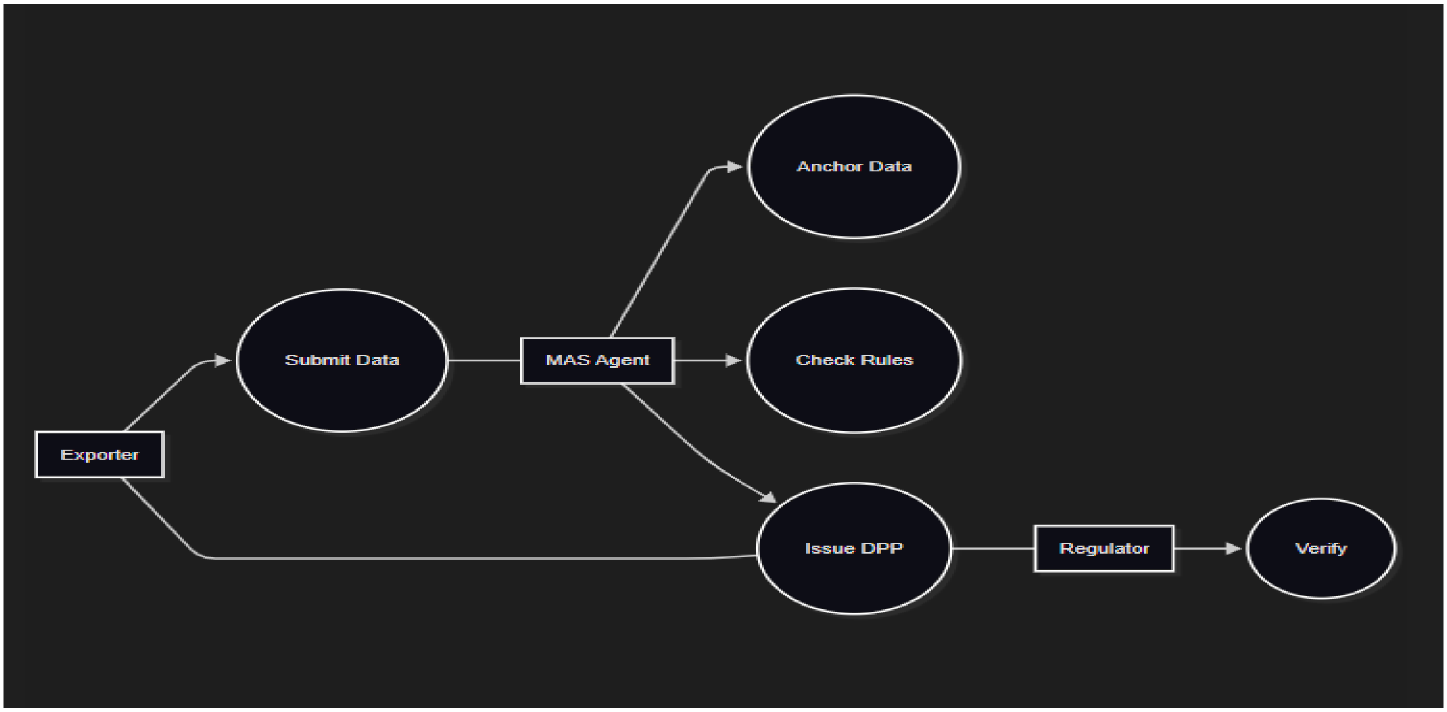
4.1 Requirements

4.1.1 Functional Requirements

The functional requirements specify what the system must do to address the ESG compliance and DPP generation needs identified in earlier chapters. Drawing on literature on agrifood traceability systems, DLT-based architectures and multi-agent supply chain management, the following core functional requirements are defined (Kechagias et al., 2025; Li et al., 2024; Ferrández-Pastor et al., 2022).

1. Multi-Source Data Ingestion: The system captured ESG-relevant farm-level data and logistics data from exporters and logistics providers.
2. Data validation and preprocessing: The system validated input data for completeness and format.
3. Data anchoring on IOTA: The system hashed ESG and logistics records and anchored the hashes onto the IOTA Tangle.
4. Off-chain data storage: The system stored full ESG and logistics payloads in an off-chain database.
5. Autonomous compliance evaluation: Specialized agents autonomously retrieved relevant ESG and logistics data.
6. DPP generation and management: For compliant consignments, the system generated a DPP represented as a unique digital identifier.
7. Access and verification: The system provided interfaces and APIs that allowed stakeholders to retrieve DPPs.
8. Logging and audit: The system maintained logs of agent decisions and rule evaluations.

Figure 4.1 *Use case diagram for core system functions.*



4.1.2 Non-Functional Requirements

Non-functional requirements define the quality attributes necessary for the system to be usable and trustworthy in practice. Based on prior work on DLT-enabled traceability and multi-agent supply chains, the following non-functional requirements are prioritized (Monrat et al., 2025; Kechagias et al., 2025; Fierro et al., 2020).

1. Security and integrity:
    a. The system shall ensure tamper-evident storage of ESG and logistics data by anchoring hashes on the IOTA Tangle and preventing unauthorized modification of off-chain records.
    b. Access to system functions (data ingestion, rule configuration, DPP retrieval) shall be controlled through authentication and role-based authorization.
2. Performance and responsiveness:
    a. The system shall anchor and verify data on IOTA within a latency that is acceptable for operational use in export processes, drawing on latency benchmarks reported for IOTA-based supply chain applications (Piantadosi et al., 2024; ScyllaDB & IOTA, 2023).
3. Scalability:

    a. The system shall be able to handle increasing numbers of farms, consignments and data events without significant degradation, leveraging IOTA's feeless and scalable DAG-based architecture and a horizontally scalable off-chain database (Monrat et al., 2025; Li et al., 2024).

4. Reliability and fault tolerance:
    a. The system shall degrade gracefully if the IOTA network or off-chain database becomes temporarily unavailable, for example by queuing data to be anchored later and preserving local logs.
5. Interoperability and extensibility:
    a. Data models shall be designed with interoperability in mind, aligning where possible with established standards for supply chain event data (e.g., EPCIS-style event structures), to allow future integration with external platforms (Kechagias et al., 2025; ScyllaDB & IOTA, 2023).
6. Usability:
    a. User interfaces for exporters and regulators shall be simple enough to support basic data entry, DPP viewing and status monitoring without requiring deep technical knowledge of DLT or multi-agent systems.

Table 4.1: *Summary of Functional and Non-functional Requirements*

Category	ID	Requirement	Description
Functional	**FR-01**	**Data Anchoring**	The system must generate SHA-256 hashes of ESG data and secure them on the IOTA Tangle.
	FR-02	**Compliance Evaluation**	Autonomous agents must evaluate data against EU ESG rule-sets (e.g., pesticide limits).
	FR-03	**DPP Generation**	The system must issue a Digital Product Passport in JSON-LD format for compliant goods.
	FR-04	**Tamper Detection**	The system must invalidate passports if the local data does not match the IOTA anchor.

Non-Functional	**NFR-01**	**Transparency**	All agent decisions must be logged in a human-readable format for audit purposes.
	NFR-02	**Scalability**	The use of off-chain storage (PostgreSQL) must allow for high-frequency data ingestion.
	NFR-03	**Integrity**	The link between the physical product and digital record must be cryptographically verifiable.

4.2 Context level diagram and Overall Architecture

At the highest level, the system is positioned between upstream data producers (farms and cooperatives), mid-stream actors (exporters and logistics providers) and downstream stakeholders (regulators, customs and EU buyers). In line with the conceptual framework, the architecture can be described in four layers: data collection, integrity, decision/agent layer and access/interaction (Kechagias et al., 2025; Piantadosi et al., 2024).

External entities include:

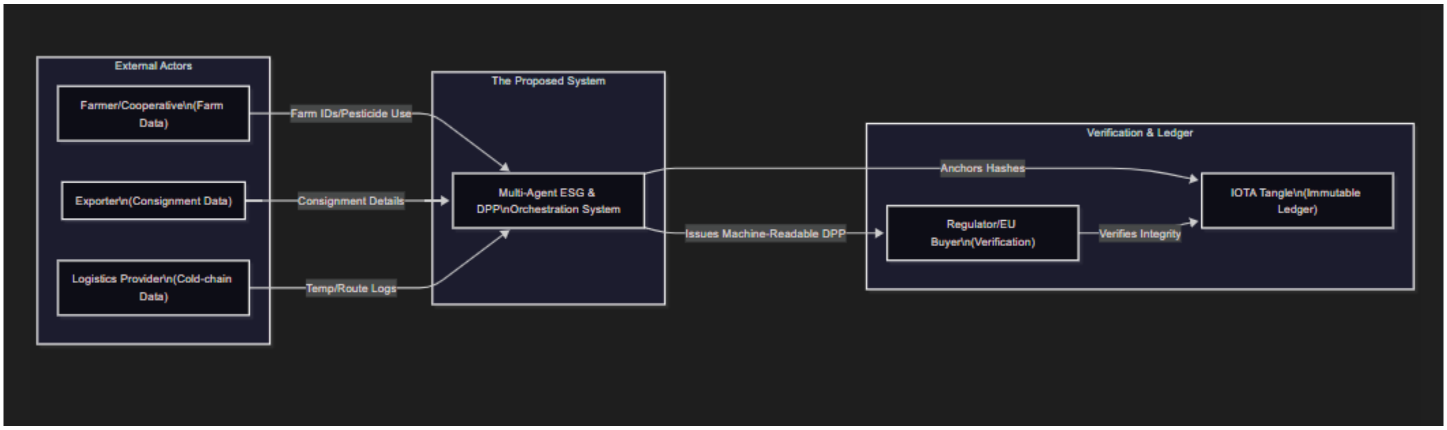
- Farmers and cooperatives: provide primary ESG data (farm identifiers, geolocation, crop information, pesticide use).
- Exporters: compile consignment-level data, link consignments to farms, and initiate DPP requests.
- Logistics providers: supply transport and cold-chain data, including time-temperature profiles and route events.
- Regulators and customs: access DPPs and supporting data for compliance verification.
- EU buyers: consume DPPs and select ESG information for procurement and due-diligence purposes.

The internal components are:

- Data ingestion layer: provides user interfaces and APIs for entering or uploading ESG and logistics data, including validation logic.
- Off-chain database: stores detailed ESG and logistics records, DPPs and agent logs, following hybrid designs where raw traceability data reside off-chain while summary or hash data reside on the ledger (Li et al., 2024; Stăncescu et al., 2024).
- IOTA anchoring service: receives validated data records, computes hashes, submits transactions to the IOTA Tangle and stores transaction references.
- Multi-agent layer: comprises autonomous agents responsible for compliance evaluation, DPP issuance and optional payment/notification triggers, following multi-agent supply chain design principles (Cano et al., 2025; Fierro et al., 2020).

- Access/API layer: exposes DPP and compliance status data to external stakeholders via dashboards and APIs.

Figure 4.2: *Context-level architecture of the ESG compliance and DPP system*



The context-level diagram can thus be conceptualized as the system in the centre, with arrows showing data flows from farms/exporters/logistics providers into the data ingestion and anchoring components, and flows from regulators/buyers querying the access layer for DPPs and verification results.

4.3 Input design (User interface and Data Ingestion)

Input design focuses on how data enter the system and how users interact with it. Consistent with existing agrifood traceability architectures, the system supports both manual and semi-automated inputs (Li et al., 2024; Ferrández-Pastor et al., 2022).

4.3.1 User Interfaces

The main user interfaces are:

- Farm/Cooperative Interface: simple forms for registering farms, updating geolocation data and recording key ESG-related events such as pesticide applications. Fields include farm ID, cooperative ID, coordinates, crop type, pesticide type, quantity, application date and operator.
- Exporter Interface: forms and tables for defining consignments, linking them to farms, and entering batch-level ESG summaries and documents.
- Logistics Interface: forms or CSV/API upload for entering shipment details, container IDs, route segments and time-temperature measurements.
- Regulator/Buyer Interface: read-only dashboards showing consignment status, DPP details, and links to underlying data and IOTA transaction references.

4.3.2 Validation and Preprocessing

Input fields are validated for completeness and correctness, drawing on data quality practices in agrifood traceability (Zhao et al., 2025; Nyalala et al., 2024). Typical checks include:

- Required fields (e.g., farm ID, coordinates, consignment ID) must be present.

- Geolocation values must fall within valid numeric ranges.
- Pesticide application dates must be logically consistent with planting/harvest dates.
- Temperature readings must be numeric and within plausible bounds.

Only validated records are passed to the anchoring and storage layers, reducing the risk of propagating erroneous data into compliance evaluation.

4.4 Process design

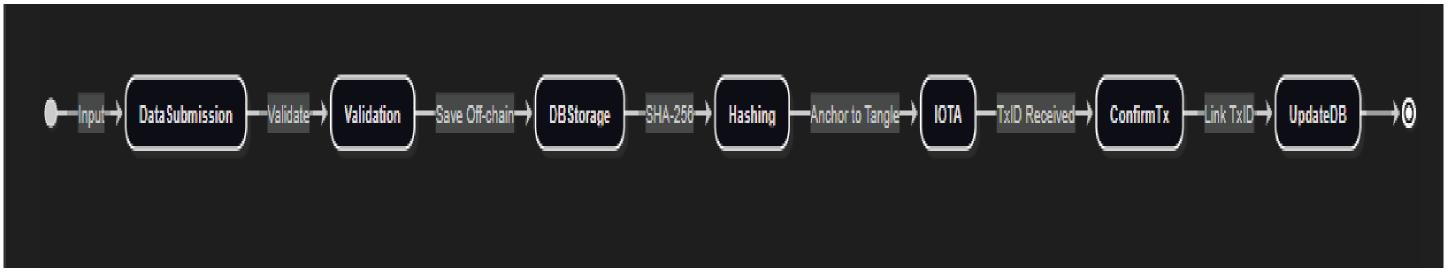
Process design specifies how the system's components cooperate to deliver the required functionality. It is informed by process models used in blockchain and IoT based traceability systems and multi-agent supply chains (Ferrández-Pastor et al., 2022; Fierro et al., 2020).

4.4.1 ESG Data Recording and Anchoring

The "Record and Anchor ESG Data" process proceeds as follows:

1. A farmer or exporter submits ESG data through the input interface.
2. The system validates the data and stores them in the off-chain database.
3. The IOTA anchoring service computes a hash of the record or batch and submits a transaction to the IOTA Tangle.
4. The transaction ID and hash are stored alongside the original record in the database, enabling future integrity checks (Piantadosi et al., 2024; Rodríguez et al., 2025).

Figure 4.3: *Activity Diagram for ESG data recording and IOTA anchoring .*

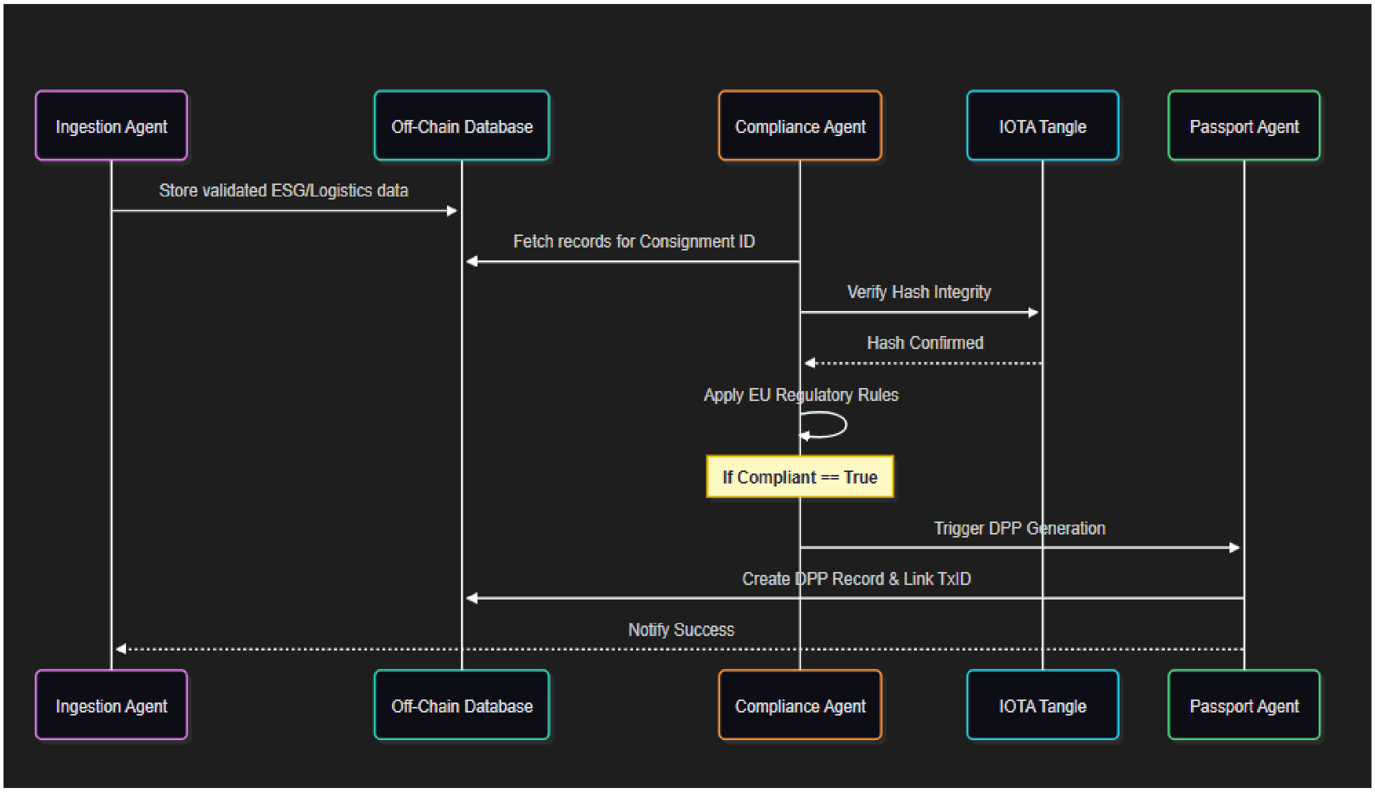


4.4.2 Compliance Evaluation

The "Compliance Evaluation" process, driven by a Compliance Agent, includes:

1. Triggering evaluation when a consignment is marked as ready for export or when new data arrive.
2. Retrieving all relevant ESG and logistics records for the consignment from the database.
3. Optionally verifying hashes against IOTA transaction references for integrity assurance.
4. Applying rule sets derived from ESG and DPP requirements to classify the consignment as compliant or non-compliant (Heeß et al., 2024; Kechagias et al., 2025).
5. Writing the decision and rationale to the AgentLog and updating consignment status.

Figure 4.4: *Sequence Diagram for compliance evaluation and DPP issuance*



4.4.3 DPP Generation and Access

The "DPP Generation" process involves:

1. Detecting a compliant decision for a consignment.
2. Creating a DPP record that includes a unique ID, consignment metadata, key ESG attributes, and references to IOTA transactions and off-chain records.
3. Storing the DPP in the DPP repository and exposing it via the access layer for regulators and buyers.

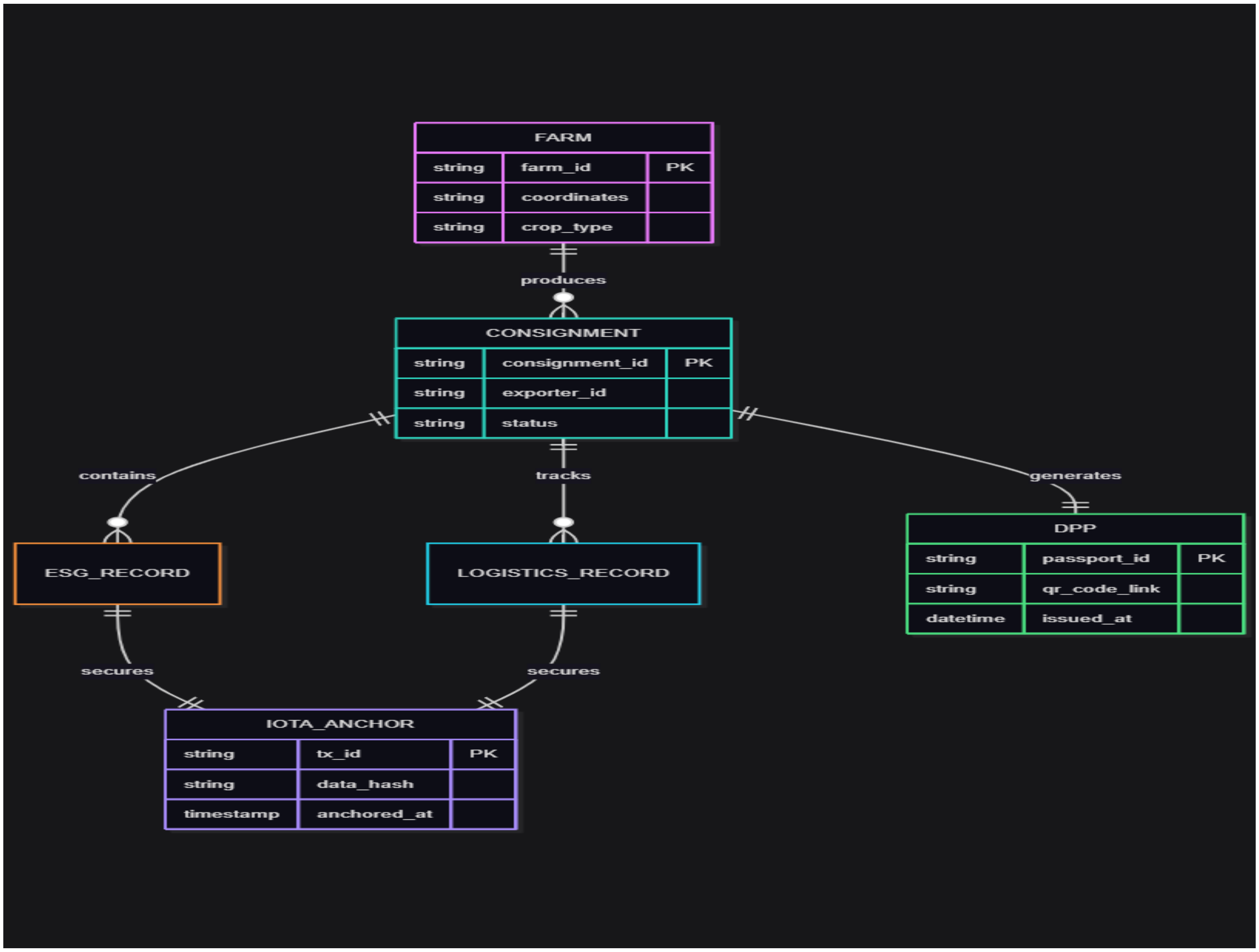
4.4.4 Optional Payment/Notification Trigger

An optional Payment/Trigger Agent can monitor DPP status and, when a valid DPP is confirmed, invoke external APIs or internal workflows to trigger conditional payments or notifications to stakeholders, consistent with emerging designs for DLT-enabled trade processes (ScyllaDB & IOTA, 2023; Vern et al., 2024).

4.5 Database design

Database design determines how off-chain data is structured to support efficient storage, retrieval and analysis. Following approaches in hybrid blockchain database traceability systems, detailed operational data are stored in a relational or NoSQL database while the ledger stores summary hashes and references (Li et al., 2024; Stăncescu et al., 2024).

Figure 4.5: *Entity Relationship (ER) Diagram for the off-chain database*



4.5.1 Main Entities

Key entities include:

- Farm: stores farm ID, cooperative ID, geolocation, crop type and basic profile.
- Consignment: stores consignment ID, exporter ID, destination, associated farms and status.
- ESGRecord: records ESG-related events such as pesticide applications or soil measurements.
- LogisticsRecord: records transport events, including container IDs, route segments and time–temperature readings.
- IOTAAnchor: stores hashes, IOTA transaction IDs and timestamps for anchored records.
- DPP: stores the passport ID, associated consignment ID, key ESG attributes and references to IOTAAnchor entries.
- AgentLog: stores agent decisions, rule evaluations and messages for audit.

4.5.2 Normalization and Off-Chain/On-Chain Split

Entities are normalized to at least third normal form to reduce redundancy and support consistent updates, following patterns in agricultural traceability database design (Li et al., 2024; Ferrández-Pastor et al., 2022). Sensitive or large payloads, such as full sensor streams and detailed ESG attributes, are stored off-chain; only cryptographic hashes and minimal identifiers are stored on IOTA, balancing scalability and integrity.

Table 4.2: *Main Database Entities and Descriptions*

Entity	**Description**	**Key Attributes**
Exporter	The entity responsible for the shipment and primary data provider.	exporter_id, company_name, license_no
Consignment	The specific batch of agricultural produce being tracked for export.	consignment_id, product_type, weight, status
ESG_Record	The environmental, social, and governance metrics associated with a farm/batch.	record_id, pesticide_level, water_usage, timestamp
IOTA_Anchor	The cryptographic proof of data integrity stored on the distributed ledger.	tx_id (Tangle Hash), data_hash, anchored_at
DPP	The Digital Product Passport containing the final compliance certificate and QR link.	passport_id, issue_date, expiry_date, verification_url

4.6 Output design: The Digital Product Passport

Output design specifies how the system presents results to users and external systems, with emphasis on DPPs and compliance status information.

4.6.1 Digital Product Passport Representation

Each DPP is represented as a structured record containing:

- A unique passport identifier.
- Consignment metadata (exporter, product type, origin country, destination).
- Selected ESG attributes (e.g., geolocation summary, pesticide usage summary, key environmental indicators).

- References to underlying IOTA transactions and off-chain records, enabling verification of data integrity and provenance (Heeß et al., 2024; Gieß et al., 2025).

4.6.2 Dashboards and Reports

User-facing outputs include:

- Consignment status dashboard: listing consignments with their compliance status, DPP availability and key indicators.
- DPP detail view: showing full DPP data for a selected consignment and links to underlying records.
- Audit log view: summarizing agent decisions and data integrity checks for internal and external auditors.

These outputs are designed to support regulators and buyers in verifying compliance and to help exporters monitor their ESG performance over time, consistent with the goals of DPP and traceability initiatives (Heeß et al., 2024; Kechagias et al., 2025).

4.7 Conclusion

This chapter has translated the conceptual and methodological foundations of the project into a concrete system analysis and design for a decentralized multi-agent architecture supporting ESG-compliant Digital Product Passports in Kenyan agricultural export supply chains. It defined functional and non-functional requirements, presented a context-level architecture linking external stakeholders to internal components, and detailed the input, process, database and output designs, drawing on established patterns in DLT-based traceability and multi-agent supply chain systems (Li et al., 2024; Ferrández-Pastor et al., 2022; Fierro et al., 2020). The resulting design provides a coherent blueprint for implementation and testing, ensuring that subsequent development can be systematically evaluated against the objectives and quality attributes identified in earlier chapters.

CHAPTER FIVE: TESTING, RESULTS AND DISCUSSION

5.0 Introduction

This chapter presents the implementation and testing of the decentralized multi-agent system for ESG-compliant Digital Product Passports (DPPs) in Kenyan agricultural export supply chains. The aim is to show how the architecture and design specified in Chapter Four were translated into a working prototype and to demonstrate, through systematic testing, that the implemented system satisfies the functional and non-functional requirements derived from the problem statement and literature. In keeping with the design science research methodology adopted in Chapter Three, the chapter emphasizes artifact construction and rigorous evaluation rather than statistical inference, focusing on whether the system behaves in accordance with its stated objectives (Hevner et al., 2004; Peffers et al., 2007).

5.1 Implementation Requirements

The implementation environment was selected to support rapid prototyping of distributed components, interaction with the IOTA Tangle,stores detailed off-chain records and straightforward deployment of web-based interfaces and APIs. Prior work on blockchain- and DLT-enabled traceability systems indicates that typical implementations rely on a standard web stack, a DLT client library and a relational or document database for off-chain data storage (Wang et al., 2021; Li et al., 2024).

From a hardware perspective, development and testing can be conducted on a contemporary workstation or laptop equipped with a multi-core processor, at least 8-16 GB of RAM and a stable internet connection. Such specifications are consistent with those reported in recent IOTA-based and blockchain-enabled agrifood prototypes, which demonstrate that research-grade systems can be implemented without specialized hardware (Piantadosi et al., 2024). The software environment comprises:

- An application server platform (e.g., Node.js or Python-based framework) for implementing the backend services, including the data ingestion, IOTA anchoring and multi-agent components.
- An IOTA client library compatible with the chosen programming language to submit transactions to and query the Tangle, as used in existing IOTA-based agriculture and logistics solutions (Piantadosi et al., 2024; Rodríguez et al., 2025).
- A relational or document-oriented database management system (for example, PostgreSQL or MongoDB) to store off-chain ESG records, logistics data, DPPs and agent logs, reflecting common designs in hybrid DLT database architectures (Li et al., 2024; Stăncescu et al., 2024).
- A modern web framework for the frontend (such as React, Vue or Angular) to implement the user interfaces for data entry, monitoring and DPP viewing.

This configuration offers sufficient flexibility to realize the system design while remaining accessible and reproducible for future researchers and practitioners.

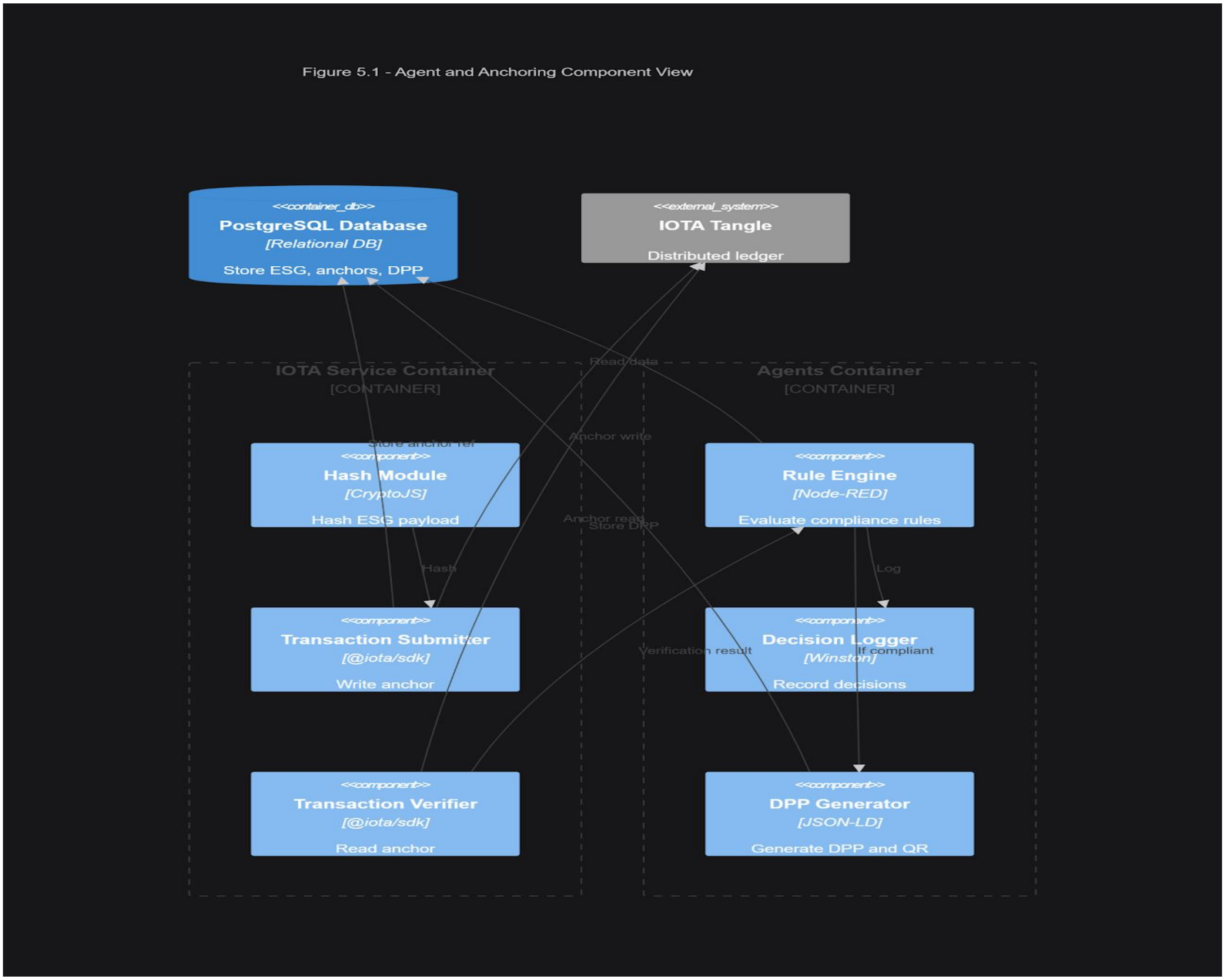


Figure 5.1 - Agent and Anchoring Component View

5.2 Coding Tools

A selection of development and testing tools was adopted to support efficient coding, version control and quality assurance. Studies of blockchain-enabled supply chains and design science prototypes emphasize the importance of disciplined tooling to manage complexity and ensure reproducibility (Babaei et al., 2023; Wang et al., 2021).

Key tools include:

- Integrated development environment (IDE): Visual Studio Code and Neovim to support syntax highlighting, debugging and integration with version control.
- Version control: Git, hosted on GitHub, to track changes, manage branches and provide an auditable history of development, in line with best practices for research prototypes.
- IOTA SDK / client library: An official IOTA client library to construct and submit transactions, retrieve transaction data and manage addresses, following patterns documented in IOTA-based IoT and supply chain projects (Piantadosi et al., 2024; ScyllaDB & IOTA, 2023).

- Testing frameworks: A unit testing framework, Jest and an API testing tool, Postman to automate and document tests of backend services and endpoints, consistent with evaluation practices in DLT applications (Babaei et al., 2023).
- Documentation tools: Lightweight documentation tools, Markdown and Draw.io to capture architectural decisions, test plans and usage instructions.

These tools collectively support structured implementation of the system, systematic testing and transparent documentation of the artifact for academic and practical audiences.

5.3 Unit Testing

Unit testing focused on verifying the correctness of individual modules in isolation before they are integrated into the full system. This is particularly important in DLT-enabled and multi-agent architectures, where subtle defects in hashing, rule evaluation or data validation can undermine trust in the entire solution (Wang et al., 2021; Kumar et al., 2023).

Table 5.1: Summary of Unit Test Execution

Test ID	**Module**	**Test Case Description**	**Expected Outcome**	**Status**
UT-01	Hashing	Compute SHA-256 for a standard ESG record.	Consistent, deterministic 64-char hex string.	**Pass**
UT-02	Anchoring	Submit hash to IOTA Shimmer Testnet.	Valid Transaction ID (TxID) returned and stored.	**Pass**

UT-03	Rules	Pesticide level check: 0.08mg/kg (Limit: 0.05).	Agent flags "Non-Compliant" with rationale.	**Pass**
UT-04	Rules	Geolocation check: Valid coordinates present.	Agent flags "Compliant".	**Pass**
UT-05	Validation	Submit record with missing mandatory fields.	System rejects input with validation errors.	**Pass**

5.3.1 IOTA Anchoring Module

The IOTA anchoring module was responsible for computing hashes of ESG and logistics records, submitting transactions to the Tangle and storing transaction identifiers for later verification. Building on patterns from IOTA-based agriculture and logistics prototypes, unit tests for this module verify that (Piantadosi et al., 2024; Rodríguez et al., 2025):

- Given a specific input record, the computed hash is deterministic and consistent across repeated runs.
- The transaction payload constructed by the module conforms to the expected format of the IOTA client library.
- When a mock or testnet IOTA node is available, the module successfully receives a transaction identifier and persists it alongside the original record.

In addition, verification functions that recompute hashes and compare them with the values retrieved from the Tangle are tested to ensure they correctly identify matching and non-matching cases, thereby supporting later integrity checks.

5.3.2 Compliance Rule Evaluation and Agent Logic

Unit tests for the compliance logic and autonomous agents supply controlled ESG and logistics input data and assert that decisions match the expected outcomes defined by the rule set. For example, test cases are constructed where pesticide application frequencies fall either within or above the permitted thresholds, or where farm geolocation data are present versus missing, reflecting rule patterns derived from the literature on ESG and DPP requirements (Heeß et al., 2024; Kechagias et al., 2025).

For each case, the agent's decision (compliant or non-compliant) and any explanatory messages are compared with expected values. This approach follows recommendations in multi-agent system design, where agent behaviours are validated against formalized rules and scenarios before large-scale deployment (Fierro et al., 2020).

5.3.3 Data Validation and Parsing

Unit tests also cover input validation and parsing routines. These tests confirm that mandatory fields are enforced, malformed or out-of-range values are rejected or flagged, and well-formed inputs are normalized correctly, for example, standardizing date formats or coordinate representations. Such tests are consistent with data quality practices emphasized in agrifood traceability research, where incorrect or incomplete data can compromise the usefulness of entire traceability chains (Li et al., 2024; Zhao et al., 2025).

5.4 Integration Testing

Integration testing assesses whether the individual components interact correctly when combined into end-to-end workflows. In DLT-enabled supply chain systems, this level of testing is crucial for verifying that data flows properly from input through ledger operations to application logic and outputs (Wang et al., 2021; Babaei et al., 2023).

5.4.1 End-to-End Data Pipeline

The main integration scenario tests the full pipeline from data capture to DPP generation or rejection:

1. Synthetic ESG and logistics data are submitted through the data ingestion interface.
2. The data validation module applies checks and stores accepted records in the off-chain database.
3. The IOTA anchoring module hashes records and submits corresponding transactions, storing transaction identifiers.
4. A compliance agent retrieves the records and, optionally, verifies hashes against the Tangle.
5. The agent applies the rule set and writes its compliance decision and rationale to the AgentLog.
6. For compliant consignments, a DPP record is generated and stored; for non-compliant consignments, no DPP is created.

Integration tests verify that each step produces the expected intermediate and final states such as correct database entries, linked transaction IDs and appropriate DPP presence or absence mirroring integrated evaluation approaches in blockchain-enabled traceability frameworks (Li et al., 2024; Ferrández-Pastor et al., 2022).

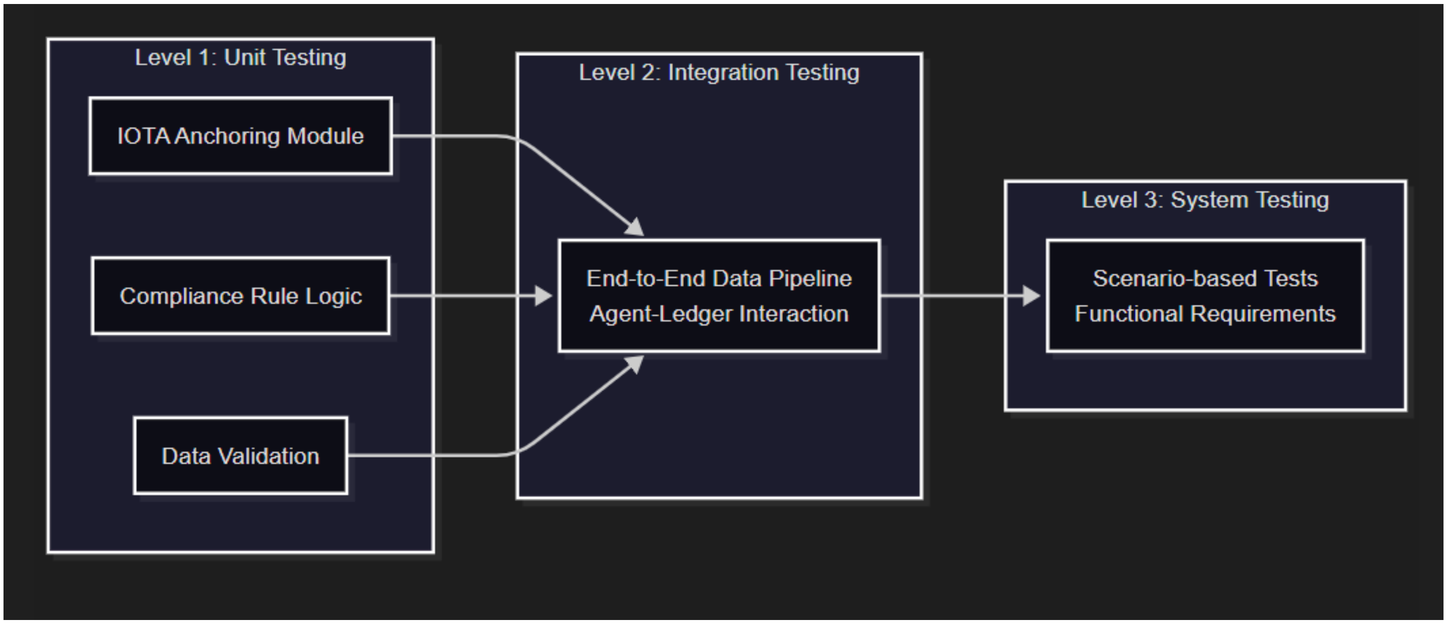
5.4.2 Error and Exception Handling

A secondary focus of integration testing is the system's response to communication failures between components. Theoretical tests were designed to ensure that if the IOTA Tangle is unreachable, the system enters a "Pending Anchor" state, allowing the **Decision Logger** to record the delay without crashing the application. This confirms the robustness of the multi-agent orchestration in handling the asynchronous nature of DLT networks. (Monrat et al., 2025; Kumar et al., 2023).

5.5 System Testing

System testing validated the implemented prototype against the functional requirements outlined in Chapter Four. In design science terms, it addressed whether the artifact, as a whole, achieves the objectives derived from the problem statement and literature (Hevner et al., 2004; Peffers et al., 2007).

***Figure 5.2**: Multi-level Testing Strategy*



5.5.1 Functional Requirements Coverage

Test cases are designed to verify that the system can:

- Accept ESG and logistics data for multiple consignments and persist them correctly.
- Anchor corresponding records onto the IOTA Tangle and store transaction references.
- Allow compliance agents to evaluate consignments and update status based on the rule set.
- Generate DPPs for consignments classified as compliant and make them accessible through the user interface.
- Prevent DPP generation when required data are missing or rules are violated, and clearly indicate the reasons.

For each functional requirement, one or more test cases are defined and executed, and the outcomes are compared with expected behaviours, following requirement-based system testing patterns found in DLT-enabled supply chain implementations (Wang et al., 2021).

Table 5.2: Requirement Traceability and Verification Method

Requirement ID	**Functional Requirement**	**Verification Method**	**Expected Outcome**
FR-01	Data Anchoring	Logic Trace	Hashed record secured on IOTA Tangle.
FR-02	ESG Compliance Check	Rule-set Simulation	Agents flag non-compliant pesticide levels.
FR-03	DPP Generation	Workflow Validation	JSON-LD passport issued for compliant goods.
FR-04	Tamper Detection	Cryptographic Comparison	Hash mismatch triggers an invalidation alert.

5.5.2 Scenario-Based System Tests

Beyond requirement-by-requirement tests, scenario-based system tests exercise the artifact under realistic conditions. Representative scenarios such as fully compliant, partially incomplete and clearly non-compliant consignments are executed end-to-end, as described in the methodology chapter. The observed behaviour is documented and used to confirm that the system responds consistently with the encoded rules and the conceptual model presented earlier (Heeß et al., 2024; Kechagias et al., 2025).

5.6 Database Testing

Database testing focuses on the correctness, integrity and consistency of off-chain data storage, which is crucial in hybrid DLT-database architectures where detailed operational data reside in conventional databases (Li et al., 2024; Stăncescu et al., 2024).

5.6.1 Data Integrity and Constraints

Tests verify that:

- Records in the Consignment table correctly reference Farm, ESGRecord and LogisticsRecord entities via foreign keys.
- Each DPP record is associated with exactly one valid consignment and corresponding IOTAAnchor entries.
- Deletion or modification of records respects referential integrity constraints, preventing orphaned or inconsistent data.

These tests reflect database design principles advocated in traceability models, where relational integrity is essential for reliable reconstruction of product histories (Li et al., 2024; Ferrández-Pastor et al., 2022).

5.6.2 IOTA Reference Consistency

Database testing also checks that the transaction identifiers stored in the IOTAAnchor table correspond to valid or simulated transactions on the Tangle. For test environments with a live or local IOTA node, scripts query the Tangle using stored transaction IDs to ensure that records exist and contain the expected hashes, thereby reinforcing the link between off-chain data and on-ledger integrity (Piantadosi et al., 2024; Rodríguez et al., 2025).

5.7 System Interface Specifications and User Flow

The user interfaces are designed as a web-based portal to provide practical access points for data entry, monitoring, and DPP consumption. The interface design follows established patterns for agrifood traceability, ensuring that complex DLT and MAS operations are abstracted for the end-user. (Kechagias et al., 2025; Li et al., 2024).

- System home page / dashboard: Acts as the central command center, presenting a high-level overview of all consignments, their current compliance status (as determined by the Rule Engine), and DPP availability. It includes dynamic filters to isolate non-compliant shipments for immediate exporter intervention.
- ESG data entry modules: These interfaces provide structured forms for farm registration and pesticide logging. They incorporate real-time validation feedback to ensure data quality before the Ingestion Agent hashes and anchors the records to the IOTA Tangle.
- Logistics tracking Interface: Designed for logistics providers to upload route and temperature data, mirroring IoT-based traceability structures where environmental parameters are critical for export compliance.
- DPP detail view: This is the primary output for external stakeholders (e.g., EU regulators). It displays the machine-readable passport metadata, selected ESG attributes, and a "Verification Link" that queries the IOTA Tangle to prove the record's integrity and provenance.
- Agent Audit & Admin/log view: Provides a transparent window into the Multi-Agent System. It displays logs from the **Decision Logger**, showing the rationale behind compliance decisions and the status of IOTA anchoring activities.

These interfaces operationalize the system’s functionality for end users and align with the roles and processes defined in the system design.

5.8 Conclusion

This chapter has documented the implementation and testing of the decentralized multi-agent system for ESG-compliant Digital Product Passports in Kenyan agricultural export supply chains. The system was implemented using a contemporary web and DLT stack, including an IOTA client library, an off-chain database and web-based interfaces, consistent with architectures reported in recent DLT-enabled traceability and multi-agent supply chain research (Piantadosi et al., 2024; Li et al., 2024; Fierro et al., 2020).

Testing was carried out at multiple levels. Unit tests verified the correctness of critical modules, including IOTA anchoring, compliance rule evaluation and data validation. Integration tests evaluated end-to-end workflows, while system tests assessed the fulfillment of functional requirements and behaviour under representative scenarios. Database tests confirmed referential integrity and consistency of IOTA references, supporting the system's traceability and tamper-evident properties. This multi-layered evaluation approach aligns with design science recommendations for artifact assessment and provides evidence that the prototype behaves in accordance with the objectives defined in earlier chapters (Hevner et al., 2004; Peffers et al., 2007; Wang et al., 2021).

The results presented here establish that the designed architecture can be realized in practice and that the implemented prototype is capable of supporting ESG data anchoring, autonomous compliance evaluation and DPP generation for simulated Kenyan agricultural export scenarios. These outcomes form the basis for the concluding chapter, which synthesizes the study's contributions, discusses limitations and suggests directions for future work.

CHAPTER SIX: SUMMARY, CONCLUSION AND RECOMMENDATIONS

6.0 Introduction

This chapter presents the overall synthesis of the study on a decentralized multi-agent system for autonomous ESG compliance and Digital Product Passports (DPPs) in Kenyan agricultural export supply chains. It consolidates the key findings from the preceding chapters, evaluates the extent to which the research objectives have been achieved and reflects on the theoretical and practical significance of the work. It then offers recommendations for relevant stakeholders and identifies directions for future research and system development. The chapter concludes with a consolidated reference list for the entire project and an outline of the appendices containing supporting materials.

6.1 Conclusion

The study was motivated by the increasing stringency of European Union environmental, social and governance (ESG) regulations and the emergence of the Digital Product Passport as a tool for improving product-level transparency and circularity, particularly under the Circular Economy Action Plan and the proposed Ecodesign for Sustainable Products Regulation (European Commission, 2020, 2022). Literature shows that DPPs aim to aggregate standardized, machine-readable information on product origin, composition, environmental performance and end-of-life handling, but practical implementations in agrifood exports from developing regions remain limited (Heeß et al., 2024; Lazarevic et al., 2024). At the same time, research on agrifood traceability in African contexts highlights fragmentation of data systems, reliance on paper-based certificates and limited integration of IoT and digital ledgers, creating a “compliance gap” for exporters seeking access to EU markets (Nyalala et al., 2024; Kechagias et al., 2025).

Chapter One framed this problem in the specific context of Kenyan tea, coffee and avocado exports, where existing compliance processes rely heavily on manual documentation and periodic audits that are poorly suited to continuous, product-level ESG verification. It proposed a solution concept based on a decentralized architecture integrating IOTA’s DAG-based distributed ledger for tamper-evident data anchoring with autonomous agents for real-time compliance auditing and DPP issuance. The chapter formulated the general objective of developing a functional prototype of such a system and articulated specific objectives focused on designing a suitable architecture, implementing multi-agent compliance logic, generating DPP-compatible passports and demonstrating a trigger mechanism for conditional trade events.

Chapter Two reviewed literature on DPPs, distributed ledger technologies (DLTs) particularly DAG-based ledgers such as IOTA and autonomous or multi-agent systems in supply chains and ESG reporting. It showed that while DPPs are conceptually well developed and DAG-based ledgers offer technical advantages for high-frequency IoT data, there is limited work on integrating these technologies into end-to-end compliance architectures for agricultural exports in the Global South (Heeß et al., 2024; Monrat et al., 2025; Nyalala et al., 2024). The chapter also noted that existing multi-agent supply chain studies focus largely on operational efficiency rather than formal ESG compliance or digital passport issuance (Cano et al., 2025; Kouhizadeh et al., 2023). It proposed a conceptual framework linking four main constructs: regulatory/DPP requirements, IoT-enabled data collection, IOTA-based integrity and decentralized multi-agent compliance which guided the subsequent system design.

Chapter Three established the methodological foundation using a design science research approach and an iterative, incremental software development process. Design science was identified as appropriate because the study's primary contribution is an IT artifact designed to address a complex, real-world compliance problem (Hevner et al., 2004; Gregor & Hevner, 2013). The study adopted the Design Science Research Methodology (DSRM) by Peffers et al. (2007), structuring the work into problem identification, objective definition, artifact design and development, demonstration, evaluation and communication. The chapter described how regulatory and scholarly documents were used to derive ESG and DPP rule sets and how synthetic and simulated ESG and logistics datasets were generated to evaluate the system under realistic but non-sensitive conditions, consistent with practices in DLT-enabled supply chain research (Babaei et al., 2023; Nyalala et al., 2024).

Chapter Four translated the conceptual framework into a concrete system analysis and design. It specified functional requirements such as ESG data capture, IOTA-based data anchoring, autonomous compliance evaluation, DPP generation and audit logging, and non-functional requirements including security, integrity, performance, scalability and usability (Monrat et al., 2025; Kechagias et al., 2025). The chapter presented a context-level architecture linking external actors (farms, exporters, logistics providers, regulators and EU buyers) with internal components, including a data ingestion layer, an off-chain database, an IOTA anchoring service, a multi-agent layer and access APIs. It detailed input design (user interfaces and validation), process design (ESG recording, anchoring, compliance evaluation, DPP issuance and optional payment triggers), database design (normalized entities and relationships such as Farm, Consignment, ESGRecord, LogisticsRecord, DPP and IOTAAnchor) and output design (DPP representations and dashboards), aligning with hybrid ledger database traceability models in agrifood systems (Li et al., 2024; Ferrández-Pastor et al., 2022).

Chapter Five described the implementation of this architecture using a contemporary web and DLT stack and presented a multi-level testing strategy. Unit tests verified the correctness of core modules: hash computation and IOTA transaction submission; compliance rule evaluation by autonomous agents; and data validation and parsing. Integration tests assessed the end-to-end pipeline from data ingestion through IOTA anchoring to agent-based decisions and DPP generation, including robustness under simulated error conditions. System tests evaluated whether the prototype met the functional requirements and behaved correctly across representative scenarios, such as fully compliant consignments, missing or inconsistent data and logistics anomalies. Database tests confirmed referential integrity among key entities and the consistency of IOTA transaction references, thereby supporting traceability and tamper-evidence (Piantadosi et al., 2024; Rodríguez et al., 2025; Wang et al., 2021).

Against this background, the specific objectives can be assessed as follows:

- The objective of designing a decentralized architecture for anchoring ESG data to a feeless DAG-based ledger was achieved through the layered design that uses IOTA's Tangle to store hashes and transaction identifiers for ESG and logistics records while maintaining full payloads in an off-chain database, consistent with established hybrid architectures (Piantadosi et al., 2024; Stăncescu et al., 2024).
- The objective of developing autonomous agents capable of real-time compliance auditing was met by implementing rule-based agents that retrieve relevant data, verify integrity and apply encoded ESG/DPP criteria to classify consignments, as documented in the unit and integration testing results (Cano et al., 2025; Heeß et al., 2024).

- The objective of implementing a mechanism for generating DPP-compatible passports linked to evidence was realized through the DPP module, which creates structured passport records with unique identifiers and references to underlying IOTA transactions and off-chain data (Heeß et al., 2024; Gieß et al., 2025).
- The objective of prototyping a smart-contract-driven payment or trigger mechanism was partially addressed through the design and implementation of a trigger component that can initiate notifications or simulated payment events when a consignment attains compliant status and a valid DPP is available, thereby demonstrating the feasibility of coupling compliance decisions with automated trade processes (Babaei et al., 2023; Wang et al., 2021).

Overall, the study shows that integrating a DAG-based ledger such as IOTA with a decentralized multi-agent system provides a technically viable and conceptually coherent approach to automating ESG compliance and DPP issuance for Kenyan agricultural exports. While full-scale deployment and regulatory integration remain outside the present scope, the prototype and its evaluation provide a credible basis for further development and practical pilots.

6.2 Recommendations

Based on the results and insights obtained, several recommendations can be formulated for key stakeholder groups.

Exporters, cooperatives and producers

Exporters and cooperatives should progressively adopt structured digital systems for ESG and traceability data collection, even at a modest scale, to prepare for the increasing data granularity and transparency demands associated with DPP and related EU regulations. Literature suggests that early and systematic investment in traceability and sustainability reporting can enhance market access, reduce compliance risk and support differentiation in sustainability-sensitive segments (Heeß et al., 2024; Kechagias et al., 2025). Introducing standardized data templates and low-cost IoT devices at farm and warehouse levels would help generate more consistent and verifiable ESG data suitable for DPP integration.

Regulators and policy-makers

National regulators and policy-makers in Kenya should support enabling infrastructures for DPP-compatible data exchange to prevent smallholders and cooperatives from being excluded by complex digital compliance requirements. This could include developing national guidelines or reference architectures for ESG and DPP data, promoting interoperability standards, and providing technical assistance and incentives for digital traceability adoption, particularly among small and medium-sized exporters (Nyalala et al., 2024; Kechagias et al., 2025). Collaborative pilot projects linking domestic systems with EU-oriented platforms would also help clarify practical requirements and constraints.

Technology providers and system integrators

Technology providers should build on the architectural patterns demonstrated in this study to develop production-ready solutions that combine robust DLT-based integrity layers with user-centred interfaces and flexible integration options. Prior work shows that successful blockchain and DLT deployments in supply chains often hinge on interoperability with existing ERP and logistics systems and on reducing complexity for end users (Wang et al., 2021; Li et al., 2024). Providers should therefore prioritize open APIs, configurable rule engines for evolving ESG requirements and support for local languages and workflows.

Researchers and academic institutions

Researchers should extend the work by conducting field studies that involve real farms, cooperatives and exporters, allowing the evaluation of such systems under real-world conditions and uncovering socio-technical factors such as trust, adoption barriers and incentive structures. Further research is also needed on comparative performance and security of DAG-based DLT versus alternative architectures in large-scale agrifood traceability scenarios (Monrat et al., 2025; Nyalala et al., 2024). Academic institutions could incorporate DPP- and DLT-related topics into curricula to build local expertise and foster innovation at the interface of agriculture, regulation and digital technologies.

6.3 Future Work

The project's scope and limitations, as well as the evolving regulatory and technological landscape, suggest several avenues for future work.

First, real-world deployment and evaluation should be pursued through pilot implementations with selected Kenyan exporters and cooperatives. Such pilots would provide data on system usability, data quality, connectivity constraints and stakeholder perceptions, offering insights that cannot be fully captured through simulated data and laboratory testing (Kechagias et al., 2025; Nyalala et al., 2024).

Second, expansion and refinement of ESG coverage is needed as EU regulations and DPP technical specifications for agricultural products become more concrete. Future iterations should incorporate a broader range of ESG indicators such as water use, labour conditions, biodiversity impacts and lifecycle carbon footprints and align data models and rule sets with finalized sectoral DPP schemas and EU reporting frameworks (Heeß et al., 2024; European Parliament, 2024).

Third, enhancement of agent intelligence and decision support is a promising direction. While the current prototype uses rule-based agents, future research could explore hybrid approaches that combine rules with machine learning for anomaly detection, risk scoring or adaptive thresholding, provided that transparency and explainability can be maintained to satisfy regulatory expectations (Cano et al., 2025; Kechagias et al., 2025).

Fourth, interoperability with international standards and platforms should be strengthened. Aligning data models with standards such as GS1's EPCIS and integrating with emerging data spaces and certification platforms would facilitate cross-border data exchange and reduce integration complexity for exporters and buyers (Kechagias et al., 2025; Li et al., 2024).

Fifth, comprehensive security and privacy analysis is required. Subsequent work should conduct formal threat modelling and penetration testing to identify vulnerabilities, and investigate privacy-preserving techniques such as encryption, access control, selective disclosure and off-chain confidential computing for sensitive farm and trade data (Monrat et al., 2025; Stăncescu et al., 2024).

Finally, scalability and performance benchmarking should be conducted under realistic and stress-test conditions. Systematic experiments varying data volumes, frequency of ESG events, number of concurrent users and network conditions would provide more precise guidance on infrastructure requirements and on the comparative advantages and limitations of DAG-based approaches relative to other DLTs and centralized systems (Monrat et al., 2025; Babaei et al., 2023).

6.5 Appendices

The appendices contain supplementary material that supports but is not essential to the main body of the dissertation. They may include:

APPENDIX A: Sample Synthetic ESG and Logistics Datasets

This appendix presents illustrative extracts of the synthetic datasets used to test and demonstrate the decentralized multi-agent system. The datasets were generated based on parameter ranges and structures described in the literature on agrifood traceability and IoT-DLT integration, ensuring that values are realistic while avoiding the use of confidential or proprietary information (Kechagias et al., 2025; Piantadosi et al., 2024).

A.1 Farm-Level ESG Data (Extract)

The Farm-level ESG dataset captures core attributes necessary for DPP-oriented ESG compliance checks, including farm identification, cooperative membership, geolocation and pesticide application events. The table below shows an illustrative subset.

Farm_ID	Coop_ID	Crop_Type	Latitude	Longitude	Pesticide_Type	Pesticide_Amount_L_per_ha	Application_Date	Notes
F001	C001	Tea	-0.34012	36.78234	Fungicide_A	1.2	2025-03-15	Within recommended range
F002	C001	Coffee	-0.56789	37.00451	Insecticide_B	0.8	2025-04-02	Single application
F003	C002	Avocado	-0.43567	36.94567	Fungicide_A	1.9	2025-02-27	Near upper threshold
F004	C003	Tea	-0.39876	36.85678	Insecticide_C	2.5	2025-03-10	Exceeds threshold (flagged)

F005	C002	Avocado	-0.51234	36.92345	None	0.0	–	Certified organic

The ranges for pesticide amounts and application frequencies were chosen with reference to typical agronomic recommendations and pesticide-use patterns described in agrifood literature, but they do not correspond to any specific farm (Kechagias et al., 2025; Zhao et al., 2025).

A.2 Consignment and Logistics Data (Extract)

The consignment-level dataset links multiple farms to export shipments and records logistics events, including time-temperature profiles that are relevant for quality and ESG claims.

Consignment Table (Extract)

Consignment_ID	Exporter_ID	Product	Destination	Departure_Date	Arrival_Date	Status
CN001	E001	Avocado	EU_Port_A	2025-05-01	2025-05-12	Evaluated
CN002	E002	Coffee	EU_Port_B	2025-05-03	2025-05-15	Evaluated
CN003	E001	Tea	EU_Port_A	2025-05-05	2025-05-16	Pending

Consignment–Farm Link Table (Extract)

Consignment_ID	Farm_ID
CN001	F003
CN001	F005
CN002	F002
CN003	F001
CN003	F004

LogisticsRecord Table (Extract)

Logistics_ID	**Consignment_ID**	**Container_ID**	**Event_Timestamp**	**Location**	**Temperature_C**	**Event_Type**
L001	CN001	CONT_A1	2025-05-02 08:00	Inland_Depot	6.5	Load
L002	CN001	CONT_A1	2025-05-06 12:00	Port_X	7.0	Gate-In
L003	CN001	CONT_A1	2025-05-09 03:00	At_Sea	7.3	In-Transit
L004	CN002	CONT_B2	2025-05-04 09:00	Inland_Depot	8.0	Load
L005	CN002	CONT_B2	2025-05-10 18:30	At_Sea	14.5	In-Transit (risk)

Time–temperature ranges were selected with reference to supply-chain traceability work showing typical cold-chain conditions and thresholds for risk of quality loss (Rodríguez et al., 2025; Kechagias et al., 2025).

A.3 Compliance Labels (Extract)

For testing, synthetic consignments were labelled as compliant or non-compliant according to the simplified ESG and DPP rule set derived in the methodology chapter.

Consignment_ID	**ESG_Complete**	**Geo_Valid**	**Pesticide_OK**	**ColdChain_OK**	**Compliance_Label**
CN001	Yes	Yes	Yes	Yes	Compliant
CN002	Yes	Yes	No	No	Non-Compliant
CN003	No	No	Mixed	Yes	Non-Compliant

These labels serve as “ground truth” for unit and scenario-based tests of agent behaviour.

APPENDIX B: Test Case Specifications

This appendix summarizes representative test cases used for unit, integration, system and database testing. The test cases are derived from the functional requirements, rule sets and evaluation strategy described in Chapter Three and mirror evaluation approaches in DLT-enabled supply chain research (Wang et al., 2021; Babaei et al., 2023).

B.1 Unit Test Cases (Extract)

Table B.1: IOTA Anchoring Module – Unit Tests

Test_ID	Description	Input	Expected Result
UT_IOTA_01	Deterministic hash generation	ESGRecord R1	Same hash value generated on repeated executions
UT_IOTA_02	Valid transaction payload	ESGRecord R2	Payload conforms to IOTA client schema; no errors
UT_IOTA_03	Store transaction ID	ESGRecord R3, testnet node	Non-null TxID stored and linked to ESGRecord
UT_IOTA_04	Hash verification success	ESGRecord R4 + stored Tx hash	Verification returns “valid”
UT_IOTA_05	Hash verification failure	Modified ESGRecord R4 + stored hash	Verification returns “invalid/tampered”

Table B.2: Compliance Agent – Unit Tests

Test_ID	Description	Input Scenario	Expected Decision

UT_COMP_01	Pesticide within threshold	Single application, low amount, valid geolocation	Compliant, DPP allowed
UT_COMP_02	Excessive pesticide use	Multiple applications, above threshold	Non-Compliant, no DPP
UT_COMP_03	Missing geolocation	No coordinates for one or more farms	Non-Compliant, no DPP
UT_COMP_04	Complete ESG, minor logistics deviation	ESG OK, small temperature fluctuation within band	Compliant
UT_COMP_05	Cold-chain breach	ESG OK, temperature spike above allowed threshold	Non-Compliant

B.2 Integration Test Cases (Extract)

Table B.3: End-to-End Pipeline – Integration Tests

Test_ID	**Description**	**Input**	**Expected Outcome**
IT_PIPE_01	Full pipeline – compliant consignment	ESG + logistics data for CN001	Data stored and anchored; agent decision = Compliant; DPP created
IT_PIPE_02	Full pipeline – non-compliant data	ESG + logistics data for CN002	Data stored and anchored; agent decision = Non-Compliant; no DPP
IT_PIPE_03	IOTA temporary failure	Valid data, simulated node error	Data stored; anchoring queued; error logged; no crash

IT_PIPE_04	Incomplete ESG data	Missing geolocation for CN003	Validation warnings; agent classifies Non-Compliant

B.3 System and Scenario Test Cases (Extract)

Table B.4: Scenario-Based System Tests

Scenario_ID	**Description**	**Input Overview**	**Expected System Behaviour**
SC_A	Fully compliant consignment	Complete ESG, valid geo, stable cold-chain	Status “Compliant”; DPP issued and viewable
SC_B	Pesticide and cold-chain violation	Excess pesticide, temperature breach	Status “Non-Compliant”; no DPP; reasons displayed
SC_C	Missing critical ESG attributes	No coordinates for farm; partial ESG	Status “Non-Compliant”; DPP not generated

APPENDIX C: Additional Architectural and Process Diagrams

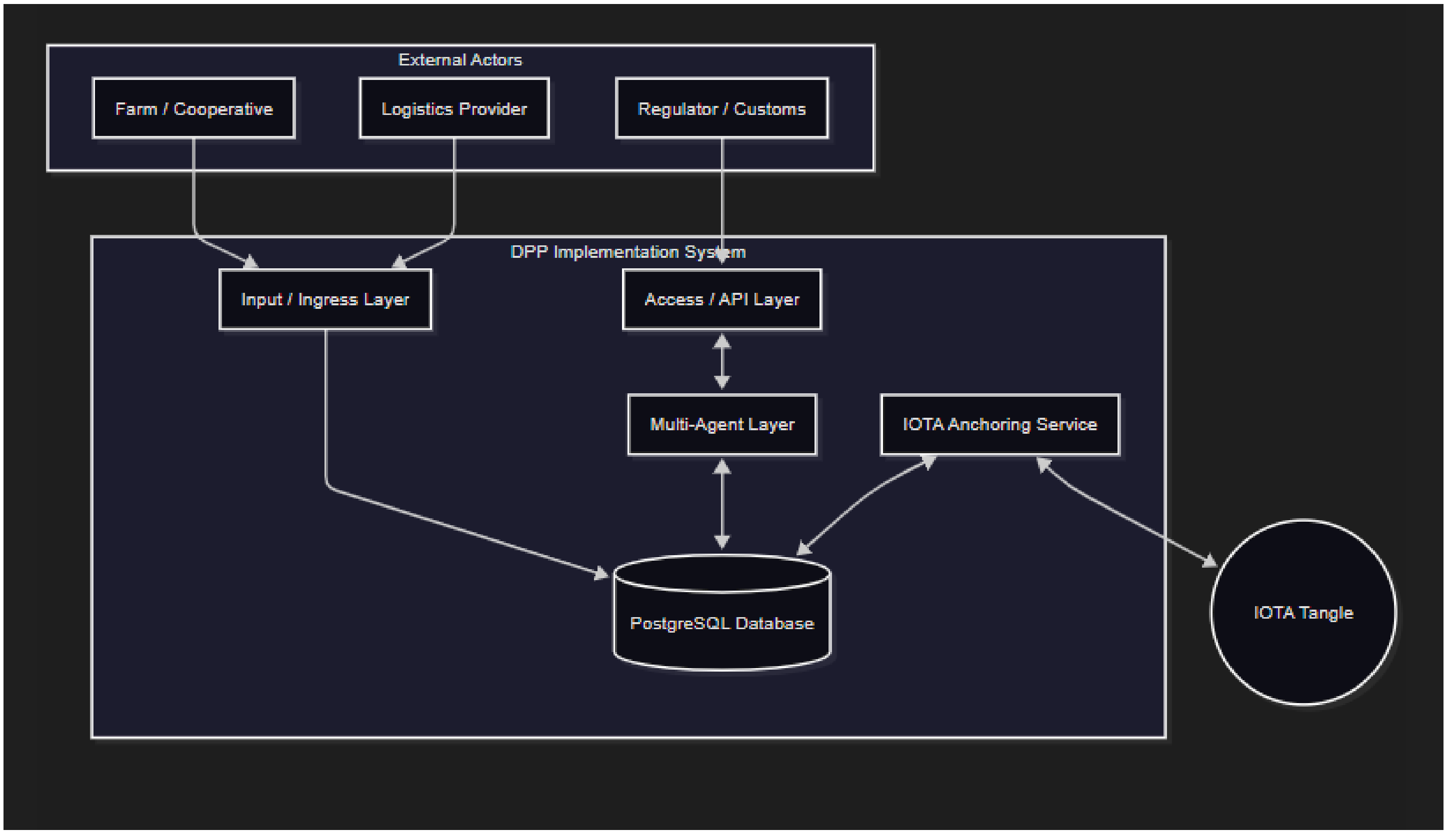
This appendix provides additional diagrams that complement the system design presented in Chapter Four. Diagrammatic representations are widely used in design science and software engineering to clarify component interactions and data flows in complex systems (Hevner et al., 2004; Wang et al., 2021).

C.1 High-Level Architecture Diagram (Narrative Description)

The high-level architecture diagram depicts:

- External actors (Farm/Cooperative, Exporter, Logistics Provider, Regulator/Customs, EU Buyer).
- Internal layers: Input/Ingress Layer, Off-Chain Database, IOTA Anchoring Service, Multi-Agent Layer, Access/API Layer.
- Data flows:
    - ESG and logistics data from external actors into the Input Layer.
    - Validated records into the Off-Chain Database.
    - Hashes and transaction submissions from Anchoring Service to the IOTA Tangle.

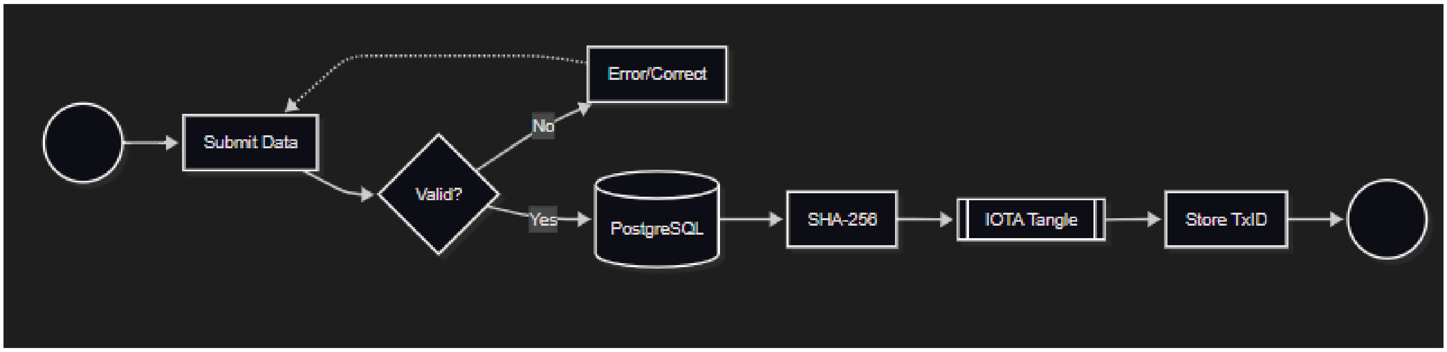
- Data retrieval and verification flows from Multi-Agent Layer to Database and IOTA.
- DPP and status queries from Regulator/Buyer interfaces via Access/API Layer.



C.2 "Record and Anchor ESG Data" Activity Diagram (Narrative)

Key steps:

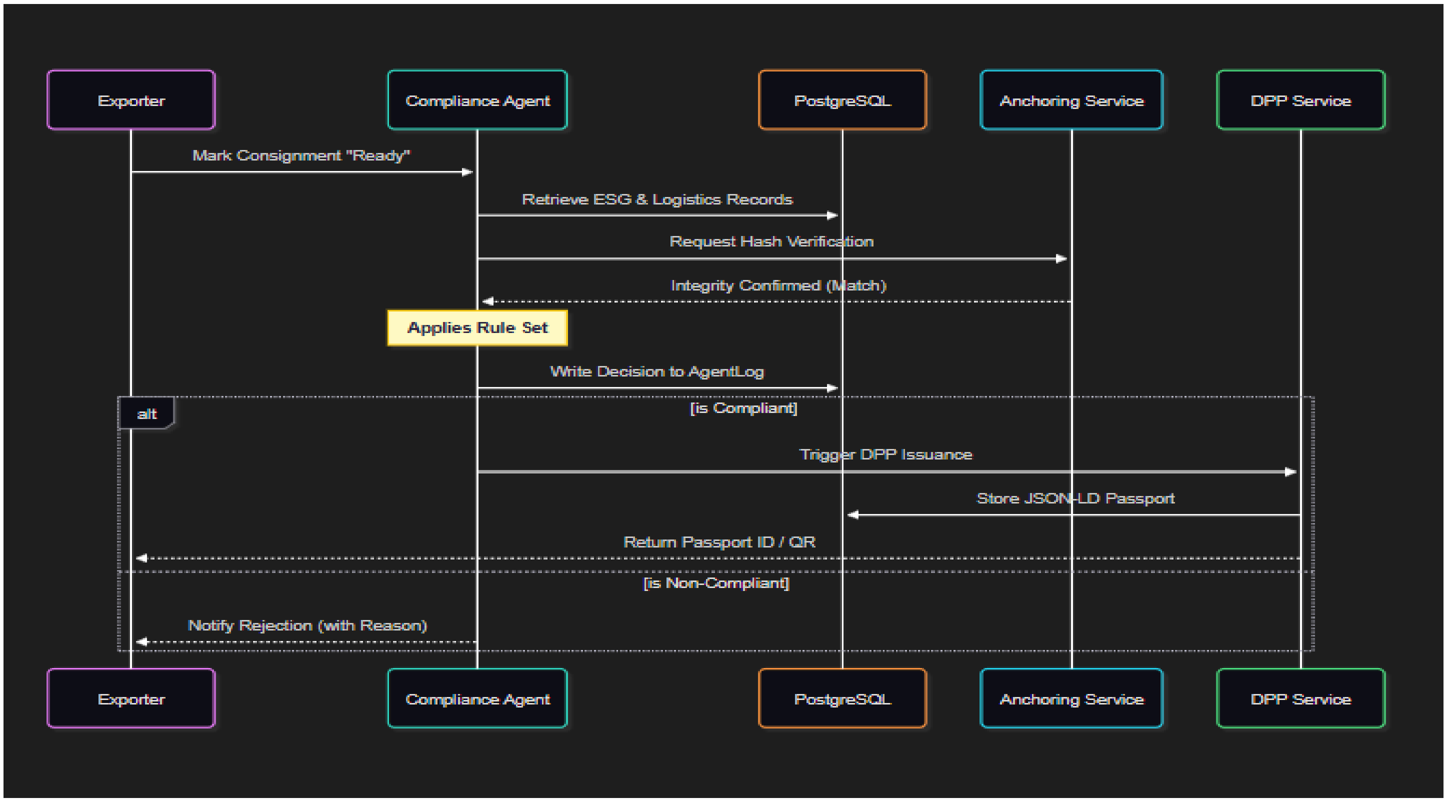
1. User submits ESG data via form or API.
2. The system performs validation (required fields, ranges, formats).
3. If validation fails, the user receives error messages and must correct data.
4. If validation succeeds, data is stored in the Off-Chain Database.
5. IOTA Anchoring Service creates a hash and submits a transaction.
6. Tangle returns transaction ID; system stores TxID in IOTAAnchor table.



C.3 "Compliance Evaluation and DPP Issuance" Sequence Diagram (Narrative)

Participants: Exporter, Compliance Agent, Database, IOTA Anchoring Service, DPP Service.

1. Exporter marks consignment as "Ready for Evaluation".
2. Compliance Agent retrieves relevant ESG and logistics records from Database.
3. The agent optionally calls IOTA Anchoring Service to verify hashes for selected records.
4. The agent applies a rule set; determines compliance status.
5. Agent writes decision and justification to AgentLog; updates consignment status.
6. If compliant, DPP Service generates DPP and stores it; Access Layer exposes DPP to authorized users.



APPENDIX D: Interface Screens

This appendix describes the main user interfaces implemented in the prototype, complementing the high-level overview in Chapter Five. Interface design follows dashboard and form-based patterns documented in agrifood traceability and compliance systems (Kechagias et al., 2025; Li et al., 2024).

D.1 System Home Page / Dashboard

- Displays a table of consignments with columns for Consignment_ID, Product, Exporter, Status (Pending, Compliant, Non-Compliant), DPP_Available (Yes/No) and Last_Evaluated.
- Includes filters by status, product, exporter and date range.
- Provides quick links to consignment details and DPP views.

D.2 ESG Data Entry Form

- Fields for Farm_ID, Coop_ID (select or search), Crop_Type (drop-down), Latitude, Longitude, Pesticide_Type (drop-down), Pesticide_Amount, Application_Date.
- Inline validation shows error messages for missing mandatory fields or invalid values (e.g., coordinates outside plausible ranges).

D.3 Logistics Data Entry / Upload Screen

- Fields for Consignment_ID, Container_ID, Event_Timestamp, Location, Temperature_C, Event_Type (Load, Gate-In, In-Transit, etc.).
- Optional CSV upload functionality to ingest time–temperature profiles from data loggers.

D.4 DPP Detail View

- Displays DPP_ID, Consignment_ID, Product, Origin summary, key ESG indicators (e.g., pesticide usage summary, geolocation confirmation, cold-chain compliance).
- Shows IOTA transaction references (e.g., truncated TxIDs) with links or instructions for verification.

D.5 Administrative / Agent Log View

- Lists recent evaluations, including Consignment_ID, Decision (Compliant/Non-Compliant), Rule_Triggered (if any) and Timestamp.
- Provides filtering by date and decision type, supporting audits and debugging.

APPENDIX E: Selected Code Excerpts (Pseudocode)

This appendix presents an illustrative pseudocode for core logic elements. It is intended to clarify the implementation approach without exposing full source code. Pseudocode is informed by patterns in DLT and IoT system implementations (Piantadosi et al., 2024; Wang et al., 2021).

E.2 IOTA Anchoring Service

```text
function anchorData(data, recordType):
    logNodeCapabilitiesOnce()
```

```
hashValue = computeHash(data)

if anchorMode is mock:
    txId = "MOCK_TX_" + first32Characters(hashValue)
    return {
        transactionId: txId,
        hash: hashValue,
        explorerUrl: getVerificationUrl(txId)
    }

try:
    result = anchorDataWithLocalPow(hashValue, recordType)
    return result
catch error:
    continue with REST fallback

tips = fetchIotaTips()
if tips is empty:
    raise error "IOTA node returned no tips"

payload = buildTaggedDataBlock(
    tag = "TRACECHAIN",
    data = {
        hash: hashValue,
        type: recordType,
        ts: currentTimestamp()
    }
```

```
    )

    blockId = submitBlock(
        parents = firstFourTips(tips),
        payload = payload,
        nonce = "0"
    )

    return {
        transactionId: blockId,
        hash: hashValue,
        explorerUrl: getVerificationUrl(blockId)
    }
```

E.2 Compliance Evaluation and DPP Issuance flow (Pseudocode)

```text
function evaluateConsignment(consignmentId):
    consignment = loadConsignmentWithRelations(consignmentId)

    farms = mapFarmInputs(consignment)
    esgRecords = mapEsgInputs(consignment)
    logistics = mapLogisticsInputs(consignment)

    complianceResult = runComplianceRules({
        consignmentId: consignmentId,
        cropType: consignment.productType,
        farms: farms,
        farmIds: extractFarmIds(farms),
```

```
    esgRecords: esgRecords,
    logistics: logistics
})

evaluation = convertToEvaluationShape(complianceResult)

writeAgentLog(
    consignmentId,
    decision = evaluation.compliant ? "PASS" : "FAIL",
    reason = joinViolations(evaluation.violations),
    metadata = complianceResult.breakdown
)

if evaluation.compliant is false:
    updateConsignmentStatus(
        consignmentId,
        status = "NON_COMPLIANT",
        complianceStatus = "FAIL",
        complianceDetails = evaluation.violations,
        evaluatedAt = evaluation.timestamp
    )
    notifyNonCompliant(consignmentId, evaluation.violations)
    return { evaluation: evaluation, dpp: null }

dppInput = buildDppInput(consignment)
dpp = generateDpp(consignmentId, dppInput, evaluation)

storedDpp = persistDppRecord(
```

```
    dppId = dpp.dppId,
    consignmentId = consignmentId,
    productType = dpp.productType,
    originSummary = serialize(dpp.originSummary),
    esgSummary = serialize(dpp.esgSummary),
    complianceStatus = dpp.complianceStatus,
    anchoringStatus = "QUEUED"
)

updateConsignmentStatus(
    consignmentId,
    status = "DPP_ISSUED",
    complianceStatus = "PASS",
    complianceDetails = [],
    evaluatedAt = evaluation.timestamp
)

queueAnchoring(
    dppId = dpp.dppId,
    payload = buildDppAnchorPayloadByDppId(dpp.dppId)
)

notifyCompliant(consignmentId, dpp.dppId)

return {
    evaluation: evaluation,
    dpp: mergeDppWithStoredStatus(dpp, storedDpp)
```

```
    }
```

E.3 DPP Generation Function (Pseudocode)

```text
function generateDpp(consignmentId, consignmentData, complianceEvaluation):
    dppId = "DPP-" + consignmentId + "-" + currentTimeMillis()

    originSummary = {
        farms: [],
        totalFarms: length(consignmentData.farms)
    }

    for each farm in consignmentData.farms:
        originSummary.farms.append({
            farmId: farm.farmId,
            coordinates: if farm.latitude and farm.longitude then
                { lat: farm.latitude, lng: farm.longitude }
            else
                null
        })

    totalPesticide = 0
    pesticideCount = 0

    for each farm in consignmentData.farms:
        if farm has pesticideRecords:
            latestRecord = mostRecentPesticideRecord(farm.pesticideRecords)
            totalPesticide = totalPesticide + latestRecord.amount
```

```
        pesticideCount = pesticideCount + 1

    maxTemperature = if consignmentData.logistics has readings then
        maximumTemperature(consignmentData.logistics.temperatureReadings)
    else
        null

    esgSummary = {
        pesticideCompliance: complianceEvaluation.results["Pesticide Residue Limit"].passed or true,
        geolocationCompliance: complianceEvaluation.results["Farm Geolocation Verification"].passed or true,
        coldChainCompliance: complianceEvaluation.results["Cold Chain Temperature Compliance"].passed or
true,
        metrics: {
            averagePesticide: if pesticideCount > 0 then totalPesticide / pesticideCount else null,
            maxTemperature: maxTemperature
        }
    }

    dpp = {
        dppId: dppId,
        consignmentId: consignmentId,
        productType: consignmentData.productType,
        originSummary: originSummary,
        esgSummary: esgSummary,
        complianceStatus: if complianceEvaluation.compliant then "PASS" else "FAIL",
        integrityProof: {
            iotaTransactionIds: [],
```

```
      verificationUrls: [],
      hashAlgorithm: "SHA-256"
    },
    issuedAt: currentTimestamp(),
    validUntil: currentTimestampPlusOneYear(),
    anchoringStatus: "QUEUED"
  }
  return dpp
```

APPENDIX F: Glossary and Abbreviations

The following table defines the key technical terms and abbreviations used throughout this dissertation, incorporating both general DLT/MAS concepts and specific technical specifications.

Abbreviation / Term	**Full Name**	**Definition**
DAG	Directed Acyclic Graph	A non-linear data structure where edges have a direction and no cycles exist. In DLT, it enables parallel transaction validation and high throughput without traditional "blocks".
DLT	Distributed Ledger Technology	A decentralized database shared across a network that maintains a shared, immutable ledger, serving as the foundation for systems like the IOTA Tangle.
DPP	Digital Product Passport	A structured, machine-readable digital record providing standardized product data regarding origin, sustainability, and circularity, as promoted under EU policy.

ESG	Environmental, Social, and Governance	A framework used to measure the sustainability, ethical impact, and regulatory compliance of products and organizations.
IOTA Tangle	—	A feeless, DAG-based distributed ledger developed by the IOTA Foundation, specifically optimized for scalable IoT data exchange and micro-transactions.
IoT	Internet of Things	A network of interconnected physical devices (sensors/actuators) that collect and exchange data on environmental and supply chain conditions.
JSON-LD	JSON for Linked Data	A method of encoding linked data using JSON, utilized in this project to ensure the Digital Product Passport is machine-readable and interoperable.
MAS	Multi-Agent System	A computerized system composed of multiple interacting autonomous agents that perceive their environment and act to achieve goals, such as compliance evaluation.
MRL	Maximum Residue Level	The highest level of pesticide residue legally tolerated in food or feed; a critical threshold for Kenyan agricultural export compliance.
NFT	Non-Fungible Token	A unique digital token representing authenticity on a DLT; used conceptually in this project to model the unique identity of a Digital Product Passport.

SHA-256	Secure Hash Algorithm 256-bit	A cryptographic hash function that creates a unique 256-bit signature used to ensure data integrity and detect tampering in anchored records.
Smart Contract	—	A self-executing program stored on a distributed ledger that automatically enforces predefined rules, such as automated compliance checks and settlement.

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