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Introduction of Palm GreenChain, a blockchain-based framework for enhanced traceability, transparency and accountable green bond financing in Malaysia

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Abstract
This study employs a theoretical, system design–based methodology to propose the Palm GreenChain framework—a blockchain-based platform aimed at enhancing traceability, transparency, financial coverage, and accountability in green bond financing for sustainable palm oil production in Malaysia. The methodology integrates Ethereum-compatible smart contracts, ESG oracles, IPFS-based data storage, and DAO (Decentralized Autonomous Organization) governance to structure a digital green bond lifecycle. Rather than relying on empirical data collection, the framework is conceptualized through the development of a multi-layered blockchain architecture and validated via comparative analysis with analogous blockchain applications in agriculture. The proposed system is designed to enable real-time traceability of green bond disbursements, automate ESG compliance verification using satellite and IoT data, and strengthen accountability and access to climate finance for smallholder farmers. By embedding performance-based returns within smart contracts, the model aligns financial incentives with conservation goals. Leveraging Malaysia's advanced land administration infrastructure and digital capabilities, the framework presents a scalable, open-source solution to reduce greenwashing, expand financial inclusion in underserved agricultural communities, and enhance transparency and investor confidence in sustainable agricultural finance. By directly linking green finance to verifiable sustainability outcomes, Palm GreenChain addresses key limitations in conventional green bond mechanisms. Its applicability across diverse agricultural sectors positions it as a replicable blueprint for broader sustainable development. The framework is openly available via its GitHub repository.

Keywords Blockchain, Green bond, Palm oil, Malaysia, Sustainable finance, Agriculture

JEL Classification Q56, G23, O33, Q14, L31

1 Introduction

Malaysia is the second-largest producer of palm oil globally, contributing approximately 25% of global supply and exporting over 16 million tonnes annually [25]. The palm oil sector accounts for a significant portion of Malaysia's GDP and provides livelihoods for over 500,000 smallholder farmers [38]. This economic dependency makes economic sustainability a critical national priority.

Despite contributing significantly to national GDP and rural employment [4], palm oil cultivation has been linked to deforestation and biodiversity loss [14]. To tackle this issue, some studies suggest using green bonds as incentive to encourage plantation owners to abide with stricter environment regulations [22].

Meanwhile, green bonds have emerged as financial instruments for funding environmental responsible projects but face criticism for unverifiable impact and potential greenwashing [10]. Conventional green bond mechanisms often lack verifiability, resulting in decreased investor trust and inefficient fund deployment [32]. In the context of Malaysian palm oil, verifying ESG claims and ensuring that funds benefit sustainable practices remains challenging [38]. The oil palm industry remains Malaysia's primary commodity, contributing to the Gross Domestic Product (GDP) at RM 48.31 billion or representing 56.8% of the total the agro-commodity sector's GDP contribution in 2020 [30]. Smallholders, who produce over RM 19 billion or 40% of Malaysia's palm oil, are typically excluded from climate finance due to a lack of data and formal credit history [36].

Blockchain technology offers a promising solution to the problems above by providing immutable records and automated contract enforcement [34]. There has been use of blockchain in improving agricultural sustainability in other regions. The application of blockchain in agriculture includes traceability, contract management, and environmental reporting [21]. Following several successful stories in application of blockchain-enabled green bonds in agriculture, this paper intends to propose a solution called "*Palm GreenChain* Malaysia". This is a pilot green bond issued on blockchain to fund Roundtable on Sustainable Palm Oil (RSPO)-certified smallholders in Malaysia. RSPO is a global, multi-stakeholder certification scheme that sets environmental and social criteria for sustainable palm oil production. It aims to reduce deforestation, protect biodiversity, and ensure fair labor practices across the palm oil supply chain. The proceeds are traceable, disbursed via smart contracts, and verified by a blockchain-stored ESG framework.

Malaysia is uniquely positioned to pioneer blockchain-enabled green bond models like Palm GreenChain due to its strong palm oil infrastructure, growing fintech adoption, and commitment to ESG policies under frameworks such as the Malaysian Sustainable Palm Oil (MSPO) certification. MSPO is Malaysia's national certification standard for sustainable palm oil. While aligned with RSPO principles, it is tailored to the Malaysian context and made mandatory for all palm oil producers in the country. It focuses on legal compliance, environmental protection, and socio-economic responsibility. Moreover, the government's digital transformation agenda, as outlined in the Malaysia Digital Economy Blueprint [24], aligns with the potential of blockchain to enhance transparency, traceability, and investor confidence in sustainable finance.

Another unique factor is Malaysia's well-defined land categorization and title system. Land ownership is classified into freehold, leasehold, and Malay Reserve land, and land use is designated as agricultural, industrial, or commercial. Additionally, the country

employs various land title types, including Master Title, Individual Title, and Strata Title. This structured land governance framework provides a legal and administrative foundation that can support smart contracts and traceable asset ownership—key components of blockchain-based sustainable finance.

Conventional green bond frameworks within Malaysia's palm oil sector are hindered by fragmented data infrastructures and limited transparency in fund allocation. This opacity disproportionately affects smallholder farmers—who account for over 40% of the nation's palm oil production—by restricting their access to climate finance due to inadequate digital records and insufficient credit histories. Furthermore, prevailing systems lack real-time monitoring capabilities, undermining the alignment of green bond disbursements with verified sustainability milestones.

By contrast, blockchain-based architectures offer a secure, transparent, and immutable alternative. Leveraging smart contracts, such systems can automate disbursements contingent on the verification of environmental, social, and governance (ESG) metrics and integrated real-time inputs from satellite imagery. This technological contrast highlights the pressing need for a systemic transformation—from lack of real-time ESG verification and accountability, exclusion of smallholders from green finance, and persistent greenwashing to digitized, decentralized infrastructures capable of delivering environmental integrity, equitable financial access and accountability. By anchoring ESG data on-chain and promoting stakeholder-centric governance models, our approach aims to improve persistent inefficiencies in sustainable finance and facilitate more inclusive climate action.

By analyzing a range of existing applications of blockchain-enabled green bonds within the agricultural sector, our paper proposes an innovative framework titled *Palm GreenChain* Malaysia. This initiative represents a pilot blockchain-based green bond designed to finance smallholders certified by the Roundtable on Sustainable Palm Oil (RSPO) in Malaysia. The *Palm GreenChain* framework illustrates the potential to enhance transactions' traceability verified by a blockchain-stored ESG framework, promote financial inclusion via tokenized green bonds, and integrate performance-linked returns to ensure accountability aligned with measurable sustainability outcomes. Capitalizing on Malaysia's advanced land administration framework and digital infrastructure, our study advances a scalable, open-source model designed to curb greenwashing, broaden financial inclusion within marginalized agricultural communities, strengthen accountability mechanisms, and bolster investor confidence in the integrity of sustainable agricultural finance.

The rest of the article follows as: Sect. 2 reports literature review. Section 3 discusses methodology. Section 4 applies comparative analysis to compare *Palm GreenChain* against other blockchain-based agricultural applications. Section 5 introduces functions of *Palm GreenChain* (Blockchain) in green bond financing. Section 6 proposes the expected outcomes. Section 7 concludes the paper.

2 Literature review

Research indicates that blockchain can increase transparency and reduce corruption in agri-financing [33]. In sectors like coffee (FairChain) and rice (Rice Exchange), blockchain is already being used to link ESG outcomes with financial instruments [23]. De Mariz [7] presents lessons from Brazil, the second-largest green bond issuer among

emerging markets and a global agribusiness hub. Brazil's experience with sustainable finance offers valuable insights for Malaysia, especially given shared challenges around deforestation, land use, and the role of commodities like palm oil, soy, and timber. These cases underscore the importance of aligning financial innovation with regulatory frameworks and local environmental realities. Several studies have examined the use of blockchain in enhancing agricultural sustainability, including traceability, contract management, and environmental reporting [21].

Existing studies have explored the interactions among sustainable finance and green technology innovation [19, 35]), however, in the realm of green bonds, the integration of digital technologies for tracking impact has been proposed to address issues of credibility and investor confidence [13, 31]. For instance, Nassiry [26] discuss the use of fintech to improve green bond frameworks in emerging economies. Similarly, Javaid et al. [20] explore blockchain's capacity to reduce transaction costs and increase compliance in green finance systems.

The application of blockchain technology in the palm oil sector offers a powerful tool to combat greenwashing by enhancing traceability, transparency, and data verifiability—key weaknesses identified in sustainable finance markets. According to the International Capital Market Association [18], greenwashing risks emerge when sustainability claims are unsubstantiated, ambiguous, or unverifiable, undermining market integrity. Blockchain's immutable ledger directly addresses this by enabling real-time, tamper-proof tracking of palm oil supply chains, ensuring that sustainability claims—such as zero-deforestation or fair labor practices—are backed by verifiable data. Yamahaki et al. [39] emphasize that insufficient disclosure and unverifiable use-of-proceeds weaken market trust and facilitate greenwashing, particularly in thematic bonds. By contrast, blockchain can automate disclosure and reporting, thereby reducing information asymmetry. Furthermore, as noted by de Mariz et al. [8], weak KPIs and inflated sustainability claims have eroded the credibility of sustainability-linked bonds, triggering investor skepticism. Blockchain's capacity to enforce and monitor credible, measurable KPIs over time could restore this trust, especially when applied to high-risk sectors like palm oil. Thus, blockchain not only strengthens accountability but also provides a structural mechanism to prevent greenwashing and uphold the integrity of sustainable finance instruments.

Beyond the technical capabilities of blockchain and traceability, it is essential to understand the broader dynamics of the green bond market—particularly the trade-offs and structural requirements for its sustained growth. Deschryver and de Mariz [9] provide a comprehensive overview of the green bond market, discussing not only its potential benefits for issuers, such as reputational gains and access to new investor pools, but also the associated costs, including compliance, certification, and disclosure obligations. They emphasize the need for stronger policy support, market standardization, and investor education to fully unlock the potential of green finance.

Another technology associated with blockchain is distributed ledger technology (DLT). DLT is the foundational technology behind blockchain and refers to a decentralized digital system for recording transactions. In the palm oil sector, DLT enables a transparent, tamper-proof system for tracking the entire supply chain from plantation to end consumer. First, from the traceability perspective, every transaction, such as harvesting, transportation, processing, and certification, can be recorded on a distributed ledger [27]. This ensures that palm oil is traceable and verified to come from sustainable,

deforestation-free sources. Second, from the accountability perspective, DLT prevents fraud, greenwashing, or manipulation of sustainability claims because records cannot be altered retroactively [29]. Third, from the stakeholder coordination perspective, DLT allows different stakeholders—farmers, mill operators, exporters, regulators, and investors—to access the same verifiable information in real time, improving coordination and trust. With DLT, stakeholders could transfer payments to other parties with more confidence [7]. By using DLT, the palm oil industry can create a more ethical and efficient supply chain, helping meet ESG requirements, attract green finance (e.g., green bonds), and improve its international reputation.

There is also evidence of blockchain-based platforms being used in environmental bond markets, such as the World Bank's issuance of the "Bond-i," a blockchain-only bond that demonstrated the feasibility of end-to-end digital finance for sustainability purposes [37]. Despite these advances, the specific application of blockchain-enabled green bonds in agriculture—particularly for palm oil—remains underexplored. This gap justifies the development and academic inquiry into tailored blockchain solutions like Palm GreenChain.

3 Methodology and description of Palm GreenChain

The study adopts a theoretical, system-design-based methodology to propose a blockchain-based platform or system architecture, using Ethereum-compatible smart contracts, to issue and manage tokenized green bonds [6]. The architecture incorporates oracles that link on-chain logic to off-chain data sources such as satellite imagery and IoT sensors [2]. A governance model modelled after DAO frameworks ensures stakeholder inclusivity and dispute resolution [16].

The architecture includes multiple layers: a smart contract layer for automation, a data oracle layer for ESG verification, and an IPFS-based storage system for off-chain document integrity [40]. Ethereum or Celo is recommended for its developer tools and environmental efficiency, respectively [28].

The Palm GreenChain platform issues tokenized green bonds using the ERC-1400 standard, ensuring compliance and interoperability [15]. Fund disbursements are governed by smart contracts linked to verifiable ESG milestones. Data is verified via satellite-based NDVI imagery and community audits, which are anchored using IPFS for data integrity [5]. Coding for the blockchain system suggested in this paper is tested and written at github.[1]

The platform utilizes a multi-signature wallet for fund approvals, incorporating stakeholders such as certifiers, investors, and local communities [6]. DAO-based governance allows protocol updates via token-holder voting, ensuring long-term adaptability and decentralized control [16].

Figure 1 shows the multi-phase workflow of *Palm GreenChain* process. Each *Palm GreenChain* project is structured into four operational phases that ensure transparency, accountability, and incentive alignment across the green bond lifecycle. The four phases included in the workflow are:

[1] Coding can be retrieved from https://github.com/KienpinTee/GreenBond/blob/main/Palm%20GreenChain.

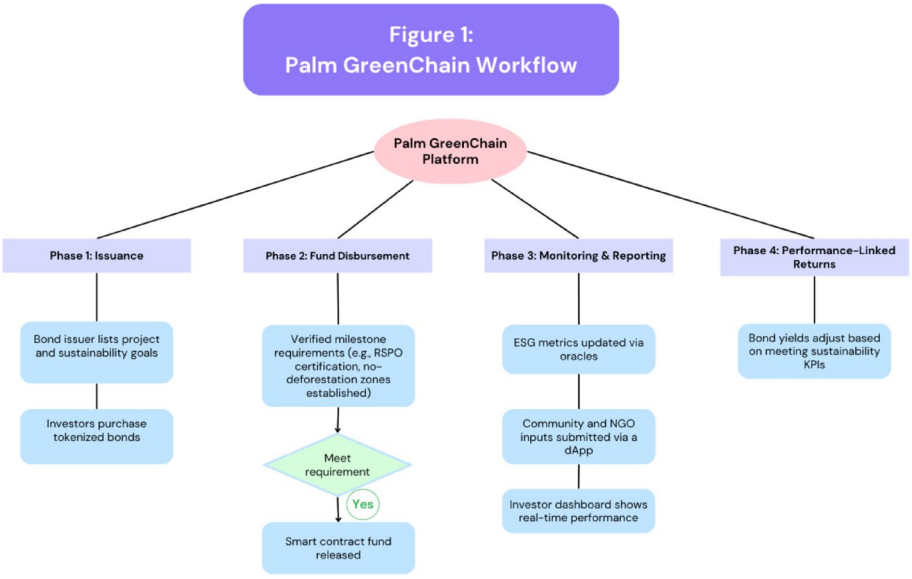

Fig. 1 Reports the four phases—Issuance, Fund Disbursement, Monitoring & Reporting, and Performance-Linked Returns— of the *Palm GreenChain* framework's workflow designed to enhance transparency, accountability, and incentive alignment. This lifecycle integrates smart contracts, blockchain oracles, and ESG-linked performance metrics to ensure credible, outcome-driven green bond financing in sustainable Palm oil agriculture

3.1 Phase 1: issuance

The process begins with the bond issuer registering a sustainability-linked project, clearly outlining its environmental objectives and KPIs. Once the project is approved, tokenized green bonds are offered to investors on a digital platform, enabling fractional ownership and greater accessibility. On issuance, DLT technology is used allows for smaller values of bonds, compared to traditional cap markets. Issuance along with DLT does not just allow for retail investors to participate but also potentially for smaller issuers.

3.2 Phase 2: fund disbursement

Funds raised from investors are locked in smart contracts that are programmed to release capital only upon achieving verifiable sustainability milestones. These triggers can include certifications such as RSPO (Roundtable on Sustainable Palm Oil) or the official designation of no-deforestation zones.

3.3 Phase 3: monitoring and reporting

Once the project is underway, ESG performance data is continuously updated via blockchain oracles that collect real-world data from IoT sensors, satellite imagery, and verified reports. A decentralized application (dApp) allows NGOs and local communities to submit ground-level updates and feedback. Investors can access a live dashboard to monitor progress and evaluate impact metrics in real time.

3.4 Phase 4: performance-linked returns

As the project progresses, bond yields are dynamically adjusted based on whether predefined sustainability KPIs are met. Higher compliance with ESG targets may trigger favourable returns for the issuer, while failure to meet them may lead to penalties or lower yields, thereby reinforcing outcome-based accountability.

Figure 2 shows how the Partnership Ecosystem functions in the Palm GreenChain model. The Palm GreenChain ecosystem operates through a collaborative framework involving multiple stakeholders. Issuers, such as palm oil cooperatives and RSPO-certified producers, initiate green bond projects by defining sustainability goals and seeking funding. Verifiers, including NGOs, ESG auditors, and certification bodies like RSPO and MSPO, are responsible for independently validating sustainability claims and monitoring compliance with environmental standards. Technology providers, such as blockchain developers and satellite imaging firms, build and maintain the digital infrastructure, enabling secure, transparent tracking of ESG data and land-use changes. Along with the use of blockchain to record and report real time data, NGOs and local communities submit ground-level updates and feedback. Any discrepancy against the defined goals will be reported to the verifiers and the grant application will be denied. Meanwhile, funders—which include institutional ESG investors, green finance funds, and international bodies like the World Bank and IFC—supply the capital by investing in tokenized bonds, thereby supporting sustainable palm oil initiatives while earning performance-linked returns.

In addition to the suggested system above, other possible alternatives of similar architecture could also be applied as below:

- Platform: Ethereum, Hyperledger, or Celo (eco-friendly blockchain)
- Green Bond Token: ERC-1400 or similar standard
- Smart Contracts: Automate fund disbursement, KPI tracking, and reporting
- Data Sources: Satellite imagery (e.g., Global Forest Watch), IoT sensors, auditors
- Verification: Third-party ESG certifiers upload data on-chain

While developing our framework above we assumed that:

1. Malaysia's digital ecosystem, including its land title systems, internet infrastructure, and blockchain literacy (especially among stakeholders like certifiers, cooperatives, and tech providers), is mature enough to support blockchain deployment in agriculture.
2. Smallholders, certifiers, NGOs, and local communities have or can rapidly acquire the capacity (digital literacy, mobile access, trust in tech) to engage with blockchain tools like dApps, digital wallets, and smart contracts.

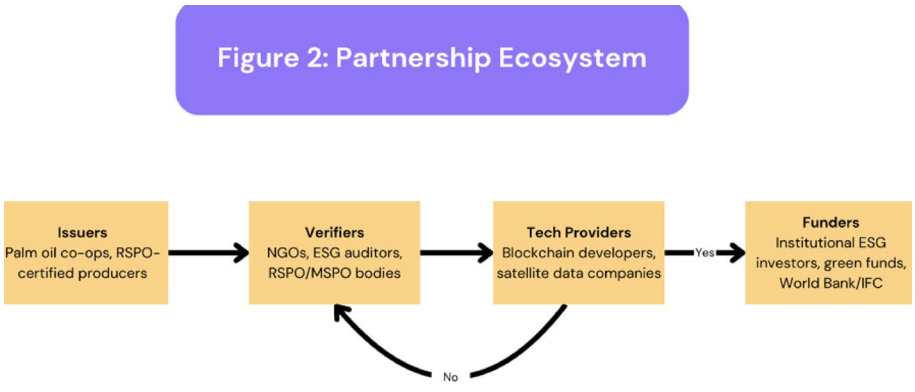

Fig. 2 Explains how the partnership ecosystem in the *Palm GreenChain* framwork enables collaborative green bond issuance through verified sustainability goals, real-time blockchain reporting, and multi-stakeholder engagement—linking RSPO-certified producers, NGOs, tech providers, and ESG investors to ensure transparency, accountability, and performance-driven funding for sustainable palm oil initiatives in Malaysia

3. Malaysia's legal and financial systems will align with blockchain-based tokenization and the issuance of digital green bonds, including recognition of smart contracts and enforcement of ESG-linked returns.
4. Certification schemes like RSPO and MSPO can provide timely, reliable, and blockchain-compatible ESG data for on-chain verification and milestone validation.
5. Stakeholders across sectors—government, certifiers, fintech firms, NGOs, and smallholders—will collaborate effectively within a decentralized, blockchain-coordinated framework.

4 Comparative analysis

In this section, we discuss other projects that have successfully expanded the potential of blockchain to deliver operational efficiencies, improved trust, and better access to capital across different agricultural products and geographies. Their successes support the feasibility of the Palm GreenChain initiative, while highlighting key learnings such as the importance of stakeholder training, infrastructure readiness, and reliable data sources.

Among the successful blockchain-based agriculture projects include:

- *BanQu*: This platform enables farmers (especially those without formal banking access) to build a verifiable digital identity and economic history using blockchain. It tracks each transaction within the supply chain—from input purchase to harvest sale—ensuring that every actor's contribution is visible and fair. Its use in the cassava and cocoa sectors in Africa and Latin America has improved credit access and reduced exploitation [3].

  The palm oil sector in Malaysia, especially among smallholders, faces similar issues of financial exclusion and lack of traceability. Integrating a system like BanQu into Palm GreenChain would allow smallholder identity verification, supply chain participation, and eventually credit scoring using blockchain-based transaction histories. This approach helps improve inclusive finance, which is crucial for equitably distributing the benefits of green bond financing.
- *AgUnity*: AgUnity equips smallholder farmers with a blockchain-enabled mobile app to record farming activities, transactions, and cooperative interactions. The system boosts trust within cooperatives and supports improved logistics and marketing strategies. Field results from Papua New Guinea and Kenya show increased farmer incomes and supply chain transparency [1].

  Malaysia's palm oil smallholders often operate in fragmented groups and informal cooperatives. A similar blockchain-based mobile solution from AgUnity could help document harvesting practices, certification milestones, and delivery timelines. By digitizing and decentralizing records, Palm GreenChain can strengthen trust among cooperatives, track sustainability compliance, and support performance-based payment mechanisms tied to green bonds.
- *FairChain*: This initiative uses blockchain to rebalance the coffee value chain by providing transparent payments and value distribution between farmers and downstream buyers. Each stage of the coffee journey is tokenized and verified on-chain. Implemented in Ethiopia and Colombia, the system has demonstrated increased fair-trade compliance and farmer empowerment [12].

  In palm oil, there is often a disconnect between producers and global buyers, with value skewed toward downstream players. By adapting FairChain's model,

Palm GreenChain can tokenize palm oil supply chain steps to make pricing more transparent, track premium payments for certified sustainable oil, and document benefit sharing with producers. This aligns well with ESG-linked financing goals and supports fair labor practices.

- *Rice exchange*: Operating as a blockchain-powered trading platform for rice, it allows buyers and sellers to execute smart contracts that automate payment, insurance, and shipment tracking. The platform's pilots in Southeast Asia have shown significant reductions in transaction times and fraud cases [11].

  The palm oil trade is complex and involves multiple intermediaries, raising risks of fraud, delayed payments, and logistical opacity. Smart contracts on Palm GreenChain can automate fund disbursement based on verified sustainability milestones (e.g., RSPO certification, zero-deforestation compliance). It also supports traceable green bond spending, improving operational efficiency and investor confidence.
- *IBM food trust*: This enterprise solution offers blockchain-based supply chain transparency for major retailers and food producers. In agriculture, it has been used to track products like lettuce and pork, ensuring food safety and rapid recall. The solution is scalable and trusted by brands such as Walmart and Nestlé [17].

  As palm oil is a globally traded commodity, integration with scalable platforms like Palm GreenChain allows for real-time traceability from plantation to retailer. This is especially important for large downstream actors (e.g., CPG brands or importers) who face reputational and regulatory risks tied to deforestation or forced labor. The IBM model shows how blockchain can be deployed at enterprise scale, combining traceability with corporate accountability, which is highly applicable for international buyers of Malaysian palm oil.

The design of the Palm GreenChain framework was directly shaped by the operational blueprints and proven outcomes of BanQu, AgUnity, FairChain, Rice Exchange, and IBM Food Trust. These systems provided critical insights in addressing transparency, accountability, traceability, and financial inclusion—core issues also tackled by Palm GreenChain in the Malaysian palm oil agriculture.

BanQu's use of blockchain for economic identity formation in unbanked farming communities influenced Palm GreenChain's mechanism for creating credit histories and enabling financial access for RSPO-certified smallholders. Similarly, AgUnity's farmer-centric mobile apps highlighted the value of grassroots usability and cooperative integration, which Palm GreenChain replicates through community-driven monitoring features and decentralized applications (dApps).

FairChain's transparent value distribution model guided the integration of ESG-linked smart contracts in Palm GreenChain, ensuring that fund disbursement aligns with verifiable sustainability milestones. Additionally, the Rice Exchange platform contributed ideas on smart contracts automating supply chain logistics and payments, directly influencing Palm GreenChain's real-time ESG tracking and performance-linked bond returns. Together, these precedents validated the feasibility of blockchain for sustainability-linked financing and informed Palm GreenChain's multi-layered architecture—including oracle integration, decentralized auditing, and tokenized financial instruments. Importantly, Palm GreenChain extends these innovations by embedding green bond functionalities specific to Malaysia's palm oil sector, demonstrating contextual adaptation rather than replication.

Table 1 Comparative analysis of Palm GreenChain and other existing frameworks

Framework	Scalability	User base	Funding model
Palm GreenChain	Medium to High – Designed with DAO governance, oracles, and modular architecture; limited by blockchain literacy and infrastructure in rural Malaysia	Primarily RSPO-certified smallholders in Malaysia's palm oil sector	No direct funding; open-source pilot framework; aims to attract ESG investors and institutional funds via green bonds
BanQu	High – Already deployed in multiple countries; scalable for different commodities	Smallholder farmers in Africa & Latin America; cassava, cocoa sectors	Commercial platform; funded by NGOs, impact investors, and partnerships with global corporations
AgUnity	Medium – Smartphone dependency limits scale in low-connectivity areas; app-based model supports gradual growth	Smallholder farmers and cooperatives in Papua New Guinea, Kenya, and others	NGO-funded pilots, partnerships with agribusinesses; sustainability grants
FairChain	Medium – Tailored to coffee supply chains; geographically focused implementations	Coffee farmers in Ethiopia and Colombia	Funded through ethical trade premiums and development cooperation funds
Rice exchange	High – Targets global rice trade with automated smart contracts and logistics integrations	Traders, insurers, shippers across Southeast Asia	Private investment and platform transaction fees; B2B SaaS model
IBM food trust	Very High – Enterprise-grade scalability with global reach; cloud-native infrastructure	Multinational food retailers, processors (e.g., Walmart, Nestlé)	Commercial solution; enterprise subscriptions and blockchain-as-a-service

IBM Food Trust, with its scalable enterprise-grade traceability solutions, provided the blueprint for Palm GreenChain's layered oracle and IPFS architecture for ESG data anchoring, ensuring real-time supply chain transparency.

Collectively, these frameworks served as foundational prototypes, directly informing Palm GreenChain's hybrid system of blockchain governance, ESG verification, and financial incentivization mechanisms (Table 1).

While blockchain-based platforms have shown success in agricultural sectors, their applicability to Malaysia's palm oil industry presents mixed outcomes. For instance, BanQu excels in creating economic identities for unbanked farmers, improving credit access and transparency. However, it lacks sector-specific ESG integration, making it insufficient for the high regulatory and environmental scrutiny palm oil faces. AgUnity's cooperative-based model boosts intra-community trust and transaction logging, but its success hinges on smartphone adoption and consistent network connectivity—both potential barriers among Malaysian smallholders with digital literacy challenges. FairChain's strength lies in equitable value distribution, relevant in correcting power asymmetries in palm oil value chains. Yet, its coffee-centric model may not easily translate to palm oil's vertically integrated, industrial nature, which demands greater environmental compliance over market fairness.

Unlike these platforms, the Palm GreenChain framework directly addresses palm-specific challenges—deforestation, land titling, and green bond traceability—through ESG smart contracts, satellite verification, and tokenized finance. Nevertheless, Palm GreenChain also inherits similar limitations: reliance on robust data infrastructure, regulatory clarity, and farmer inclusivity.

In sum, while existing frameworks provide valuable design insights (e.g., farmer identity, traceability, fairness), they must be significantly customized—or hybridized with Palm GreenChain—to meet palm oil's complex sustainability and governance needs.

5 Functions of the Palm GreenChain (blockchain) in green bond financing for palm oil

In this section, we introduce the objectives of our proposed solution. Ideally, the Palm GreenChain, shall provide the following applications.

5.1 Traceable use of green bond proceeds

Blockchain is used to track exactly how and where green bond funds are spent. Green bonds are issued on a The Palm GreenChain platform with smart contracts that release funds only when sustainable milestones are verified (e.g., no-deforestation certified equipment, reforestation efforts, or RSPO-certified practices). This traceable feature helps prevent greenwashing and ensures accountability.

5.2 Supply chain transparency

Palm oil supply chain data is integrated onto blockchain to prove sustainability compliance. IoT sensors and satellite data are used to monitor land use, and log harvesting, transport, and processing steps on-chain. Bond issuers and investors can verify that palm oil linked to the project is deforestation-free and traceable.

5.3 Tokenized green bonds for greater accessibility

Green bonds are tokenized to allow fractional investment, even from retail or ESG-focused investors globally. Bond issuers can create blockchain-based digital securities (security tokens) representing ownership in the green bond. Bond tokenization boosts broader investor participation, lower issuance cost, and enhanced liquidity.

5.4 ESG data anchoring and auditing

Third-party ESG audit reports, satellite images, and environmental impact metrics can be stored on a blockchain. IPFS or a private-permissioned blockchain is used to timestamp and anchor environmental data. This feature ensures audit integrity, prevents data tampering, and builds investor trust.

5.5 Smart contracts for performance-based payments

Bonds can be constructed in a way that payments (e.g. coupon rates) vary based on sustainability KPIs. Investors could adjust return of a smart contract based on verified metrics like forest cover, emissions, or biodiversity scores. This feature aligns financial incentives with environmental performance.

5.6 Decentralized green certification

Bond issuer can create a blockchain-based registry of green certifications (e.g. RSPO, MSPO, or independent verifiers). This registry allows certifiers to issue digital credentials on-chain tied to land parcels or plantation operators. This process makes certifications tamper-proof and easier for investors to verify.

5.7 Community-driven monitoring

The Palm GreenChain platform enables local communities and NGOs to upload evidence (e.g., images, drone footage) to the blockchain. Decentralized apps (dApps) can be

used to reward whistleblowing or environmental stewardship using green tokens. This feature aims to empower grassroots oversight and improves governance.

6 Expected outcomes

Based on the objectives given to the Palm GreenChain, we expect our model to:

- Increase transparency in green bond issuance [10], such as enabling real-time tracking of fund flows and ensuring that disbursements align strictly with pre-approved ESG milestones.
- Enhance ESG compliance through automated data verification [33], for example, by using satellite imagery to confirm zero-deforestation zones and IoT sensors to track water usage and emissions in plantations.
- Improve financial access for sustainable smallholders [36] by allowing small producers to tokenize their operations and demonstrate compliance, thus making them eligible for climate finance, microloans, and preferential investment terms.
- Mitigate deforestation by aligning financial incentives with verifiable conservation efforts [14], such as rewarding farmers who maintain forest buffers or adopt certified sustainable practices through smart contract-based disbursements.

7 Conclusion

This paper presents the Palm GreenChain framework as a blockchain-enabled solution to enhance the issuance and governance of green bonds in Malaysia's palm oil sector. We established the significance of palm oil to Malaysia's economy, the environmental concerns associated with its cultivation, and the country's unique readiness—thanks to its structured land system, ESG initiatives, and digital infrastructure—to implement this innovation.

We propose a blockchain-based design incorporating smart contracts, decentralized ledgers, IoT integration, and ESG oracles to verify sustainable practices. This architecture aims to enable end-to-end transparency, automate compliance, and facilitate tokenized fund disbursement.

We also examine similar blockchain implementations in the agriculture sector, including BanQu, AgUnity, and Rice Exchange. These projects demonstrated notable successes in improving traceability, farmer inclusion, and ethical trading, providing valuable blueprints for Palm GreenChain's adaptation.

The applications of Palm GreenChain in Malaysia include its integration with national land title systems, smart monitoring of deforestation, and automated ESG-compliant fund allocation through smart contracts. These use cases illustrate its potential to reinforce environmental regulations, boost investor trust, and incentivize sustainable palm oil production.

In "The Expected Outcomes" section, we outlined how the Palm GreenChain model can deliver transparency in fund flows, improve ESG compliance using smart technologies, expand financial inclusion for smallholders, and incentivize conservation efforts through performance-linked smart contracts.

Despite its promise, the implementation of Palm GreenChain in Malaysia faces several challenges. First, blockchain adoption in the agricultural sector remains low, particularly among smallholder farmers who may lack digital literacy or access to necessary infrastructure. Ensuring equitable access to the system will require extensive training,

outreach, and support mechanisms. Second, integrating blockchain with existing land and agricultural data systems could face technical and bureaucratic hurdles. Malaysia's land title systems, while structured, are decentralized across state governments, which may slow down interoperability and data-sharing initiatives. Third, the regulatory environment for blockchain and digital assets in Malaysia is still evolving. Clarity around the legal enforceability of smart contracts and the issuance of tokenized assets under green bond frameworks will be critical to attracting institutional investors. Finally, data privacy and security concerns may arise due to the immutable nature of blockchain records. Balancing transparency with compliance to data protection laws such as Malaysia's Personal Data Protection Act (PDPA) will require careful system design.

By aligning green finance with verifiable sustainability outcomes, Palm GreenChain addresses critical shortcomings in traditional green bond mechanisms. Its potential application in other agricultural sectors positions it as a replicable blueprint for broader sustainable development. Future research should focus on real-world pilot implementation and evaluate its scalability across diverse geographies and commodities.

Author contributions
Kienpin Tee: Conceptualization, Methodology, Software, Formal analysis, Validation, Investigation, Writing – original draft, Writing – review & editing, Data curation Ghulame Rubbaniy: Validation, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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Data availability
Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
We grant *Discover Sustainability* the right to publish the author's work.

Competing interests
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