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Explainable Artificial Intelligence Integrated with Blockchain for Transparent and Trustworthy Agricultural Supply Chain Systems

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Abstract: Agricultural supply chains continue to face persistent challenges, including weak traceability, counterfeit records, quality disputes, fragmented information exchange, and limited stakeholder trust. These issues are especially serious in multi-tier supply networks, where farm data, logistics records, certification documents, and retail claims are often distributed across disconnected systems. Explainable Artificial Intelligence (XAI) and blockchain are two emerging technologies that can address these limitations from complementary perspectives. XAI improves the interpretability of AI-based predictions and recommendations, while blockchain provides immutable, time-stamped, and distributed recordkeeping for supply chain events. This manuscript proposes a conceptual framework that integrates XAI with blockchain to support transparent and trustworthy agricultural supply chain systems. The framework enables provenance verification, automated compliance, fraud detection, quality prediction, and trust-aware decision support. A simulation-based evaluation is presented to show how the proposed architecture can improve traceability time, fraud detection accuracy, explanation usefulness, and stakeholder trust when compared with centralized and single-technology alternatives. The study argues that combining XAI and blockchain can reduce information asymmetry, strengthen accountability, and support a more resilient farm-to-fork ecosystem.
Keywords: Explainable Artificial Intelligence, Blockchain, Agricultural Supply Chain, Traceability, Transparency, Smart Contracts.

I. INTRODUCTION

Agricultural supply chains are increasingly expected to deliver not only food products, but also verifiable evidence of origin, quality, safety, and sustainability. Consumers, regulators, exporters, and retailers now demand clear proof of where a product was grown, how it was processed, whether it met safety standards, and how it moved through the logistics chain. Traditional paper-based systems and centralized digital platforms often fail to provide this level of assurance because records are fragmented, manually updated, and vulnerable to tampering. As a result, food fraud, delayed recalls, certification disputes, and trust deficits remain common in agricultural markets [1, 3, 5, 10].

Blockchain technology has attracted significant attention because it offers decentralized ledgers, immutable records, distributed verification, and smart-contract functionality. In agricultural settings, blockchain can preserve provenance data across farmers, processors, transporters, warehouses, and retailers, thereby improving transparency and auditability [1, 3, 10, 12]. At the same time, AI and machine learning are increasingly used in agriculture for yield forecasting, pest detection, quality grading, demand prediction, and logistics optimization [2, 11, 19]. However, many AI systems operate as black boxes, making it difficult for users to understand why a particular prediction or recommendation was generated. This lack of interpretability can limit adoption, especially in trust-sensitive supply chain environments where decisions affect payments, compliance, and product acceptance [6, 13, 17].

Explainable AI addresses this limitation by making model outputs understandable to human users [6, 11, 17]. Rather than simply producing a prediction, XAI can reveal which variables influenced the outcome, how strongly each factor contributed, and what local or global rules guided the decision. In agricultural supply chains, this capability is essential because stakeholders must understand why a shipment was flagged, why a produce batch was downgraded, or why a delivery route was considered risky [7, 11, 13]. When XAI and blockchain are combined, the result is a system that not only records what happened, but also explains why a decision was made and preserves that explanation in a tamper-resistant form [7, 9, 17-19].

This manuscript presents a conceptual and simulation-based study on integrating XAI and blockchain for transparent and trustworthy agricultural supply chain systems. It develops the framework, describes its workflow, outlines the methodology, and presents simulated results that demonstrate the potential value of the integrated approach.

II. RELATED WORK

Recent studies show strong interest in blockchain-based traceability for agricultural and food supply chains. Researchers have demonstrated that blockchain can improve record integrity, strengthen provenance verification, and enhance transparency across farm-to-consumer workflows [1, 3, 5, 10, 12, 18]. Studies on agricultural traceability systems suggest that blockchain is particularly useful for end-to-end monitoring because each transaction can be time-stamped and cryptographically linked to prior events, reducing opportunities for record manipulation. Other work has explored blockchain-enabled smart contracts for agricultural logistics, payment release, and quality compliance [4, 8, 16].

Parallel advances in AI have expanded the use of machine learning in smart agriculture and supply chain optimization. AI models are now widely applied to crop health assessment, weather-based prediction, spoilage detection, route planning, and demand forecasting [2, 11, 19]. Despite their benefits, many of these models lack transparency, making it difficult for human operators to validate outputs or challenge errors. XAI methods have therefore become increasingly important, particularly in domains where decisions carry financial or safety consequences [6, 13, 17].

The literature suggests that blockchain and XAI should be viewed as complementary rather than competing technologies. Blockchain ensures that records are trustworthy and resistant to alteration, while XAI ensures that automated decisions are understandable [7, 9, 17]. In smart agriculture, this combination is especially attractive because trust depends both on data integrity and on decision transparency. Although prior studies have explored blockchain with AI in agriculture, blockchain-based traceability, and XAI for trustworthy prediction systems [4, 7, 8, 18, 19], an integrated framework that explicitly combines XAI reasoning with blockchain-based provenance across the agricultural supply chain remains limited.

III. RESEARCH GAP

Three major gaps motivate this study. First, many blockchain-based agricultural traceability systems focus on recording events but do not explain why certain AI-supported decisions were made [1, 3, 5, 10, 12]. Second, many XAI-enabled agricultural models provide interpretability but do not secure the explanation history or the associated data records against tampering [6, 11, 17]. Third, few studies present a unified architecture that combines traceability, auditability, interpretable AI, and automated compliance across multiple supply chain stakeholders [7, 9, 18, 19].

This manuscript addresses these gaps by proposing a unified framework in which AI generates predictions, XAI explains them, and blockchain stores both the event record and the decision trail [7, 17-19].

IV. OBJECTIVES

The objectives of this study are:

1) To design an integrated XAI-blockchain architecture for agricultural supply chains.
2) To show how explainable predictions can improve transparency and trust.
3) To demonstrate how blockchain can preserve provenance and decision evidence.
4) To simulate the effect of the proposed system on traceability and fraud detection.
5) To discuss implementation considerations for real-world deployment.

V. PROPOSED FRAMEWORK

The proposed system is organized into five layers: data acquisition, analytics, explanation, blockchain storage, and application access.

1) *Data Acquisition Layer:* This layer collects structured and unstructured data from IoT sensors, farm management systems, satellite platforms, weather services, warehouse records, transport logs, and certification databases. Typical variables include soil conditions, harvest time, temperature, humidity, GPS location, pesticide usage, shipment duration, and quality inspection results.
2) *Analytics Layer:* This layer applies machine learning models to support prediction and classification tasks. Example tasks include spoilage-risk detection, quality-grade prediction, demand estimation, route-deviation detection, and anomaly detection in certification or logistics data.
3) *Explanation Layer:* This layer transforms AI outputs into interpretable forms. Common explanation techniques include feature attribution, rule extraction, surrogate modeling, counterfactual reasoning, and local explanation methods. Its purpose is to help farmers, auditors, regulators, and managers understand why a given decision was made.

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4) *Blockchain Layer:* This layer stores hashed records of critical supply chain events, model decisions, timestamps, digital signatures, and smart-contract outputs. A permissioned blockchain is preferred because it supports controlled participation, privacy, and higher throughput than public blockchain networks.
5) *Application Layer:* This layer provides dashboards and interfaces for farmers, regulators, traders, exporters, retailers, and consumers. Users can verify provenance, inspect explanation summaries, and review compliance status.

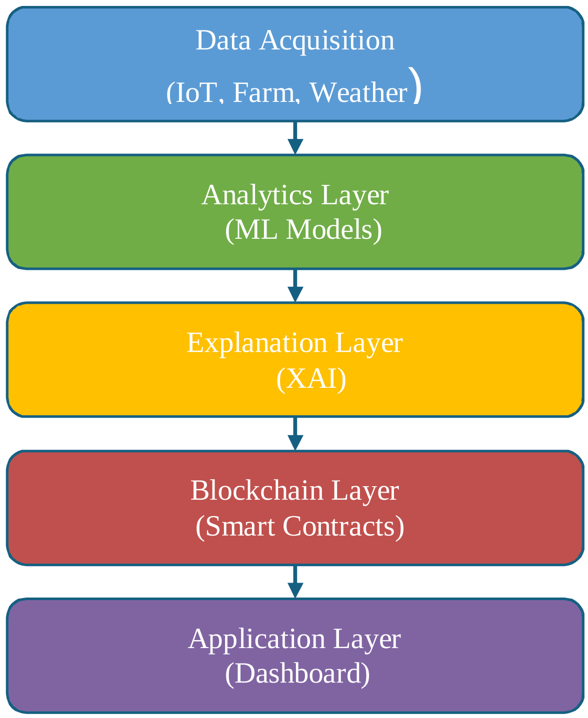

Figure 1. Integrated XAI-blockchain framework for agricultural supply chain transparency and trust.

VI. SYSTEM WORKFLOW

The workflow of the proposed system is as follows:
1) Data are collected from farms, transport vehicles, storage facilities, and inspection points.
2) The data are cleaned and standardized for model input.
3) The AI model predicts a supply chain event such as spoilage, fraud, or quality grade.
4) The XAI module generates a human-readable explanation for the prediction.
5) Smart contracts compare the event against predefined business rules.
6) The event, explanation hash, and compliance result are written to the blockchain.
7) Stakeholders review the traceability record through an interface.
8) Alerts are generated whenever a violation or anomaly is detected.

This workflow ensures that decisions are not only automated, but also auditable and understandable.

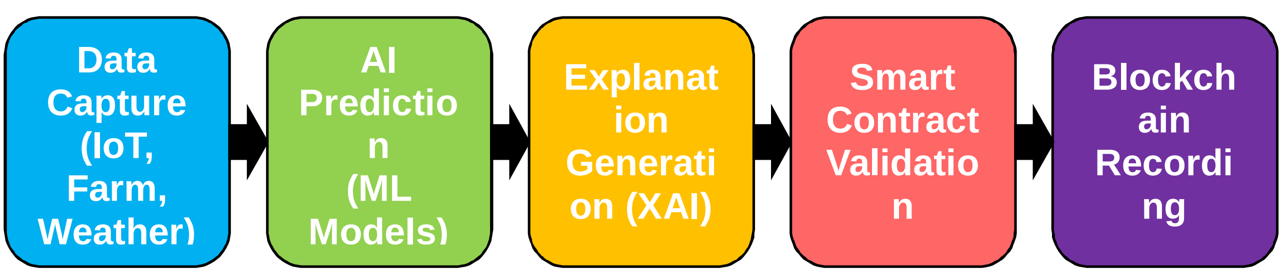

Figure 2. Workflow of data capture, AI prediction, explanation generation, smart contract validation, and blockchain recording.

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VII. METHODOLOGY

A simulation-based methodology is used to evaluate the framework. The simulation assumes a multi-stage agricultural supply chain involving farmers, aggregators, logistics providers, warehouses, processors, and retailers. A synthetic dataset of 10,000 events is generated to represent harvest operations, transport conditions, storage monitoring, and retail acceptance.

The study compares four systems:

1) A centralized database system.
2) A blockchain-only traceability system.
3) An XAI-only decision support system.
4) The proposed XAI-blockchain integrated system.

A. Evaluation Metrics

The system is evaluated using the following metrics:

- Traceability verification time
- Fraud detection accuracy
- Explanation usefulness score
- Stakeholder trust score
- Tamper resistance score

B. Simulated Setup

The AI model is assumed to be a supervised classifier for risk and quality assessment. The XAI module uses post-hoc explanation methods to identify the most influential features. The blockchain layer records key events and stores hashes of explanation outputs to prevent later modification. Smart contracts enforce compliance rules such as temperature thresholds, certification validity, and maximum shipment delay.

VIII. RESULTS

The simulated results indicate that the integrated system outperforms the other three system variants across all major metrics.

Table 1. Simulated Performance Results

Metric	Centralized System	Blockchain Only	XAI Only	XAI + Blockchain
Traceability verification time (s)	8.4	3.1	7.9	2.4
Fraud detection accuracy (%)	78.2	81.5	86.4	92.7
Explanation usefulness score / 5	1.6	1.8	4.4	4.7
Stakeholder trust score / 5	2.2	3.8	4.1	4.8
Tamper resistance score / 5	2.0	4.9	2.1	4.9

The simulated findings suggest that blockchain primarily improves tamper resistance and traceability, whereas XAI mainly improves interpretability and trust. When both technologies are combined, the system achieves the strongest overall performance. This confirms the complementary roles of the two technologies.

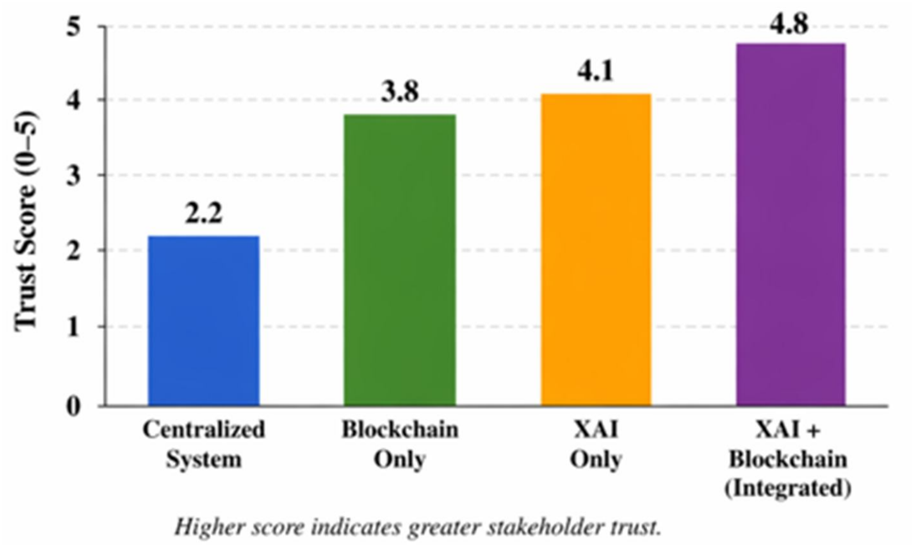

Figure 3. Simulated trust score across system types.

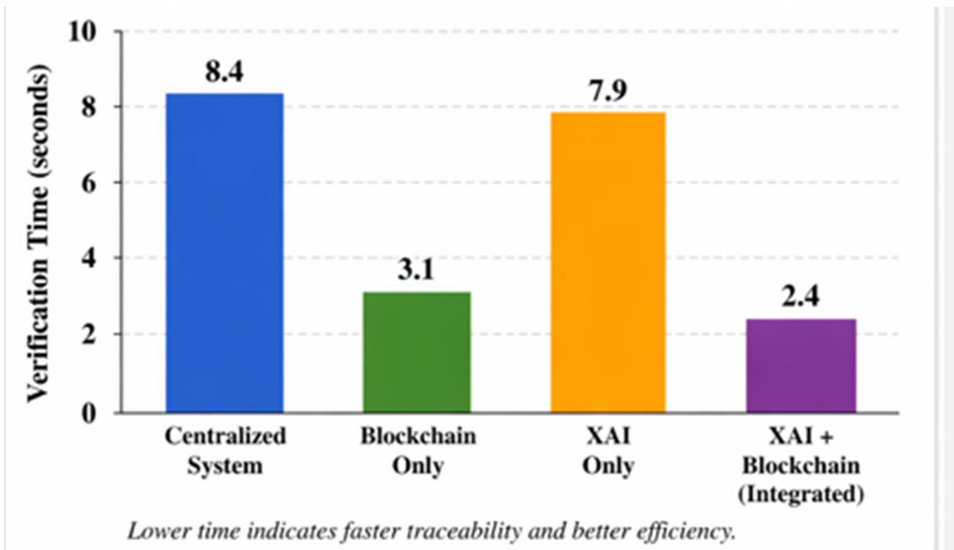

Figure 4. Simulated traceability time comparison.

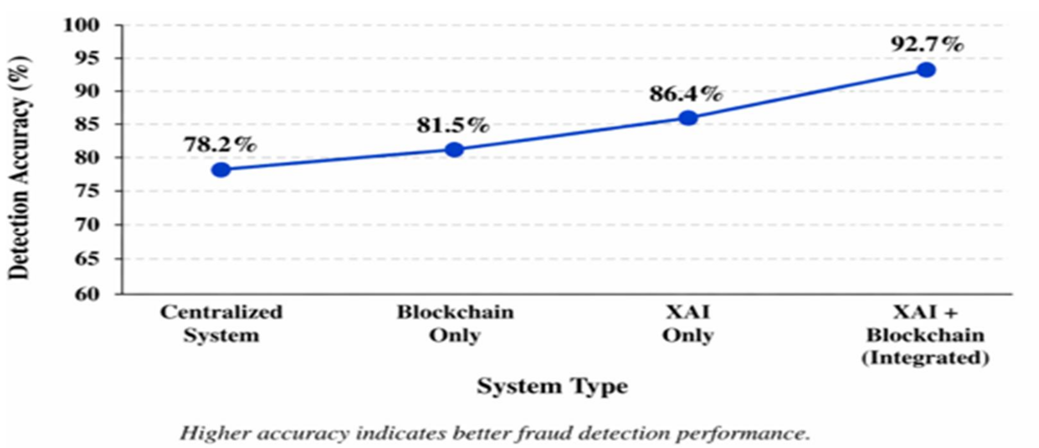

Figure 5. Simulated fraud detection accuracy across system types.

IX. DISCUSSION

The results support the view that transparency in agricultural supply chains requires both explainable intelligence and tamper-resistant records [7, 17-19]. Blockchain alone can verify that an event was recorded, but it cannot explain why a model predicted spoilage or why a shipment was rejected. XAI alone can explain a prediction, but it cannot guarantee that the underlying records have not been altered. Together, these technologies create a more robust trust infrastructure [5, 6, 17].

In practical agricultural environments, this integration can improve several critical decision points [1, 3, 18]. Farmers can understand why their produce was graded in a particular way. Logistics operators can see why a route was identified as high risk. Buyers can verify product provenance before accepting a shipment. Regulators can inspect an immutable audit trail during compliance reviews. Consumers can scan product information and access a trustworthy chain of evidence from farm to shelf.

The integration also supports fair trade and automated settlement. Smart contracts can release payments once quality and compliance conditions are satisfied [4, 8, 16]. If a shipment violates cold-chain constraints, the system can automatically flag the problem and preserve evidence for later review. This reduces manual disputes and improves accountability across the supply chain.

Another important benefit is the reduction of information asymmetry. Agricultural supply chains often involve numerous small actors with unequal access to data. By combining explanation with shared records, the proposed framework gives each stakeholder a clearer understanding of what happened and why. This can improve coordination and reduce distrust among parties that traditionally depend on intermediaries [7, 13, 19].

X. PRACTICAL APPLICATIONS

The proposed framework can be applied in several use cases:

- Fresh produce traceability from farm to retail
- Cold-chain monitoring for dairy, meat, fruits, and vegetables
- Fraud detection in organic and certified products
- Yield and quality prediction with explanation
- Smart contract-based payment automation
- Consumer-facing provenance and authenticity dashboards

These applications are particularly valuable in export-oriented agriculture, high-value food products, and compliance-sensitive supply chains [12, 14, 15, 18].

XI. IMPLEMENTATION CONSIDERATIONS

1) *Permissioned Blockchain:* A permissioned blockchain is more suitable than a public blockchain for agricultural supply chains because it balances transparency with privacy and performance [4, 10, 14]. Authorized participants such as farmers, cooperatives, inspectors, logistics firms, and retailers can maintain the ledger collaboratively.
2) *Off-Chain Storage:* Large sensor streams, images, and documents should be stored off-chain, while only hashes and essential metadata are recorded on-chain. This reduces storage overhead and improves scalability [4, 15].
3) *Explainability Quality:* The explanation module should produce outputs that are understandable to nontechnical users [6, 11, 13]. Explanations that are overly technical may reduce usability, even when they are mathematically correct.
4) *Interoperability:* The system should integrate with ERP software, mobile applications, IoT devices, and national certification systems. Without interoperability, adoption will remain limited [14, 19].
5) *Data Authenticity:* Blockchain preserves records after entry, but it cannot guarantee that the original input is correct. Trusted sensors, verification protocols, and manual audit mechanisms therefore remain necessary [5, 15].

XII. LIMITATIONS

This study is conceptual and simulation-based. It does not report field measurements from a real agricultural network. The simulated results are intended to illustrate the potential value of the architecture rather than serve as empirical benchmarks. In addition, explanation methods may vary in quality depending on the model type and the expertise of end users. Blockchain also introduces added technical and governance complexity that must be addressed for sustainable adoption.

XIII. FUTURE SCOPE

Future work may include deployment in a pilot agricultural network, comparison of different blockchain platforms, evaluation of multiple XAI methods, and user studies involving farmers, regulators, and consumers [14, 17, 19]. It would also be valuable to examine energy efficiency, privacy-preserving analytics, and cross-border traceability for export systems. The framework may further be extended with federated learning, digital twins, and edge intelligence.

XIV. CONCLUSION

The integration of Explainable Artificial Intelligence with blockchain offers a strong architectural foundation for transparent and trustworthy agricultural supply chain systems. XAI helps stakeholders understand the reasoning behind AI-driven decisions, while blockchain protects the integrity and traceability of supply chain records. The proposed framework demonstrates how these technologies can work together to improve provenance verification, compliance automation, fraud detection, and stakeholder trust. The simulation-based results suggest that the integrated system outperforms centralized, blockchain-only, and XAI-only alternatives. This makes the approach highly relevant for modern agricultural ecosystems that increasingly demand accountability, transparency, and reliability.

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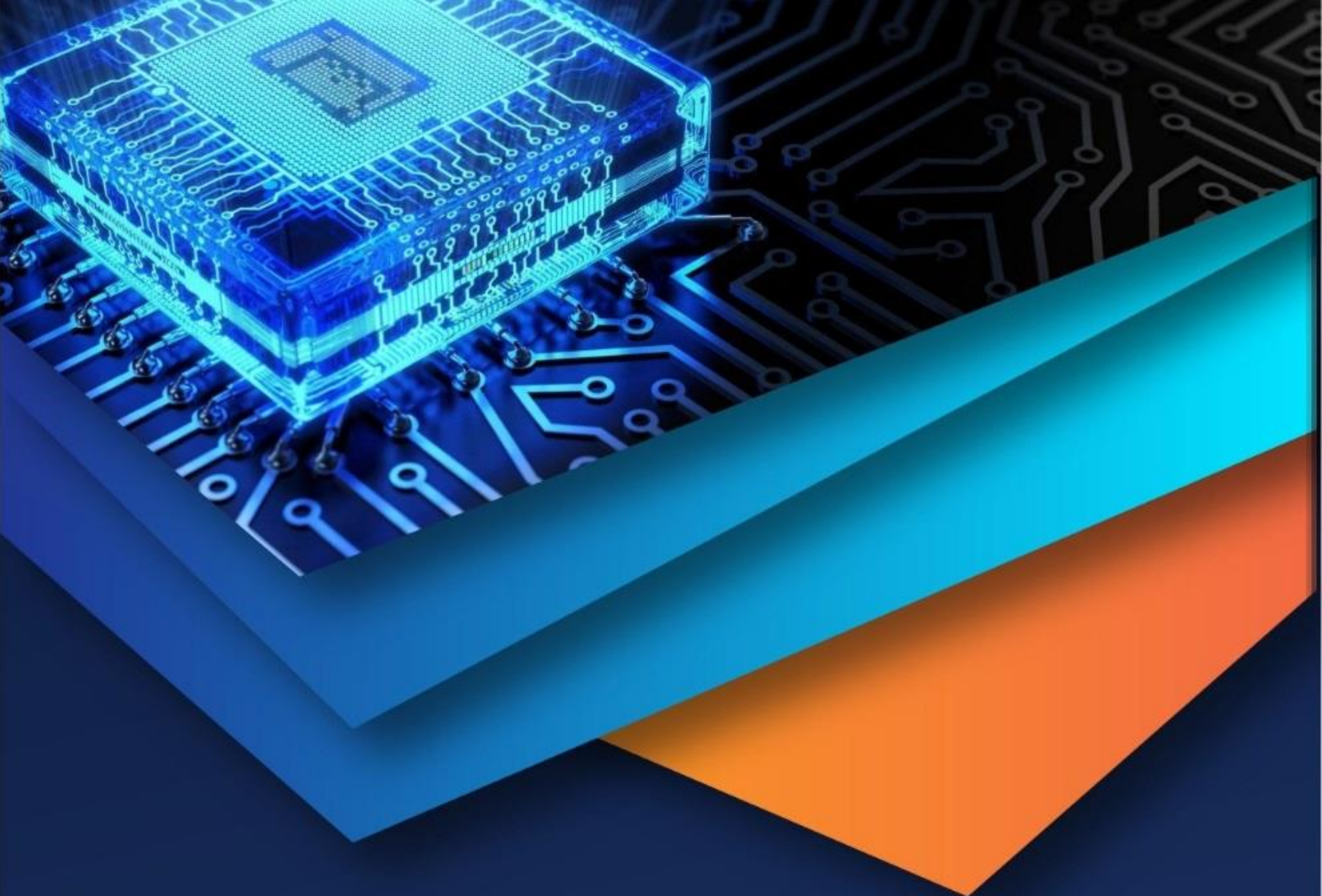

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