

# Orchestrating the Circular Smart Palm Ecosystem: A Design Science Research Using TOGAF-Based Enterprise Architecture

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**Abstract:** The global palm oil industry is currently confronting a sustainability trilemma involving production efficiency, regulatory compliance (e.g., EUDR), and environmental circularity. Existing supply chain models are characterized by fragmented information systems, where Operational Technology (OT) remains disconnected from Enterprise IT, resulting in traceability gaps and underutilized biomass waste. This study addresses these challenges by designing a comprehensive Enterprise Architecture (EA) for a Circular Smart Palm ecosystem. Adopting a Design Science Research (DSR) methodology, the research applies the TOGAF Architecture Development Method (ADM), supported by ArchiMate 3.1 modeling, to develop an integrated architectural blueprint. The proposed architecture consolidates blockchain-enabled traceability, digital export compliance, IoT-driven bioenergy valorization, and value-added kernel processing into a unified enterprise framework. The resulting architecture is qualitatively validated through architectural consistency analysis and gap assessment between the As-Is and To-Be states. From a theoretical perspective, this study contributes to Enterprise Architecture literature by extending EA as an integrative mechanism for circular bioeconomy implementation in sustainability-driven agribusiness ecosystems. The findings demonstrate that enterprise-level architectural integration can transform sustainability compliance from an operational constraint into a strategic enabler for traceability, circular value creation, and digital governance.

**Keywords:** Enterprise Architecture; Design Science Research; TOGAF ADM; Circular Bioeconomy; Palm Oil Traceability; Blockchain.

## INTRODUCTION

The agricultural sector, particularly the palm oil industry, is undergoing a structural transformation driven by accelerated sustainability regulations and digitalization pressures in the post-2021 global economy. While sectors such as financial services have successfully transitioned into integrated digital ecosystems, agribusiness operations—especially palm oil supply chains—remain largely characterized by fragmented, linear, and data-disconnected models. This structural lag presents a critical vulnerability as the industry faces a sustainability trilemma: balancing productivity optimization, stringent regulatory compliance such as the European Union Deforestation Regulation (EUDR), and the socio-economic inclusion of smallholders within global value chains (Olech & Anyebe, 2024; Wahyuni et al., 2025).

A fundamental driver of this challenge lies in the persistent disconnect between Operational Technology (OT) and Information Technology (IT). In many palm oil enterprises, data related to Fresh Fruit Bunch (FFB) provenance is still manually recorded or stored in isolated systems, resulting in information silos that sever traceability between upstream plantation activities and downstream commercial processes. Simultaneously, the prevailing linear “take–make–dispose” production paradigm continues to treat biomass by-products—particularly Palm Oil Mill Effluent (POME)—as environmental liabilities rather than strategic resources. Recent studies highlight that such inefficiencies not only inflate operational costs but also expose firms to reputational risk, regulatory exclusion, and the loss of access to premium sustainability-driven markets (Judijanto, 2024; Environmental Technology & Innovation, 2023).

Addressing these interconnected challenges requires more than the adoption of isolated digital tools. Instead, a holistic architectural blueprint is necessary to align sustainability objectives with enterprise-wide digital

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capabilities. Enterprise Architecture (EA) provides a strategic mechanism to integrate business processes, information systems, and technology infrastructure into a coherent transformation roadmap. Among existing frameworks, The Open Group Architecture Framework (TOGAF) is particularly suitable due to its iterative Architecture Development Method (ADM), which has been validated in recent studies as an effective approach for managing complex digital and sustainability-oriented transformations across industries (Vinardo et al., 2023; Emerald Insight, 2024).

Accordingly, this research aims to design a comprehensive “Smart Palm” Enterprise Architecture that orchestrates traceability, regulatory compliance, and circular economy practices within a unified digital ecosystem. Unlike prior studies that address blockchain-based traceability or bioenergy valorization as standalone solutions, this study adopts an integrated architectural perspective. By employing TOGAF ADM and ArchiMate modeling, the proposed architecture converges blockchain-enabled immutable traceability with IoT-driven bioenergy valorization, enabling the transformation of environmental compliance from an operational burden into a source of competitive advantage. The proposed model demonstrates how digital interoperability can unlock new revenue streams through premium certified palm oil products, renewable energy generation, and carbon credit monetization within a circular smart palm ecosystem.

Despite the growing body of research on blockchain-based traceability and circular economy initiatives in the palm oil and agri-food sectors, existing studies predominantly address these domains in isolation. Prior research has largely focused either on the technical implementation of blockchain for transparency and compliance, or on engineering-oriented bioenergy and waste valorization solutions, without providing an enterprise-level architectural integration that aligns sustainability objectives, digital governance, and organizational strategy. Moreover, the application of Enterprise Architecture frameworks in this context remains limited to compliance-oriented traceability, leaving the circular bioeconomy dimension underexplored.

To address these gaps, this study adopts a Design Science Research approach to design a TOGAF-based Enterprise Architecture for a Circular Smart Palm ecosystem. The proposed architecture systematically integrates blockchain-enabled traceability, IoT-driven bioenergy valorization, and export compliance within a unified enterprise governance framework.

From a scientific perspective, this research contributes to the Enterprise Architecture literature by extending EA beyond IT alignment toward an integrative mechanism for circular bioeconomy orchestration in sustainability-driven agribusiness ecosystems. By positioning Enterprise Architecture as a conceptual bridge between Operational Technology, digital governance, and circular value creation, this study advances the theoretical understanding of EA’s role in enabling systemic sustainability transformation.

## LITERATURE REVIEW

This section delineates the theoretical foundations and empirical antecedents necessary to construct the proposed “Smart Palm” Enterprise Architecture. The review is stratified into specific domains to provide a comprehensive understanding of the technological and strategic components involved.

### Digital Transformation and Sustainability in the Palm Oil Industry

The palm oil industry has experienced increasing digitalization pressure following heightened global sustainability regulations and decarbonization agendas introduced after 2021. Regulatory instruments such as the European Union Deforestation Regulation (EUDR) have fundamentally altered the governance landscape of agri-food supply chains by requiring verifiable proof of deforestation-free sourcing and transparent land-use data. Recent studies emphasize that sustainability compliance has shifted from voluntary certification toward mandatory, data-driven accountability mechanisms embedded within enterprise information systems (Olech & Anyebe, 2024; Wahyuni et al., 2025).

However, despite growing adoption of digital technologies, many palm oil enterprises continue to operate within fragmented operational structures. Production, logistics, compliance, and sustainability reporting are often supported by disconnected applications, limiting end-to-end visibility and weakening decision-making capabilities. This fragmentation underscores the need for architectural integration rather than isolated technological deployment (Emerald Insight, 2024).

### Blockchain-Based Traceability in Agri-Food Supply Chains

Blockchain technology has emerged as a dominant digital enabler for traceability within agri-food supply chains due to its immutable, decentralized, and auditable data structures. Post-2021 literature consistently identifies blockchain as a foundational infrastructure for farm-to-fork transparency, particularly in high-risk commodities such as palm oil (Computers and Electronics in Agriculture, 2024; Wahyuni et al., 2025).

Several studies demonstrate that blockchain-based traceability systems significantly enhance data integrity by recording critical provenance attributes such as geolocation, harvest time, and producer identity. Rajput et al. (2025) further argue that blockchain adoption supports circular economy principles by enabling accountability

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across production cycles and facilitating sustainability-oriented value creation. Nevertheless, most existing architectures remain technology-centric, focusing on ledger design, consensus mechanisms, or data structures, while overlooking enterprise-level integration with business processes and regulatory workflows (MDPI Sensors, 2023).

Moreover, Zaw et al. (2025) highlight that while TOGAF-driven blockchain frameworks improve governance and access control, many implementations still lack integration with operational data sources such as IoT sensors or waste management systems, limiting their strategic impact.

### **Circular Economy and Bioenergy Valorization in the Palm Oil Sector**

The circular economy paradigm has gained prominence in the palm oil industry as a strategic response to environmental externalities and resource inefficiency. Recent research emphasizes the transformation of palm oil biomass waste—particularly Palm Oil Mill Effluent (POME)—into renewable energy and bio-based products as a critical decarbonization pathway (Environmental Technology & Innovation, 2023; Process Safety & Environmental Protection, 2025).

Judijanto (2024) provides a comprehensive review of palm oil valorization technologies, highlighting anaerobic digestion as a mature and economically viable solution for converting POME into biogas. More recent studies extend this perspective by framing bioenergy production as part of a broader circular bioeconomy ecosystem, where waste streams generate both physical outputs (energy) and digital sustainability assets such as carbon credits (Frontiers in Sustainability, 2025).

Despite these advancements, the majority of bioenergy studies remain engineering-oriented and detached from enterprise digital governance. The lack of integration between bioenergy operations and enterprise information systems limits the monetization of environmental benefits and weakens traceability between waste generation, emissions reduction, and financial reporting (Integrated Circular Economy & Green Supply Chain Planning Model, 2025).

### **Enterprise Architecture as an Integrative Framework**

Enterprise Architecture (EA) has been widely recognized as a strategic instrument for managing complex digital transformations, particularly in sustainability-driven contexts. Recent EA research emphasizes its role in aligning business strategy, information systems, and technological infrastructure into a coherent transformation roadmap (Emerald Insight, 2024; ResearchGate, 2025).

In supply chain contexts, EA enables interoperability between Operational Technology (OT) and Information Technology (IT), allowing real-time operational data to inform strategic decision-making and compliance processes. Studies demonstrate that without an architectural framework, digital initiatives tend to exacerbate system fragmentation rather than resolve it (Enterprise Architecture Development to Strengthen Sustainability in Supply Chains, 2025).

The Open Group Architecture Framework (TOGAF), particularly its Architecture Development Method (ADM), is increasingly applied in sustainability-oriented transformations due to its structured, iterative, and governance-driven approach. Zaw et al. (2025) confirm that TOGAF-based architectures enhance traceability governance in agri-food systems; however, they also note that most implementations focus narrowly on compliance, without integrating circular economy value creation.

### **The Open Group Architecture Framework (TOGAF)**

Rather than serving merely as an IT architecture framework, TOGAF is increasingly positioned as a strategic governance mechanism for managing complex, sustainability-driven transformations. In the context of the palm oil industry, where regulatory compliance, traceability, and circular economy initiatives intersect across organizational and technological boundaries, TOGAF ADM provides a structured approach to align business strategy, information systems, and operational technologies. Its iterative and capability-oriented nature makes TOGAF particularly suitable for orchestrating sustainability objectives that extend beyond isolated system implementations, enabling enterprise-wide integration of digital governance and circular value creation.

### **ArchiMate Modeling Language**

ArchiMate is employed in this study not as a generic modeling notation, but as an integrative language that enables explicit visualization of relationships between business value creation, information systems, and physical operational infrastructure. In sustainability-driven palm oil ecosystems, where traceability, bioenergy operations, and compliance processes span both Operational Technology and Information Technology, ArchiMate facilitates architectural coherence and stakeholder understanding. By making dependencies and value flows explicit across layers, ArchiMate supports the design and qualitative validation of enterprise architectures aimed at circular bioeconomy integration rather than isolated digital solutions.

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**Previous Research & State of the Art**

To position this study within the contemporary body of knowledge, a comparative analysis of recent research related to blockchain traceability, circular economy, and Enterprise Architecture in agri-food systems was conducted. Table 1 summarizes the current state of the art and highlights the research gaps addressed by this study.

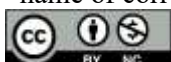
Table 1. State of the Art Comparison

Authors	Focus Area	Methodology	Limitation/Research Gap
<b>Wahyuni et al. (2025)</b>	Blockchain in Food Supply Chains	Literature Review & Bibliometric Analysis	Provides comprehensive mapping of blockchain research but does not address enterprise-level architectural integration or circular economy processes.
<b>Computers &amp; Electronics in Agriculture (2024)</b>	Blockchain-based Agricultural Traceability	Survey & Evaluation Framework	Focuses on technical evaluation of traceability systems; lacks integration with bioenergy or sustainability monetization.
<b>Rajput et al. (2025)</b>	Blockchain & Circular Economy	Conceptual Framework	Explores blockchain-circular economy linkage but does not provide an enterprise architecture or implementation roadmap.
<b>Judijanto (2024)</b>	Palm Oil Waste Valorization	Technology Review	Emphasizes bioenergy and valorization technologies without integration into digital governance or enterprise systems.
<b>Zaw et al. (2025)</b>	TOGAF-based Traceability	Food TOGAF Framework ADM	Focuses on traceability governance; does not integrate circular bioeconomy or OT-based bioenergy processes.
<b>This Research (2025)</b>	<b>Integrated Smart Palm Ecosystem</b>	<b>TOGAF ArchiMate ADM &amp;</b>	<b>Novelty:</b> Integrates Blockchain Traceability AND Bioenergy/Circular Economy into a unified Enterprise Architecture.

As synthesized in Table 1, prior research demonstrates substantial progress in individual domains of blockchain-based traceability and circular economy practices within agri-food supply chains. Nevertheless, the comparative analysis reveals a structural fragmentation in existing studies, where technological solutions are developed and evaluated in isolation without an enterprise-level architectural perspective. This fragmentation limits the ability of organizations to align sustainability initiatives with digital governance, strategic decision-making, and cross-domain value creation, thereby highlighting the need for an integrative Enterprise Architecture approach.

Overall, the existing literature demonstrates that the technologies required to support sustainability in the palm oil industry such as blockchain for traceability, IoT for operational monitoring, and bioenergy systems for waste valorization are already well established and technically mature. However, prior studies predominantly address these solutions in a fragmented manner, focusing on individual technologies or operational domains without providing an enterprise-level architectural integration. The primary research gap therefore lies not in the absence of technological capabilities, but in the lack of a holistic Enterprise Architecture that orchestrates these heterogeneous solutions into a coherent governance and value-creation framework.

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This study addresses this gap by positioning Enterprise Architecture, grounded in TOGAF ADM and articulated through ArchiMate modeling, as the integrative layer that aligns traceability, regulatory compliance, and circular bioeconomy initiatives within a unified Smart Palm ecosystem.

**METHOD**

This study adopts a **Design Science Research (DSR)** paradigm, where the primary research outcome is a prescriptive artifact in the form of an Enterprise Architecture blueprint. DSR is particularly suitable for this research as it focuses on the design and evaluation of innovative solutions to complex organizational problems through the creation of structured artifacts. In this context, the artifact developed is a TOGAF-based Enterprise Architecture designed to address traceability, sustainability, and circular economy challenges within the palm oil industry.

The research methodology is structured into five sequential phases, ensuring a systematic progression from problem identification to architectural design and validation. The overall research framework is illustrated in Figure 1.

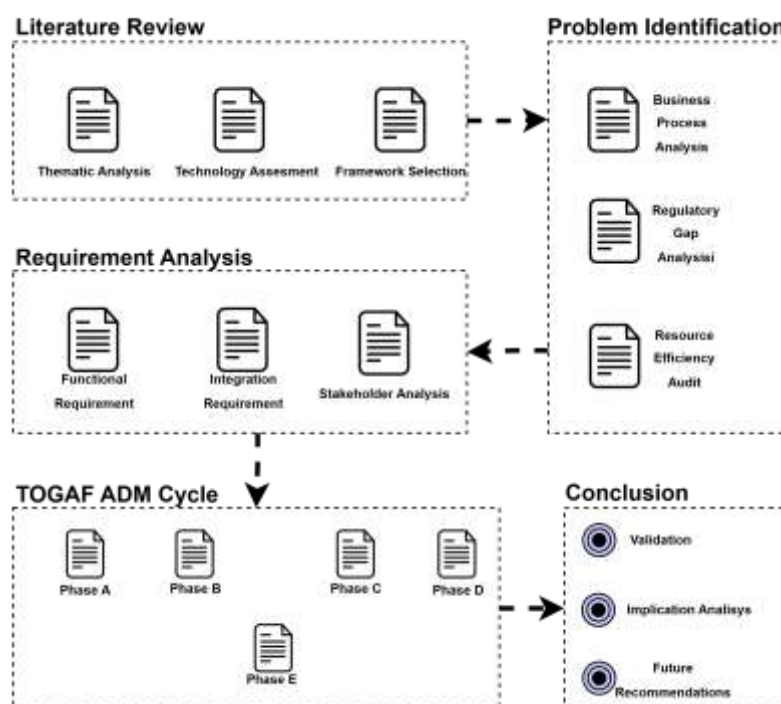


Fig 1. Research Methodology Flowchart

The methodology consists of five distinct phases:

**Literature Review**

The research begins with a comprehensive literature review to establish a strong theoretical foundation and identify the current state of research in digital transformation and sustainability within agri-food supply chains. The review focuses on recent studies ( $\geq 2021$ ) related to blockchain-based traceability, circular economy and bioenergy valorization in the palm oil industry, and Enterprise Architecture frameworks such as TOGAF and ArchiMate.

This phase serves two primary purposes: (1) to assess the maturity and limitations of existing technological and architectural approaches, and (2) to identify research gaps where enterprise-level integration between traceability systems and circular economy processes remains insufficiently addressed. The findings from this phase inform the formulation of the research problem and architectural requirements.

**Problem Identification**

Based on insights derived from the literature review, the study proceeds to problem identification. This phase aims to formalize the core challenges faced by the palm oil industry in the context of sustainability-driven digital transformation. Three primary problems are identified: (1) the lack of end-to-end traceability linking smallholders to downstream markets, (2) the absence of verifiable and integrated data to support regulatory compliance such

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as EUDR, and (3) the underutilization of biomass waste, particularly Palm Oil Mill Effluent (POME), which is commonly treated as an environmental liability rather than a value-generating resource. These challenges are further exacerbated by the systemic disconnect between Operational Technology (OT) deployed in plantations and mills, and Information Technology (IT) systems used for enterprise management and reporting. This phase establishes the need for a holistic architectural approach rather than isolated technological solutions.

### Requirement Analysis

Following problem identification, a requirement analysis is conducted to translate the identified challenges into functional and non-functional architectural requirements. Functional requirements include the ability to capture geospatially accurate Fresh Fruit Bunch (FFB) provenance data, integrate operational data from mills and bioenergy facilities, and automate sustainability and carbon accounting processes. Non-functional requirements focus on data integrity, interoperability, scalability, and regulatory compliance.

The requirement analysis ensures that the proposed architecture aligns with business objectives, sustainability goals, and regulatory demands. These requirements form the basis for designing the target Enterprise Architecture in subsequent TOGAF ADM phases.

### TOGAF ADM Cycle

The core of this research utilizes The Open Group Architecture Framework (TOGAF) Version 9.2, specifically the Architecture Development Method (ADM). This iterative cycle is chosen for its ability to align complex business strategies with IT execution. The specific phases executed in this study are:

Preliminary Phase: Defining the framework and principles for the digital transformation.

Phase A (Architecture Vision): Establishing the strategic vision of "Smart Palm, Green Future" and identifying key stakeholders.

Phase B (Business Architecture): Modeling the four key revenue streams (Premium CPO, Export, Bioenergy, Derivatives) using ArchiMate to visualize business processes.

Phase C (Information System Architecture): Designing the Data Architecture (Blockchain ledgers, Carbon registries) and Application Architecture (ERP Modules).

Phase D (Technology Architecture): Defining the physical infrastructure, including IoT sensors, Cloud servers, and Connectivity layers.

### Artifact Evaluation

In alignment with the Design Science Research paradigm, the evaluation of the proposed artifact focuses on assessing the relevance, coherence, and theoretical soundness of the designed Enterprise Architecture rather than empirical system performance. Given the conceptual and architectural nature of this study, a qualitative evaluation approach is adopted.

The evaluation is conducted through three complementary criteria. First, an architectural consistency check is performed to examine the logical alignment and traceability across ArchiMate layers, ensuring that business objectives, application services, and technology components are coherently integrated within the proposed TOGAF-based architecture. This consistency assessment verifies that sustainability goals, traceability requirements, and circular economy processes are systematically supported by the underlying information systems and infrastructure.

Second, a stakeholder alignment assessment is applied to evaluate whether the architectural elements address the needs and expectations of key stakeholders, including smallholders, mill operators, regulatory bodies, and international buyers. This assessment ensures that the proposed architecture supports regulatory compliance, operational feasibility, and value creation across the palm oil value chain.

Third, an expert-informed architectural validation is incorporated by grounding the design decisions in established Enterprise Architecture principles and contemporary scholarly literature. The proposed architecture is evaluated against best practices derived from prior TOGAF-based and sustainability-oriented EA studies, serving as a form of expert-based validation through theoretical triangulation.

Collectively, these evaluation criteria provide a structured qualitative validation of the artifact, demonstrating that the proposed Enterprise Architecture satisfies the defined requirements and effectively addresses the identified research gap related to fragmented sustainability solutions in the palm oil industry.

### Conclusion

The proposed Enterprise Architecture is validated through a qualitative evaluation approach. Validation is conducted by assessing the consistency and alignment of architectural elements across ArchiMate layers, ensuring coherence between business objectives, application services, and technology components. Additionally, a gap

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analysis is used to evaluate the extent to which the proposed “To-Be” architecture addresses the identified shortcomings of the existing “As-Is” state.

The methodology concludes by synthesizing the architectural artifacts and evaluating their ability to resolve the sustainability trilemma of productivity, regulatory compliance, and circular economy integration. This approach confirms the feasibility and relevance of the proposed architecture as a strategic blueprint for digital transformation in the palm oil industry.

**RESULT**

This section presents the architectural artifacts produced through the execution of TOGAF ADM Phases A–D. The primary research output is a set of integrated Enterprise Architecture blueprints that operationalize blockchain-based traceability and IoT-driven circular economy within the palm oil industry.

**Phase A: Architecture Vision**

The initial phase established the strategic direction based on the Strategic Business Model.

1. Vision Statement: "Smart Palm, Green Future" - transforming the organization from a commodity supplier to a data-driven, sustainable energy and agriculture enterprise.
2. Stakeholder Map: Key entities identified include Smallholders (Source S1), International Buyers (Market S3), and Renewable Energy Firms (Partner S9).
3. Scope: The architecture covers the end-to-end flow from plantation management to global export and waste valorization.

THE BUSINESS MODEL CANVAS				
KEY PARTNERS	KEY ACTIVITIES	VALUE PROPOSITIONS	CUSTOMER RELATIONSHIPS	CUSTOMER SEGMENTS
<ul style="list-style-type: none"> <li>• Palm oil smallholders and plantation companies</li> <li>• Fresh Fruit Bunch (FFB) suppliers and intermediaries</li> <li>• Palm oil mills (PKS) and kernel processing facilities</li> <li>• Logistics and transportation providers</li> <li>• Certification and sustainability bodies (RSPO, ISPO)</li> <li>• Research institutions</li> </ul>	<ul style="list-style-type: none"> <li>• Plantation cultivation, harvesting, and agronomic management</li> <li>• Processing of FFB into crude palm oil (CPO) and derivatives</li> <li>• Kernel processing and value-added production</li> </ul>	<ul style="list-style-type: none"> <li>• Availability of high-quality palm-based products</li> <li>• Certified sustainable palm oil production</li> <li>• Premium-grade CPO, kernel flour, and downstream derivatives</li> <li>• Verified sustainability and environmental compliance</li> <li>• Traceable production aligned with global</li> </ul>	<ul style="list-style-type: none"> <li>• Long-term contracts with industrial buyers</li> <li>• Cooperative partnerships with smallholders</li> <li>• Technical and sustainability support</li> </ul>	<ul style="list-style-type: none"> <li>• Palm oil mills and processing industries</li> <li>• Palm-based food manufacturers</li> <li>• International commodity buyers</li> <li>• Export markets (e.g., India, China, Europe)</li> <li>• Renewable energy sector (biofuel/B35–B50 programs)</li> </ul>
	<p><b>KEY RESOURCES</b></p> <ul style="list-style-type: none"> <li>• Plantation land and cultivation infrastructure</li> <li>• Human resources and operational expertise</li> <li>• Palm oil mills and kernel</li> </ul>		<p><b>CHANNELS</b></p> <ul style="list-style-type: none"> <li>• Direct contractual agreements with industrial buyers</li> <li>• Distributor networks</li> <li>• Export and international trade channels</li> </ul>	
<p><b>COST STRUCTURE</b></p> <ul style="list-style-type: none"> <li>• Plantation operational and labor costs</li> <li>• Logistics and transportation expenses</li> <li>• Processing and milling costs</li> <li>• Sustainability certification expenses</li> <li>• Research and development investments</li> <li>• Environmental management and compliance costs</li> </ul>		<p><b>REVENUE STREAMS</b></p> <ul style="list-style-type: none"> <li>• Premium CPO sales</li> <li>• Kernel and derivative product sales</li> <li>• Export contracts</li> <li>• Bioenergy and renewable resource revenue</li> </ul>		
<p>1</p>		<p>Architecture Figure 3 illus for sourcing and processi</p>		

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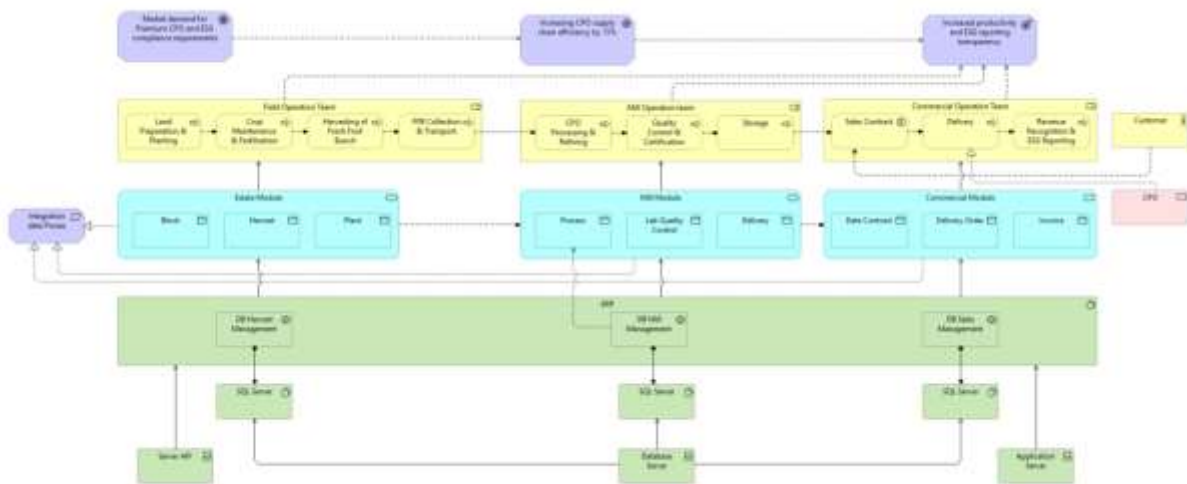


Fig 2. Revenue Stream Premium CPO Sales

The Premium CPO Sales architecture is designed to establish end-to-end traceability and quality assurance from upstream smallholders to the palm oil mill, thereby enabling the production of certified premium-grade crude palm oil. In this architecture, plantation-level activities—specifically land preparation and harvesting—are digitally integrated with the mill reception process, eliminating the traditional discontinuity between upstream agricultural operations and downstream industrial processing.

At the point of Fresh Fruit Bunch (FFB) delivery, a Digital Grading Service is introduced as a core business service to objectively assess fruit quality based on standardized parameters. This service replaces subjective and manual grading practices by utilizing digital inputs that are recorded and associated with specific plantation blocks and farmer identifiers. As a result, quality data becomes verifiable, auditable, and directly linked to production outcomes within the enterprise system.

The integration of these processes and services enables the mill to produce not generic commodity CPO, but Traceable Premium CPO, whose provenance can be traced back to defined geo-referenced plantation units. This architectural design transforms traceability into a value-creating capability, allowing producers to differentiate their products, comply with international sustainability requirements, and access premium markets that demand verified origin and quality assurance.

## 2. Revenue Stream 2

Global Export Compliance Architecture Figure 4 depicts the export fulfillment process designed to mitigate regulatory risks.

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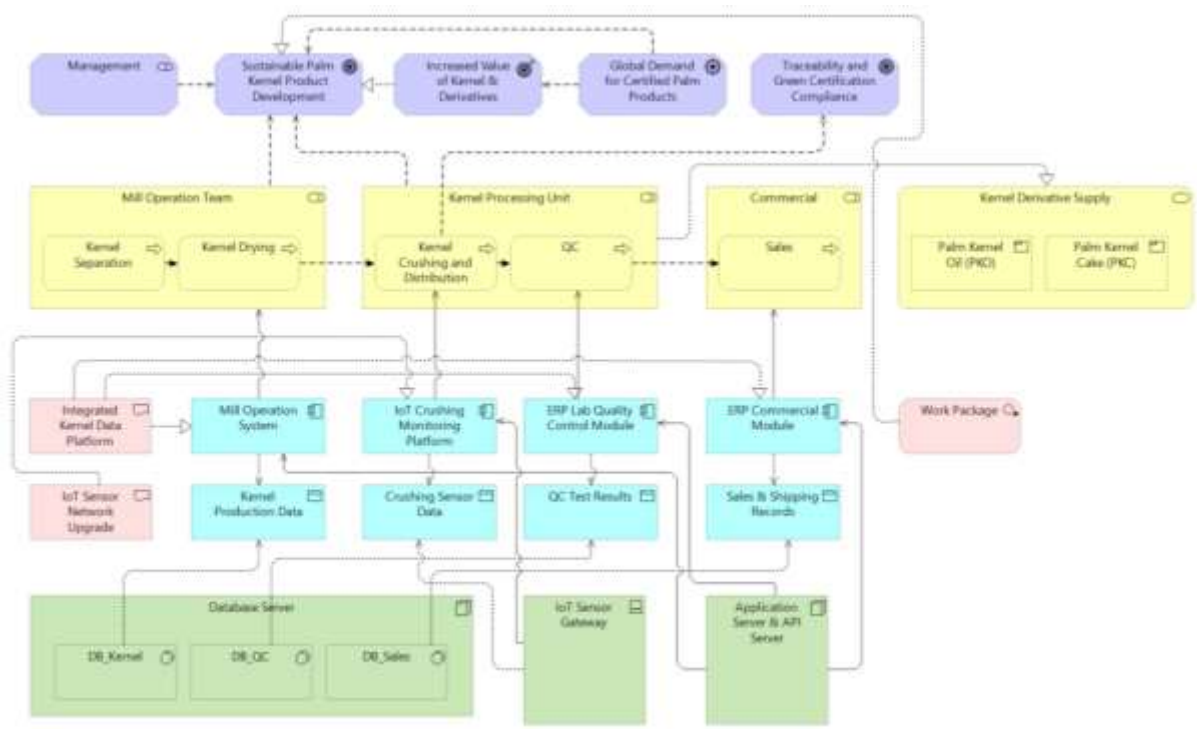


Fig 3. Revenue Stream Global Export Compliance

The Global Export Compliance architecture reframes export activities as an enterprise governance capability rather than a standalone logistical process. The proposed design structurally embeds regulatory and sustainability compliance within the business architecture, ensuring that export readiness is governed consistently across commercial, operational, and documentation domains.

From an architectural standpoint, compliance verification is positioned as an integrated enterprise service that is activated alongside commercial engagement, enabling regulatory requirements to be addressed proactively rather than reactively. This architectural arrangement reduces dependency on manual controls and minimizes the risk of downstream disruption caused by incomplete or misaligned compliance information.

As an architectural outcome, the proposed design enables export compliance to be managed as a coherent, enterprise-wide capability that aligns contractual commitments, logistics coordination, and sustainability governance within a unified digital framework, thereby supporting reliable access to international markets without reliance on fragmented control mechanisms.

### 3. Revenue Stream 3

Bioenergy & Circular Economy Architecture Figure 5 presents the novel waste-to-energy business model.

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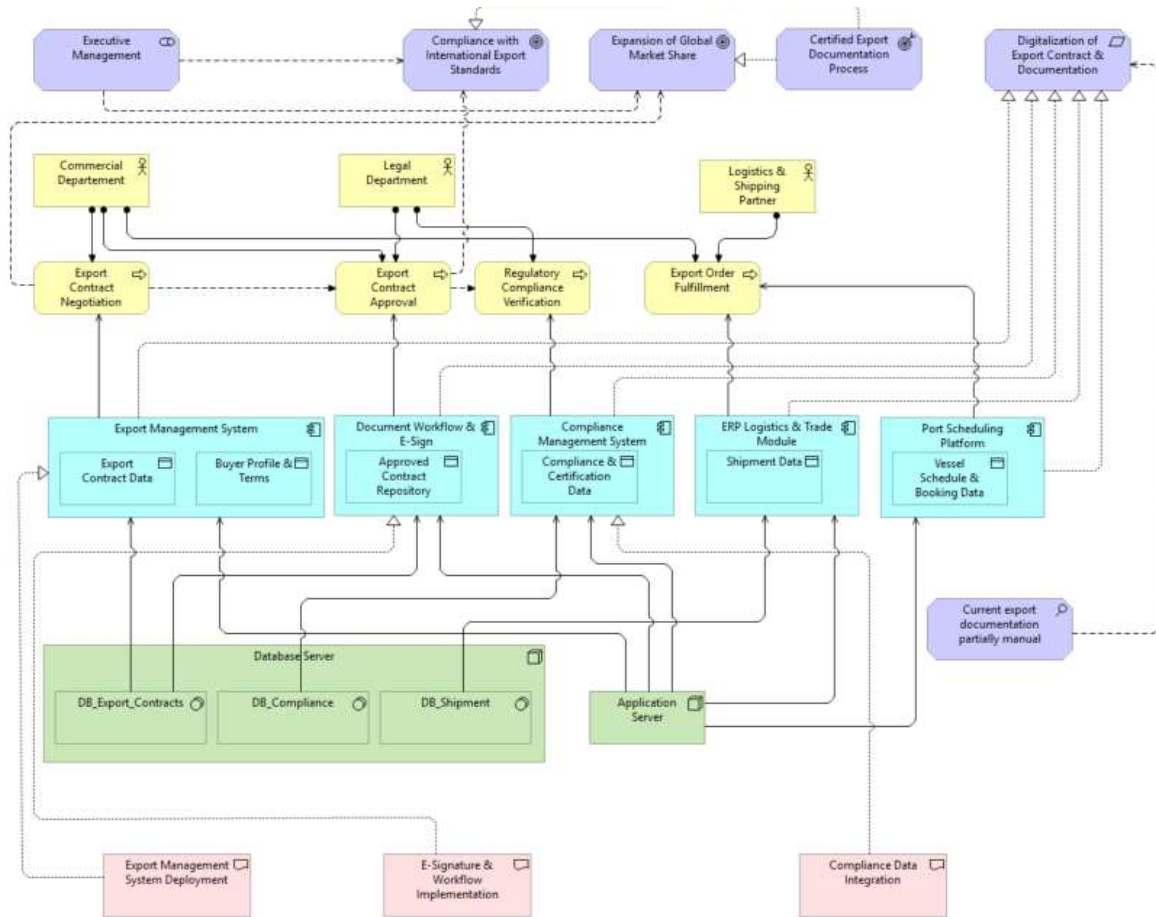


Fig 4. Revenue Stream Bioenergy & Circular Economy

The Bioenergy and Circular Economy architecture repositions palm oil mill by-products as enterprise-managed resources within a circular bioeconomy framework rather than as isolated operational waste streams. The proposed design introduces an architectural separation between physical bioenergy operations and enterprise-level sustainability governance, enabling waste valorization activities to be systematically governed within the broader enterprise architecture.

From an architectural perspective, IoT-enabled bioenergy operations are structurally integrated with enterprise data and governance services, allowing environmental performance data to be captured, governed, and utilized at the enterprise level. This integration enables sustainability metrics to be consistently linked with traceability, reporting, and decision-making mechanisms, without emphasizing the underlying engineering processes.

As an architectural outcome, the proposed design establishes circular economy implementation as an enterprise capability, where bioenergy production and emissions-related data are managed within a unified governance framework that supports sustainability accounting and strategic oversight, rather than being confined to isolated operational systems.

#### 4. Revenue Stream 4

Kernel Derivative Architecture Figure 6 outlines the value-added manufacturing process.

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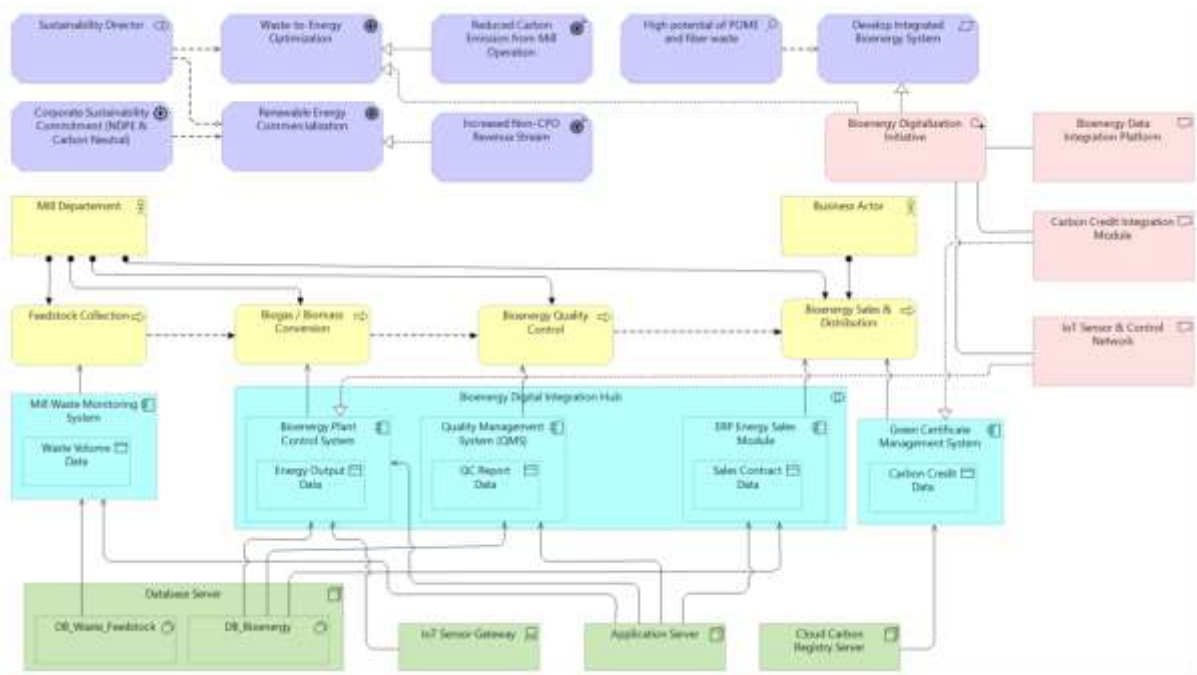


Figure 5. Revenue Stream Kernel Derivative

The Kernel Derivative architecture positions downstream kernel processing as a structured enterprise capability rather than a secondary operational activity. The proposed design integrates kernel-based manufacturing within the overall enterprise architecture, enabling quality governance and product differentiation to be managed consistently across downstream value-added processes.

From an architectural standpoint, quality control is embedded as an enterprise service that governs downstream processing activities, ensuring alignment between production specifications, traceability requirements, and enterprise data standards. This architectural arrangement enables kernel derivatives to be managed within the same governance framework as upstream and midstream operations, rather than as isolated manufacturing functions.

As an architectural outcome, the proposed design establishes kernel derivatives as part of an integrated value-added capability within the Smart Palm ecosystem, reinforcing enterprise-level coherence across product diversification, quality governance, and sustainability-oriented production without reliance on fragmented operational controls.

**Phase C: Information System Architecture**

To support the business processes above, the following systems were designed:

1. Application Architecture A modular ERP ecosystem is proposed:
  - Estate Module: Mobile-based input for agronomic data (fertilizer, yield).
  - Mill & Bioenergy Module: SCADA-integrated system to monitor OER (Oil Extraction Rate) and Biogas volume.
  - Commercial & Export Module: Manages contracts, hedging, and e-signatures.
2. Data Architecture The design prioritizes data integrity through:
  - Traceability Ledger: A blockchain-based structure storing "Genesis Data" (Location, Time, Farmer ID).
  - Carbon Registry: A database recording emissions avoided (tCO<sub>2</sub>e) for trading purposes.

The resulting Business Architecture demonstrates how sustainability objectives can be translated into monetizable value streams, thereby transforming traceability and waste management from compliance-driven activities into strategic business capabilities.

**Phase D: Technology Architecture**

The infrastructure layer is designed to bridge the physical-digital divide:

- IoT Layer: Deployment of sensors at Weighbridges (Weight), Sterilizers (Temperature), and Digester Tanks (Pressure).
- Connectivity: Utilization of LoRaWAN for wide-area coverage in remote estates, ensuring data transmission to the Central Cloud ERP.

The Technology Architecture enables continuous data acquisition from physical operations, effectively bridging Operational Technology and Information Technology within a unified enterprise platform.

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## DISCUSSIONS

The results of this study indicate that the sustainability challenges faced by the palm oil industry are not merely operational or technological, but fundamentally architectural in nature. The proposed Smart Palm Enterprise Architecture demonstrates how fragmented traceability practices, linear waste management models, and disconnected digital initiatives can be systematically transformed through an integrated TOGAF-based architectural framework. By focusing on TOGAF Phase E (Opportunities and Solutions), this section interprets the architectural outcomes and evaluates their relevance against contemporary industrial and regulatory challenges.

### Gap Analysis: Transition from As-Is to To-Be Architecture

The gap analysis reveals substantial structural differences between the existing operational model (“As-Is”) and the proposed “Smart Palm” target architecture (“To-Be”). As summarized in Table 2, the current state is characterized by paper-based traceability, siloed sustainability reporting, and manual export compliance processes. These limitations expose organizations to regulatory risks, inefficiencies, and lost market opportunities.

In contrast, the proposed architecture establishes a digitally integrated ecosystem where blockchain-enabled traceability ensures immutable farm-to-mill visibility, IoT-enabled bioenergy systems convert waste liabilities into measurable assets, and automated export compliance reduces operational risk. This transition illustrates how Enterprise Architecture can function as a strategic mechanism to close operational gaps, rather than merely documenting existing systems. The findings align with recent literature emphasizing the need for enterprise-level integration to operationalize sustainability objectives in agri-food supply chains (Wahyuni et al., 2025; Zaw et al., 2025).

### Addressing the Sustainability Trilemma

The proposed architecture directly addresses the sustainability trilemma faced by the palm oil industry—economic viability, environmental compliance, and social inclusion—through architectural orchestration rather than isolated technological adoption. From an economic perspective, the diversification of revenue streams into bioenergy production and kernel-based derivatives reduces dependency on volatile crude palm oil (CPO) markets. This supports recent arguments that sustainability initiatives must be economically embedded within core business models to ensure long-term viability (Rajput et al., 2025).

In terms of environmental compliance, blockchain-based traceability enables verifiable proof of deforestation-free sourcing, supporting regulatory requirements such as the European Union Deforestation Regulation (EUDR). By embedding compliance mechanisms directly into enterprise systems, sustainability shifts from a post-hoc reporting activity to a real-time operational capability. Furthermore, social inclusion is enhanced through the Estate Module, which digitally integrates smallholders into the value chain, enabling transparent grading, fair pricing, and improved access to global markets. This finding reinforces recent studies that highlight digital inclusion as a critical pillar of sustainable agri-food ecosystems (Olech & Anyebe, 2024).

### Novelty: Convergence of Operational Technology and Information Technology

A key contribution of this research lies in demonstrating the convergence of Operational Technology (OT) and Information Technology (IT) within a unified Enterprise Architecture. Unlike traditional architectures where mill operations and enterprise systems operate independently, the proposed design integrates IoT-enabled operational data directly into enterprise applications and financial systems. For example, in the bioenergy value stream, methane capture data measured by IoT sensors is automatically translated into carbon credit records within the enterprise ledger, enabling real-time sustainability accounting and monetization.

This convergence operationalizes the circular economy concept by linking physical waste processing activities with digital governance and financial realization. Recent circular economy and bioeconomy studies emphasize the importance of digital integration for transforming environmental performance into measurable business value; however, they often lack an enterprise architectural perspective (Judijanto, 2024; Frontiers in Sustainability, 2025). This study extends the literature by demonstrating how Enterprise Architecture serves as the enabling layer that connects cyber-physical systems with strategic sustainability outcomes.

### Implementation Strategy and Practical Implications

Based on the architectural dependencies identified, a phased implementation roadmap is proposed to ensure feasibility and risk mitigation. The initial phase focuses on establishing the digital foundation through core ERP deployment and estate-level data capture, ensuring reliable and standardized data intake. The second phase emphasizes connectivity and OT integration through IoT sensor deployment and mill infrastructure upgrades. The final phase activates advanced capabilities, including blockchain-based traceability and bioenergy monetization, enabling differentiation through premium exports and carbon trading.

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From a practical standpoint, this phased strategy provides industry practitioners with a realistic pathway for transitioning toward a circular smart palm ecosystem without disrupting existing operations. Nevertheless, this study is limited to architectural design and qualitative validation. Future research should extend this work by examining implementation governance, cybersecurity architecture, and quantitative assessments of economic and environmental impact.

Despite its conceptual contributions, this study is subject to several limitations that should be acknowledged. As a Design Science Research focused on Enterprise Architecture design, the proposed Smart Palm architecture is inherently conceptual and does not constitute an empirical implementation. Consequently, its effectiveness in real-world operational environments may be influenced by organizational readiness, governance maturity, and resource availability.

From an implementation perspective, translating the proposed architecture into practice introduces several risks. These include governance challenges related to cross-organizational coordination among smallholders, mills, and external partners; cybersecurity risks associated with integrating IoT devices and blockchain platforms into enterprise systems; and cost-related constraints stemming from infrastructure deployment and change management. Additionally, the architectural flexibility required to adapt to evolving sustainability regulations may impose further complexity in long-term governance.

These limitations do not diminish the architectural validity of the proposed framework, but rather highlight the need for future research to examine implementation governance, cybersecurity architecture, and economic feasibility as extensions of the present study.

## CONCLUSION

From an academic perspective, this study contributes to the Enterprise Architecture literature by demonstrating how EA can be positioned beyond traditional IT alignment toward an integrative mechanism for orchestrating circular bioeconomy initiatives in sustainability-driven agribusiness contexts. By applying a Design Science Research approach grounded in TOGAF ADM and articulated through ArchiMate modeling, this research advances the theoretical understanding of Enterprise Architecture as a governance and integration layer that aligns Operational Technology, digital traceability, and sustainability objectives within a unified conceptual framework. The proposed architecture extends existing EA applications in agri-food systems by explicitly incorporating circular economy and bioenergy dimensions as enterprise-level capabilities.

From a policy and practical standpoint, the proposed Smart Palm Enterprise Architecture provides a structured reference model for industry practitioners and policymakers seeking to operationalize sustainability regulations such as deforestation-free sourcing and carbon accountability. By embedding traceability, export compliance, and circular economy processes within an enterprise governance framework, the architecture offers a systematic pathway for aligning regulatory requirements with organizational strategy and digital infrastructure. This approach supports informed decision-making, risk mitigation, and long-term sustainability planning in the palm oil industry, while remaining adaptable to evolving regulatory and market conditions.

Future research is encouraged to extend this study by examining implementation governance, cybersecurity architectures, and quantitative assessments of economic and environmental impacts. Such investigations would further validate the applicability of the proposed framework and support its adoption in real-world palm oil ecosystems.

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