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Artificial intelligence-blockchain synergy ensures Indonesia's compliance with European Union's Deforestation-free regulation

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ABSTRACT

This paper introduces a new model that incorporates blockchain and artificial intelligence (AI) in creating traceability on agricultural supply chains to meet European Union's (EU's) regulation on deforestation-free products. This model stands for the system that would be applied for monitoring origins and routes with regard to verifying the status of products being free from deforestation. Particularly, this addressed the European Union's Deforestation-free Regulation products (EUDR)-related issues in Indonesia focused on smallholders and their linkage to traceability tools. The proposed conceptual model demonstrates how blockchain technology combined with AI in agricultural supply chains enhances transparency and reliability in the line of improving environmental sustainability as well as boosting consumers' confidence. Integration of blockchain and AI increases agricultural supply chain transparency, traceability, and reliability whereby smart contracts can execute automatically such as releasing payments once certain conditions are met.

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1. INTRODUCTION

The integrity of agricultural supply chains has become increasingly critical as global awareness of environmental impact and ethical sourcing continues to rise. Compliance with regulatory frameworks such as the European Union's Deforestation-free Regulation products (EUDR) is crucial for ensuring that agricultural products meet stringent environmental and ethical standards [1], [2]. EUDR seeks to ensure that certain agricultural commodities consumed within the European Union (EU) are not linked to deforestation [3]–[5]. This is accomplished by regulating the import of commodities from producer countries. The regulation aims to mitigate and control the impacts of deforestation, which exacerbates the global climate crisis by increasing greenhouse gas emissions [6]. Deforestation leads to a reduced carbon sink capacity, loss of biodiversity, and diminished ecosystem resilience against diseases and pests [7], [8].

This paper proposes a comprehensive model that integrates blockchain technology and artificial intelligence (AI) for the traceability of agricultural products within the supply chain, particularly for compliance with EUDR. In the ever-evolving landscape of technology, these two innovations stand out for their potential to revolutionize industries and reshape the way we work, communicate, and transact [9], [10]. Individually, they represent groundbreaking advancements, but together, their combined power holds the promise of unlocking new frontiers and catalyzing unprecedented growth and efficiency across various domains.

By leveraging these advanced technologies, the origin and journey of agricultural products can be meticulously tracked and verified [11] to ensure they are free from deforestation or forest degradation. In previous research, integrating AI and blockchain technology can significantly improve accuracy, efficiency, and compliance in inventory auditing [12]–[14]. By combining AI's predictive analytics and data processing capabilities with blockchain's secure and transparent ledger system [15], [16], this integration tackles traditional auditing challenges [17]. It enables more precise inventory tracking, enhances fraud detection, and ensures adherence to regulatory standards [18], [19]. Also, other research applied these two approaches in vaccine supply chain [20] by enhancement vaccine supply chain efficiency and improves coordination using AI, while blockchain technology enhances transparency, reduces tampering, and improves traceability in the vaccine supply chain.

The proposed conceptual model in this research enhances transparency and trustworthiness in the agricultural supply chain by utilizing blockchain technology to securely record data on a blockchain ledger. This ensures that transactions and movements of agricultural products are securely stored and fully traceable, which is crucial for proving compliance with the EUDR and other international standards. According to Bosona and Gebresenbet [21], blockchain technology enables: i) complete traceability by providing comprehensive traceability information, blockchain helps mitigate risks associated with information loss and data tampering; ii) fraud and tampering prevention by enabling the inherent features of blockchain make it resistant to fraud and tampering, thereby increasing the reliability of information shared throughout the supply chain; iii) increased transparency and trust by promising a decentralized and immutable blockchain ledger. This ensures that all stakeholders have access to the same information, increasing transparency and building trust between consumers and regulators.

Starting from the source, including farmers, agricultural companies, and processors, data is recorded in a secure blockchain system. This data goes through a validation and consensus process among network nodes to ensure its authenticity and accuracy. The blockchain stores the data in blocks that are cryptographically sealed and linked, creating a permanent and immutable record of each product's journey. The system generates barcodes associated with each agricultural product, serving as unique identifiers. These barcodes enable efficient tracking and verification of products throughout the supply chain. By scanning the barcode, authorized parties can verify the product's origin and quality, ensuring compliance with regulations like the EUDR.

Furthermore, AI-powered data analysis tools extract insights from the collected data, allowing for enhanced monitoring, compliance verification, and quality control. This can inform strategic decisions and optimize supply chain processes. In summary, the integration of blockchain and AI in the traceability of agricultural products not only ensures adherence to stringent regulatory standards like the EUDR but also promotes a transparent and ethical supply chain. This paper explores the conceptual model which shows how these technologies offer significant potential for safeguarding environmental sustainability and consumer trust in the agricultural sector.

2. EUDR OVERVIEW

The EUDR aims to ensure that commodities consumed within the EU are not linked to deforestation [22]–[25]. This is achieved by regulating the import of commodities from producer countries. The regulation is designed to mitigate and control the impacts of deforestation, which contributes to the global climate crisis by increasing greenhouse gas emissions [26]–[28]. Deforestation contributes to the global climate crisis by increasing greenhouse gas emissions [17] and has other severe consequences, such as reducing carbon sink capacity, loss of biodiversity, and decreased ecosystem resilience against diseases and pests [29], [30].

The EU acknowledges that its consumption contributes to global deforestation and forest degradation [31], [32]. By regulating the consumption of products such as beef, coffee, cocoa, natural rubber, palm oil, soybeans, and timber, the EU hopes to decrease global deforestation rates [5], [33]. If left unchecked, the EU estimates its contribution to global deforestation could rise by 280,000 hectares each year until 2030. Nearly 90% of global deforestation is due to agricultural expansion, highlighting the necessity of this regulation [34].

Under the deforestation-free regulation, operators and traders are required to demonstrate that their products do not contribute to deforestation or forest degradation [35]–[37]. This regulation supports the EU's commitment to combat biodiversity loss, as outlined in the United Nations convention on biological diversity, the European green deal, and the EU biodiversity strategy for 2030 [38]–[40]. Additionally, it contributes to the sustainable development goals (SDGs), including SDG 15 (life on land), SDG 13 (climate action), SDG 12 (responsible consumption and production), SDG 2 (zero hunger), and SDG 3 (good health and well-being).

The regulation comprises 86 considerations, nine chapters, and 38 articles [41]. The chapters cover general provisions, obligations of operators and traders, member state responsibilities, product entry and exit procedures, country benchmarking and cooperation, substantiated concerns, information systems, reviews, and final provisions. Two annexes detail relevant commodities and products and the due diligence statement. Starting in June 2023, operators and traders have 18 months to comply, with small and micro enterprises given additional time to adapt. Since the announcement of the deforestation-free rule, there has been significant global interest [36] and numerous inquiries regarding traceability, scope, obligations, definitions, due diligence, benchmarking, partnerships, and implementation timelines [42].

3. EUDR ACCEPTANCE IN INDONESIA

Rules for deforestation free commodities were passed by the EU on 6th December, 2022 [3]. In response, Indonesia is a major producer of palm oil, coffee, cocoa, and natural rubber [43], [44] and have raised several concerns. Nevertheless, the new regulation is of concern to Indonesia that has made significant efforts to lower its deforestation rate, pledged to the Paris Agreement, CBD, and SDGs. The regulation would hit smallholders in Indonesia's agriculture, who are vital to the country's agricultural sector as well as traders and other economic growth in the sector.

Indonesia's government also expressed concerns about the regulation's definitions of deforestation, existence of clear definition for smallholders, country benchmarking system, due diligence requirements and geolocation data requirements. To address these concerns, Indonesia has established a joint task force with five workstreams: i) inclusivity of smallholders in supply chains: contributing towards addressing impediments in providing quality food to smallholder farmers and their inclusion in value chains; ii) relevant certification schemes: reviewing and improving certification schemes to allow for compliance with deforestation-free regulations; iii) traceability tools: supporting smallholders, reviewing, and merging digital traceability tools with EU due diligence requirements; iv) scientific data on deforestation and forest degradation: using scientific data to assess how countries are progressing. Also, it guarantees transparency and fairness; v) protection of privacy data: provides platforms for violating data protection compliance with both EU and Indonesian laws, and ensures data protection compliance with both EU and Indonesian laws.

Geolocation is a key consideration in Indonesia and magnifies as a challenge for commodities produced by smallholders such as palm oil. Indonesia has tools named Indonesia Sustainable Palm Oil (ISPO) certification system [45], [46] and the registration certificate of cultivated plants or *surat tanda daftar budidaya* (STDB) which provides aids on how to meet traceability criteria but other commodities such as natural rubber, cocoa, and coffee still present some difficulties. At present, the STDB can understood as a basic mapping tool for identifying smallholder businesses as well as a social and environmental tool that aims to improve welfare and promote better environmental practices [47], [48]. In the same way, the plantation licensing information system or *sistem informasi perizinan perkebunan* (SIPERIBUN) could prove useful in terms of traceability data although it must respect general data protection regulation since it deals with personal data.

Recently, the Indonesian government is looking for how to comply with deforestation free regulation including by asking consent from data owners to use their personal data in the traceability system. To effectively implement zero deforestation commitments both the public and private sectors are required to collaborate [49]. Public policies can complement private activities, and public policies constitute a solid basis for environmental governance. Legal reforms and enforcement are often weak or poorly done in commodity producing countries, but public policies can make up some of the gap. By working together, this partnership prevents ineffective fragmented efforts and ensures that entrepreneurship from the private sector is supported by a strong legal framework backed by consistent enforcement, strong public governance, and level playing field for companies.

4. CONCEPTUAL MODEL TOWARDS BLOCKCHAIN AND AI-BASED TRACEABILITY SYSTEM EUDR PRODUCTS IN INDONESIA

In this paper, we suggest the use of blockchain and AI in the traceability of agricultural products, particularly for compliance with EUDR. It is very crucial for ensuring that the origin and journey of products meet stringent environmental and ethical standards. This advanced system helps guarantee that the agricultural goods imported into the EU are not linked to deforestation or forest degradation. As can be seen on Figure 1, there are five main blocks, initial registration and identification block, data recording and encryption block, barcode and AI system block, compliance and enforcement block, and Indonesian government regulatory.

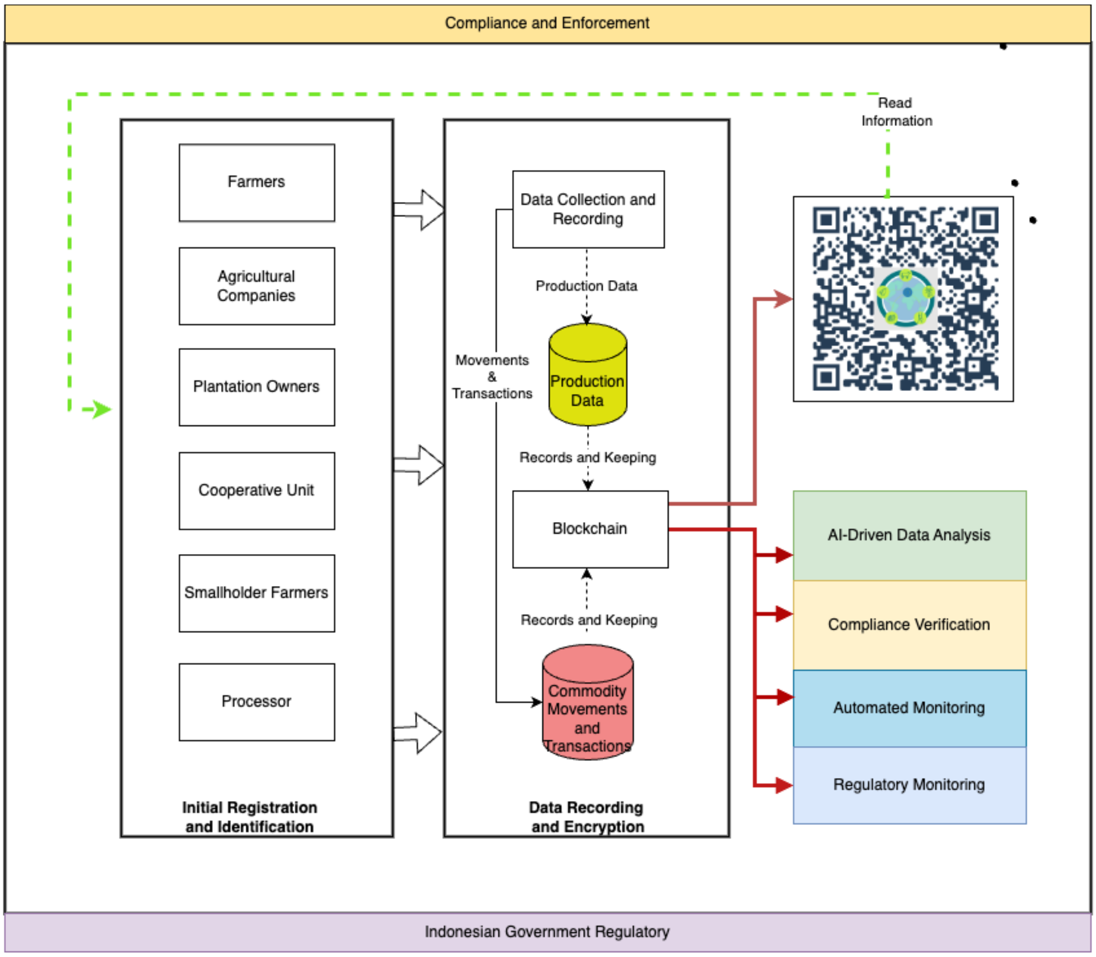

Figure 1. Conceptual model for blockchain and AI-driven EUDR traceability system

The first block shows where the supply chain starts, from farmers, agricultural companies, plantation owners, cooperative units, smallholder farmers, and processors. In this supply chain, farmers can sell their products to agricultural companies, cooperative units, and directly to processors. Meanwhile, other stakeholders' entry the data to the data recording system. Table 1 shows the list of type of data would typically be entered into such system. As we can see from second block on Figure 1, second block, once data is entered and recorded, the data will be used on a blockchain system and it goes through the following steps:

– Validation and consensus: nodes of the network check data first before certifying its authenticity to other nodes of the same network. This is usually accompanied by some kind of consensus that many nodes in the network have to approve the adding of new data to the block chain.
– Inclusion in a block: on reaching threshold, money or transaction related data is accumulated with other authenticated data into a block. This in turn is secured digitally through cryptography to the previous block and the series of block form a chain hence the name blockchain.
– Distribution across the network: in the blockchain technology, after the data has been put in the block it is shared with the nodes, which are copies of the block chain. This decentralization also guarantees that data remain safe and should nodes be compromised, the data remains intact.
– Permanent storage: in other words, as soon as the data has been integrated in the blockchain, it turns into an unalterable record on the chain. It cannot be edited or removed; thus, it enhances data security and its efficiency guarantees data stability. Any change or addition means that information must be entered as new records and not overlay the existing data.
– Availability for access: this means that once data is on the blockchain it is accessible by anyone with ways of viewing the blockchain which is only open to those who have the authorization. From experience, depending on the type of blockchain (public, private or consortium based), permissions may be granted according to the type of access control.

- Data analysis and insights: the other parties who are allowed to access the information are also allowed to use analytic tools to make sense of the information on the blockchain. For instance, they can keep records of a particular product, analyze those records to make analysis, as well as predicting the future trends and even recognize abnormality.
- Use in smart contracts: information recorded in the block chain can also serve contractual usage of smart contracts, these are contracts which are in essence coded into the block chain. For instance, in the agricultural supply chain, payments can be made through smart contracts to be made in the event of particular needs being met.

Table 1. Type of data and its details that are required

No	Type of data	Details
1	Producers information	- Farmers/producers data: name, location, contact information, certification status. - Farm details: size, location (GPS) coordinates, type of crops grown.
2	Agricultural practices	- Land use data: information on land ownership, land use history, and compliance with land use regulations. - Cultivation practices: details on planting dates, crop varieties, use of fertilizers and pesticides, irrigation practices
3	Environmental data	- Deforestation monitoring data details: satellite images, deforestation alerts, compliance with forest protection regulations. - Sustainability metrics: data on soil health, water usage, biodiversity impact, and carbon footprints.
4	Harvest and post-harvest data	- Harvest date: information on when crops are harvested. - Yield data: quantity of crops harvested and quality assessments. - Storage conditions: information on storage facilities, conditions (temperature, humidity), and duration of storage.
5	Processing and manufacturing	- Processing details: information on where and how the agricultural products are processed (e.g., milling, packaging). - Manufacturing practices: compliance with food safety standards, use of additives, and packaging materials.
6	Transportation and logistics	- Transportation records: details on the logistics providers, routes taken, and transportation conditions. - Shipping data: information on shipping dates, volumes, and receiving locations.
7	Certification and compliance	- Certification data: records of certifications obtained (e.g., organic, fair trade, deforestation-free). - Audit reports: results of audits and inspections by regulatory bodies. - Compliance documentation: proof of compliance with national and international standards.
8	Traceability data	- Product tracking: unique identifiers (e.g., QR codes, RFID tags) for tracking products from farm to consumer. - Batch and lot numbers: information on specific batches and lots to ensure traceability in case of recalls.
9	Transaction data	- Sales records: details of transactions, including buyer and seller information, transaction dates, and prices. - Export documentation: export permits, customs declarations, and related paperwork.
10	Consumer information	- Product labels: information available to consumers, such as origin, certifications, and sustainability practices. - Feedback and complaints: records of consumer feedback and complaints for continuous improvement.
11	Data governance and security	- Access logs: records of who accessed the data and when. - Data integrity checks: mechanisms to ensure data has not been tampered with, leveraging blockchain's immutability.

The system records data on the blockchain so that all transactions and movements of agricultural products are safely recorded and traceable so as to bring about transparency and trustworthiness of the whole supply chain. The third block explained the process of barcode generation on the blockchain system. The barcode is generated, assigned to the product, and then distributed to assignees like farmers, producers, distributors, and many more. It functions as a product tracking mechanism through the entire supply chain, with every scan updating the product’s journey to the blockchain.

At different points, the system does verification and authentication of the product’s origin, quality and it is in compliance with the EUDR. Consumers can scan the barcode when the product has reached the end of the supply chain to see detailed details on where the product came from, where it travelled, and what it’s been certified. AI analyzes data from barcode scans of assets and process them to pick up patterns and monitor compliance as well as optimizing efficiency. There is the chance that feedback is given by consumers that are recorded and analyzed for product improvement.

The use of barcode data is by companies and regulators for quality control checks and audits to show that they adhere to safety and ethical standards. This barcode information can be integrated within other enterprise resource planning (ERP) such as inventory management and logistics to speed up operations. In general, the barcode is a pivotal device that enables tracking of the product's path, adherence to the standard, visibility and accountability throughout the chain of supply. The proposed blockchain and AI-based traceability system for agricultural products in Indonesia relies on several key roles of Indonesian government regulations:

- Setting national standards: Indonesian regulations establish national standards for agricultural practices, including land use, forest protection, and environmental sustainability. Producers and stakeholders within the country are guided by these standards. Regulations also act as benchmarks for compliance in Indonesia and guarantee that agricultural products meet criteria from both domestic and foreign standards.
- Alignment with international regulations: to enable export and meet the global agricultural products demand of sustainably sourced agricultural products, Indonesian regulation can be aligned with international standards like EUDR. Furthermore, these regulations will help in mutual recognition of mutual agreements for agricultural exports in terms of certification and authorization process.
- Licensing and certification: agricultural producers are granted a permit or license from government agencies, that verifies they are complying with regulatory standards and are permitted to join in the blockchain based system. The government may also control the certification process to check that a product complies with international standards and would have certifications.
- Monitoring and enforcement: national regulations and standards are monitored and complied to by governmental agencies. The blockchain system supports this process by providing transparent immutable records of supply chain activities. The government's enforcement actions against non-compliance can be corporate fines, penalties, or licenses suspension in cases of non-compliance.
- Data protection and privacy: national regulations and standards are complied with by governmental agencies. The addition of the blockchain system helps this process by giving a transparent, immutable supply chain records for all of the activities. If non compliance occurs, the government can enforce actions such as fines, penalties, suspension of licenses.
- Stakeholder engagement: this can allow for collaboration with industries and help maintain sense of collaboration with governmental regulations, that supply chain activities are aligned with national goals of sustainable agriculture. The government can also provide education and training of farmers and others who will carry out, understand and enforce the regulations.
- Facilitating innovation: by applying Indonesian regulations, the technologies of blockchain and AI can be encouraged in the agricultural sector, providing a framework and incentives for their use. Furthermore, regulations facilitate research and development covering traceability solutions for further innovation.
- Indonesian government regulations, in turn, would provide the necessary assistance with regard to compliance, monitoring, and enforcement for the effective implementation of a blockchain and AI-based traceability system of agricultural products, which will ensure supply chain integrity and sustainability for the benefit of domestic producers and international markets.

The fifth block introduced the need for compliance engagement and enforcement by the EU. Compliance and enforcement are of paramount importance to the effectiveness, reliability, and further development of the blockchain and AI-based traceability system of agricultural products-which are highly demanding in environmental and ethical dimensions, as specified within EUDR. Thus, this component shall play a role in regulatory compliance, guaranteeing quality, setting enforcement regulations, and engaging in stakeholder collaboration.

Regulatory compliance includes adherence to standards. The system ascertains that agricultural product comply with regulations like the EUDR by tracking the products from their origin to the end-user and identifying any deviation from set standards. It also includes origin verification. The system, through blockchain, verifies the origin of the agricultural products to ascertain these are not related to deforestation or forest degradation. The system allows running quality control checks and audits. Businesses and regulators can utilize data from barcodes and blockchain records to conduct quality control checks on products against safety and ethical standards. The system also makes regular audits possible by way of clear, unalterable records of the supply chain with a view to assessing compliance with regulations, as well as internal quality benchmarks.

Finally, the enforcement of the regulations covers the action of sanctions for non-compliance. For those cases when it is found that certain products violate the regulations, enforcement actions can be taken against responsible parties according to the system through the use of penalties, fines, or restrictions. Automation of actions can be done by using smart contracts that automate the enforcement measures, including the holding up of transactions or release of payments upon the fulfillment of the conditions of compliance. Set mechanisms for compliance and enforcement allow integrity in the value chain to ensure that such risks as environmental damage and unethical practices are avoided, while at the same time upholding standards. This goes a long way in enhancing the sustainability of the agricultural products for consumer confidence.

5. CONCLUSION

This work proposes a novel model of blockchain and AI technologies in agricultural supply chains as a solution to traceability and compliance with EUDR. The model enables to track origins and paths of products, providing the ability to guarantee deforestation free status, addressing concerns about traceability tools and smallholders in Indonesia. This innovative approach for transparency, reliability and consumer trust in the whole agricultural chain will stimulate environmental sustainability. The smart contracts, barcodes, and integration with other systems all come together to simplify and maintain integrity of supply chain operations. In addition, the engagement and facilitation of government regulations and enforcement mechanisms that are vital for the success of this system for both local producers and outreach to international markets in providing sustainability of agricultural products and confidence to agricultural products. The scalability and adoption of the system could be one of the future potential challenges for a proposed model that integrates the blockchain and AI for traceable in agricultural supply chains. Despite this, using blockchain and AI to increase the transparency and reliability of the supply chain is a great idea, but it would definitely have its share of issues such as, how to implement such technology on a larger scale over different agricultural sectors and a number of different agricultural regions. With broad smallholder and stakeholder adoption, resistance to change, and technical barriers to scalability, this could present key challenges to future implementation of this model. Furthermore, gaining the required facilities for acceptance which are often reliant on excessive investment, achieving market penetration, and remaining viable while navigating complex regulatory and compliance environments, each possessing their own EUDR jurisdiction boundaries, can also be difficult.

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [SPR], upon reasonable request.

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