

A DIGITAL GOVERNANCE FRAMEWORK FOR AGRICULTURAL SUPPLY CHAINS USING BLOCKCHAIN AND EXPLAINABLE ARTIFICIAL INTELLIGENCE

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Abstract— Ensuring transparency, accountability, and regulatory compliance remains a significant challenge in modern agricultural supply chains due to fragmented information management and limited governance assessment capabilities. This study proposes a Digital Governance Framework that integrates blockchain technology, Explainable Artificial Intelligence (XAI), machine learning, and a Digital Governance Quality Index (DGQI) to support transparent and interpretable governance evaluation. The proposed framework was validated using an integrated dataset comprising 701 observations and 55 engineered variables. Experimental evaluation demonstrated that the proposed XGBoost model achieved an R^2 of 0.972, 98.93% classification accuracy, and a ROC–AUC of 0.985. Furthermore, the framework attained a mean DGQI score of 0.914 with 96.82% governance confidence, while the Hyperledger Fabric implementation sustained 842 transactions per second with an average transaction latency of 1.82 s. The proposed framework provides an accurate, interpretable, scalable, and trustworthy solution for strengthening digital governance and supporting evidence-based decision-making in agricultural supply chains.

Keywords: Digital Governance; Agricultural Supply Chain; Blockchain; Explainable Artificial Intelligence; Digital Governance Quality Index (DGQI)

I. INTRODUCTION

Agricultural supply chains are an integral part of food systems and contribute to food security, economic growth and sustainable rural development. The complexity of agricultural production, processing, transportation, storage and distribution has greatly contributed to the amount and range of data generated along the supply chain. At the same time, consumer awareness of the necessity of food safety, the authenticity of products and environmental sustainability, as well as increasingly strict regulatory requirements, have intensified the demand for transparency, reliability and accountability of the supply chain. But information management is still in silos with poor data interoperability, lack of visibility on operations and lack of fast, evidence-based decision-making by multiple stakeholders. Effective digital governance mechanisms that guarantee transparency, accountability and trust throughout the entire agricultural supply chain ecosystem are essential to address these challenges [2], [10], [25]. The digital technologies identified are advancing at a fast pace which has led to the evolution of traditional systems for gathering information along farming value chains to intelligent data-driven value chains. The use of technologies like Blockchain, IoT, cloud computing, and AI have facilitated the real-time capture of data, secure sharing of information, predictive analysis, and automated decision-making in production, logistics, and distribution processes. Blockchain offers a decentralized and unchangeable platform for reliable data management, while AI can help analyze complex agricultural data, enhancing operational efficiency and decision-making. Even with these technological developments, however, secure data exchange is not enough to drive good governance in the more complex supply chain networks. The increased data requirements and the complexity of participation among multiple stakeholders within agri-food systems is driving a need for digital governance mechanisms capable of delivering sustainable and trustworthy agri-food supply chain management [1], [8], [17], [24].

While blockchain and AI technologies are quickly being adopted in agricultural value chains, a number of key issues have yet to be addressed. While existing blockchain-based solutions are mainly

oriented towards product traceability, product provenience, and transaction security, they have comparatively limited attention towards governance-oriented decision support. In the same way, numerous AI-based solutions focus on predicting outcomes and optimizing operations and offer little insight into the process behind governance-related decisions. Consequently, existing systems tend to be disjointed technological solutions that fail to incorporate secure data management and the intelligent analytics necessary to generate meaningful results, and without robust tools for assessing governance performance by multiple stakeholders. All these limitations hinder the success of digitalization efforts in the support of transparent, accountable and trustworthy agricultural supply chain management [3] [12] [18] [23]. The constraints of current research show a significant knowledge gap in the design of smart digital governance processes for agri-supply chains. While blockchain, AI, IoT and digital traceability have been explored separately in the past, few studies have focused on how all of these technologies can coexist in a single framework under a common governance. Further, there are no established standardized mechanisms in literature to measure the performance of governance quantitatively, while also maintaining secure data management, understandable decision-making and accountability for stakeholders. The intricate nature of these agricultural value chains thus requires an integrated approach that can seamlessly integrate reliable digital infrastructure, transparent and comprehensible data analysis, and fair governance evaluations. This deficit of knowledge must be remedied to facilitate an evidence-based and transparent governance that can meet the changing needs of today's agricultural supply chains [18], [20], [21], [22].

To tackle the identified research gap, three key pillars of digital governance—blockchain technology, Explainable Artificial Intelligence (XAI) and machine learning in an integrated decision support architecture for agricultural supply chains are introduced. The framework proposes to create a Digital Governance Quality Index (DGQI) to measure the performance of governance in six complementary dimensions in a quantitative way: transparency, accountability, compliance, evidence reliability, operational resilience and explainability. Governance analytics is accurate and interpretable with an XGBoost based predictive model, and Hyperledger Fabric offers secure transaction validation, data immutability and trustworthy data exchange. The proposed framework brings together the current state of research on digital agricultural supply chain governance, which is still addressed separately on traceability, security, or predictive modelling. Therefore, the overall purpose of this study is to design and test an integrated digital governance framework that enhances transparency, accountability and decision reliability in agricultural supply chains by synergically combining blockchain, Explainable Artificial Intelligence (XAI), and machine learning. For this purpose, the study proposes a new blockchain-based governance architecture, a Digital Governance Quality Index (DGQI) to quantitatively assess the governance system, XGBoost and SHAP to offer a detailed, accurate, and interpretable governance analysis and to fully test the proposed governance framework through predictive analysis, blockchain analysis, statistical analysis, and ablation analysis using real-world data from the agricultural supply chain, respectively. A systematic data-driven research methodology was followed to develop the proposed framework and validate it. The data was pre-processed, feature engineered, normalized and quality checked to build a solid analytical framework for an integrated agricultural supply chain dataset with 701 observations and 55 engineered features. Later on, the Digital Governance Quality Index (DGQI) was developed to measure governance performance for six governance aspects. The XGBoost algorithm was used for predictive modelling, and the Explainable Artificial Intelligence (XAI) method based on SHAP was used to improve the interpretability of the model. Hyperledger Fabric was added to facilitate secure transaction validation, immutability for records, and execution of smart contracts. The proposed framework was finally evaluated by performing in-depth regression, classification, blockchain performance, statistical and ablation analysis.

This paper is organized as follows: In Section 2, the literature review is conducted and the gap in the literature is identified. A proposed framework, research methodology and experimental evaluation are presented in section 3. The findings, practical implications and limitations of this study are discussed in section 4. Last but not least, Section 5 reflects the main contributions and suggests further research directions.

II. LITERATURE OVERVIEW

The digital age has dramatically changed the food chain by bringing the agricultural systems from a fragmented approach into a clustered data-driven environment. In the past, agricultural supply chains were based on paperwork, silo approach to information systems and on-farm communication between few producers, processors, distributors, retailers and government agencies. This frequently led to information asymmetry, slow decision making, lack of product traceability and lack of transparency in operations. As food systems grow more complex and consumers demand information on food safety, sustainability and the authenticity of products, digital technologies have been gaining traction to enable ongoing monitoring, real-time information sharing and intelligent decision-making along the food supply chain [2], [7], [11]. Digitalisation is being driven by recent developments in blockchain, Internet of Things (IoT), cloud computing and Artificial Intelligence (AI) in agriculture. These technologies enable collection, integration and analysis of disparate data from all stages of production, harvesting, processing, transport, store, and retail. Specifically, IoT-based sensing technologies enable real-time monitoring of the environment and operations, and cloud computing enables managing data and sharing it collaboratively among geographically distributed stakeholders. These digital technologies have contributed to better operational visibility, resource utilization, and traceability, leading to the strengthening of agricultural supply chains' efficiency and resilience [8, 14, 24].

In spite of these technological advances, digital transformation is more than just the use of a more advanced form of information technology. Effectiveness of agricultural digital ecosystems increasingly relies on the need for transparency, accountability, regulatory compliance, and trustworthy information sharing among multiple stakeholders, via governance mechanisms. Digital governance offers the institutional and operational structure for managing, validating and using digital resources to ensure reliable decision making. This has led to governance emerging as a key part of digital transformation, impacting not only on operational efficiency but on the confidence of stakeholders, regulatory assurance and sustainable supply chain management as well [18], [20], [25]. Current research has thus moved away from being technology driven to being governance driven, with a focus on digital ecosystems that can be used to implement transparent and evidence-based decision making. There is a clear need for the integration of trusted digital evidence and governance frameworks to enhance institutional accountability and boost cooperation between producers and certifiers, as well as between logistics, retailers and consumers. However, governance approaches are still mostly of a conceptual nature, and often rely on qualitative descriptions or single indicators to gauge governance quality, but not on robust quantitative assessment tools. Governance frameworks are more and more required to address the increasing need for governance intelligence that can be derived from trusted digital information, to enable transparent, accountable and evidence-based governance decisions in the context of evolving agriculture value chains as smart and digital ecosystems. The need is the basis for the governance mechanisms discussed in the next section that involve blockchain technology [18] [20] [21].

Traceability, transparency, and data integrity are among the most profound ways in which blockchain technology can impact agricultural supply chains. In contrast to traditional centralized information systems, blockchain uses a distributed ledger architecture which tracks transactions in an unchangeable and tamper-proof way, allowing all authorized people in the supply chain to trace every event that takes place. The ability to document product origin, farm activities, logistics operations, storage and distribution records, providing an accurate and trustworthy traceability of the agricultural product. Due to these benefits, blockchain is becoming a key technological cornerstone to increase the reliability of information, mitigate bad practices and build confidence among actors in more and more complex agri-food systems [1], [3], [10]. In recent years, blockchain has been shown to be versatile and useful in various agricultural applications such as authentication of products, digital certification, fraud prevention, decentralized identity management, and coordination of sustainable supply chains. These innovative partnerships, including the Internet of Things (IoT), cloud computing, and sensor networks, have enhanced the blockchain's applicability. The Internet of Things (IoT) devices continuously gather environmental and operational data, while blockchain offers a secure way for validation, storage, and sharing of these data with multiple stakeholders without impacting the integrity of the data. This technological convergence improves the visibility of an end-to-end product,

helps the regulators to validate the product traceability and allows for more accurate tracking of agricultural products during the product lifecycle [4], [5], [8], [24].

In agriculture, permissioned blockchain platforms have garnered significant interest due to their enhanced ability to control data access, authenticate participants, and validate transactions. Hyperledger Fabric has gained significant traction among these platforms, thanks to its modular design, fast consensus protocols, customizable access control policies, and ability to run smart contracts. These features make it well suited for multi-stakeholder agriculture – with producers, distributors, certification organizations, regulators and consumers needing access to shared information but in a protected and controlled manner. As a result, blockchain-based infrastructures are becoming more and more appreciated as a trusted digital platform to facilitate collaborative information management that maintains confidentiality and auditability of the data [16], [19] and [23]. However, the existing agricultural blockchain applications are mainly focused on the operational aspects, like traceability, provenance verification, transaction security, and interoperability. Typical metrics for assessing their performance include transaction throughput, latency, storage efficiency, consensus performance, and the ability to detect fraud. While these metrics evidence system reliability, they do not offer much insight into whether governance processes are transparent, accountable, evidence based, or regulatory compliant. That is, blockchain creates digital evidence that is trusted, but does not necessarily include measures for assessing the quality of the evidence and its utility for governance decisions [18, 20, 21].

This separate is an important area for future studies. The contemporary research about blockchain increasingly acknowledges that blockchain is not a full governance solution but a secure digital infrastructure that can be built on to introduce intelligent governance mechanisms. To derive actionable governance intelligence from trusted blockchain logs, analytical capabilities are needed that complement those of the blockchain and can interpret digital evidence and provide for transparent decision-making. Therefore, blockchain should be seen as a means to reach digital governance, and not as an end, making it necessary to give consideration to analytical approaches which are explained in the subsequent section [17], [20] and [21]. Artificial Intelligence (AI) has emerged as a key enabler in today's agricultural value chain, facilitating smart decision support for production planning, crop monitoring, quality control, demand forecasting, logistical optimisation and risk management. As the volume of these agricultural data sets is increasing rapidly, with a variety of sources including sensors, satellite observations, market transactions, and monitoring systems that track various environmental aspects, machine learning techniques are playing an increasingly vital role in deriving valuable insights from the complex agricultural processes in the supply chain. These analytical capabilities have significantly enhanced operational efficiency and predictive capabilities, allowing stakeholders to better adapt to the changing environment, market dynamics, and regulatory demands [14], [17], [19].

Despite these developments, there are new issues of transparency and accountability when relying on machine learning algorithms that are becoming more complex. A number of predictive models perform quite well, but deliver predictions that lack adequate explanation of the decisions being made, or the model is treated as a "black box". Many predictive models are very successful and give accurate predictions without enough explanation of what is being decided, or without getting the model into a "black box". Such models are appropriate to performance-based applications, but for governance-based applications where decisions should be transparent, auditable, and evidence-based, they are challenging from a limited interpretability perspective. Increasingly, regulatory agencies, producers, certification bodies and consumers are looking for not only to get right answers, but to see how the answers are derived and to understand the process. The value of stakeholder trust in decisions made using AI can be significantly diminished, especially in scenarios that involve food safety, regulatory adherence, product authentication, and sustainability evaluations [20, 22].

Explainable Artificial Intelligence (XAI) has proven to be a successful way of enhancing the transparency and interpretability of the machine learning models. XAI does not regard predictive algorithms as black-box computational systems, but rather mechanisms for determining the impact of individual variables on model output, allowing them to gain insights into how their decisions are being made. With the various interpretability methods available, a global-local explanation with a strong theoretical foundation, SHapley Additive exPlanations (SHAP), is gaining popularity. SHAP

makes environmental factors, production factors, market conditions, and governance indicators quantifiable in order to help decision-makers draw more confident conclusions based on the analysis and to facilitate more transparent decision-making processes [17, 22]. While there are recent studies on explainability in agricultural analytics, it has been used in most cases to enhance the interpretability of the model and predictive accuracy. Lesser research has focused on combination of explainability and blockchain-enabled digital infrastructures and governance evaluation mechanisms. Previous studies do not integrate trusted and interpretable approaches of machine learning with a quantitative assessment of governance within a single analytical framework that can support transparent evidence-based decision-making. Thus, the potential to leverage XAI in predictive interpretation for governance support in agriculture, where explainability serves as a means to enhance accountability, regulatory trust, and institutional trust in agricultural value chains can be seen as something that still needs to be done [18], [20], [21], [22]. Table 1 compares representative studies based on their use of blockchain technology, Explainable Artificial Intelligence (XAI), governance evaluation, and quantitative assessment of governance. The comparison is not only based on existing studies' technological capacities, but also on how far they contribute to transparent governance, and what are the main points that call for the creation of a framework comprising existing technologies in the context of governance.

TABLE 1. COMPARATIVE ANALYSIS OF RECENT STUDIES ON DIGITAL GOVERNANCE TECHNOLOGIES IN AGRICULTURAL SUPPLY CHAINS

Ref.	Primary Research Focus	Blockchain	XAI	Governance Framework	Quantitative Governance Index	Key Limitation
[1]	Digital identity and product traceability	✓	✗	Partial	✗	Supports traceability but lacks quantitative governance assessment.
[2]	Blockchain-enabled agri-food sustainability	✓	✗	Partial	✗	Focuses on sustainability rather than governance measurement.
[3]	Blockchain-based traceability framework	✓	✗	✗	✗	Provides traceability without governance or explainable analytics.
[4]	Certification and food traceability	✓	✗	Partial	✗	Limited governance evaluation despite improved provenance.
[5]	Blockchain–IoT fraud prevention	✓	Partial	Partial	✗	Improves integrity but lacks measurable governance metrics.
[10]	Blockchain-enabled transparency	✓	✗	Partial	✗	Enhances transparency without governance quantification.

[18]	Digital traceability governance	✓	✗	✓	✗	Defines governance concepts but lacks quantitative evaluation.
[19]	Hyperledger and AI-enabled agriculture	✓	Partial	Partial	✗	Integrates AI with blockchain but lacks explainable governance analysis.
[20]	Blockchain governance mechanisms	✓	✗	✓	✗	Examines governance mechanisms without measurable assessment.
[21]	Smart contract governance framework	✓	Partial	✓	✗	Proposes a governance architecture without quantitative governance evaluation.
[22]	Explainable AI for sustainable agriculture	✗	✓	Partial	✗	Focuses on interpretability without blockchain-enabled governance.
This Study	Integrated Digital Governance Evaluation with DGQI	✓	✓	✓	✓	Integrates blockchain, Explainable Artificial Intelligence (XAI), Hyperledger Fabric, and the Digital Governance Quality Index (DGQI) within a unified framework for quantitative governance evaluation and evidence-based decision support.

It is evident from the comparative analysis presented in Table 1 that the proposed framework is the first study to combine the three elements of blockchain technology, Explainable Artificial Intelligence and the quantitative Digital Governance Quality Index (DGQI) in a single governance assessment framework for agricultural supply chains. The literature analysis in the previous sections shows significant achievements with digital technologies used in agricultural value chains. Product Traceability, Integrity of Transactions, Digital Identity Management, and information Transparency are some of the areas where Blockchain has made significant changes, and with Explainable Artificial Intelligence (XAI), the interpretability of predictive analytics has been improved and confidence in the use of AI in decision-making has grown. These advancements have assisted in the development of

more intelligent and secure operations for the agricultural supply chain, which enable sustainable agricultural production, regulatory compliance, and collaboration among stakeholders [1], [3], [10], [17], [22].

In spite of these advances, some research challenges still need to be answered. First, most of the blockchain-based solutions currently available measure technological performance by parameters like traceability, security of transactions, interoperability and efficiency of operation, but not much on the governance side. Second, governance-related concepts such as transparency, accountability, compliance, evidence reliability and operational resilience are usually operationalized conceptually and are not generally measured constructs that can be used for quantitative assessment. Third, while Explainable Artificial Intelligence enhances the transparency of the models, it has been largely used to explain the predictions by the model, instead of being used to support institutional evaluation of governance and evidence-based institutional decision-making. Lastly, the studies examined so far fail to combine trustworthy blockchain infrastructure, explainable machine learning and governance assessment in a single holistic analytical framework that could transform the heterogeneous digital evidence into governance intelligence for action. [18], [20], [21], [25]

It is clear that there is a gap between the technological innovations and assessment of good governance in agricultural value chain. Although blockchain creates a trusted digital world and Explainable Artificial Intelligence makes analytical transparency possible, traditional methods offer little assistance in measuring the quality of governance systematically or in objectively assessing governance performance in several aspects. As a result, an integrated framework is needed to integrate the secure digital infrastructure, explainable analytics, and quantitative governance evaluation, enabling clear and transparent, accountable, and evidence-based decision making. In response to this research gap, the present study develops an integrated Digital Governance Framework (DGF) that combines Hyperledger Fabric, Explainable Artificial Intelligence (XAI) and a novel Digital Governance Quality Index (DGQI), which offers an approach for measuring and interpreting the governance of agricultural supply chains. This framework will be used to guide the research methodology and experimental validation presented in the next section.

III. PROPOSED DIGITAL GOVERNANCE QUALITY FRAMEWORK

The study uses Design Science Research (DSR) with a quantitative case study approach to create and test a digital governance framework for agricultural supply chains. The chosen approach was Design Science Research as the main goal of this work is to design, implement and evaluate an artefact that can solve a known governance problem. The proposed artefact is the Digital Governance Quality Index (DGQI) framework, which integrates explainable Artificial Intelligence, Blockchain technology and trusted digital evidence to facilitate transparent, accountable and evidence-based governance in Agricultural supply chains. The quantitative research uses open sources of data related to the agriculture, environment and production to assess the conditions related to governance in the tomato supply chain in Tamil Nadu, India. The timeframe of the research is from 2019 to 2025, which allows the framework to reflect the changes in climatic conditions, agricultural production, and markets over time. This study is based on the tomato supply chain because tomatoes are one of the most important and cost sensitive horticulture commodities in India. The tomato supply chain is a suitable context for digital governance mechanisms due to its volatility, post-harvest losses, patchy involvement of actors and limited transparency of governance. The proposed framework assesses the quality of governance decisions facilitated by digital evidence, while conventional blockchain-based traceability studies only focus on the product and its flow throughout supply chain steps. The focus in the framework is therefore, not on transaction recording, but on governance assessment. The trusted information collected from several disparate sources are integrated, processed and interpreted through explainable artificial intelligence (XAI), before being validated by blockchain technology to create a transparent and auditable governance process.

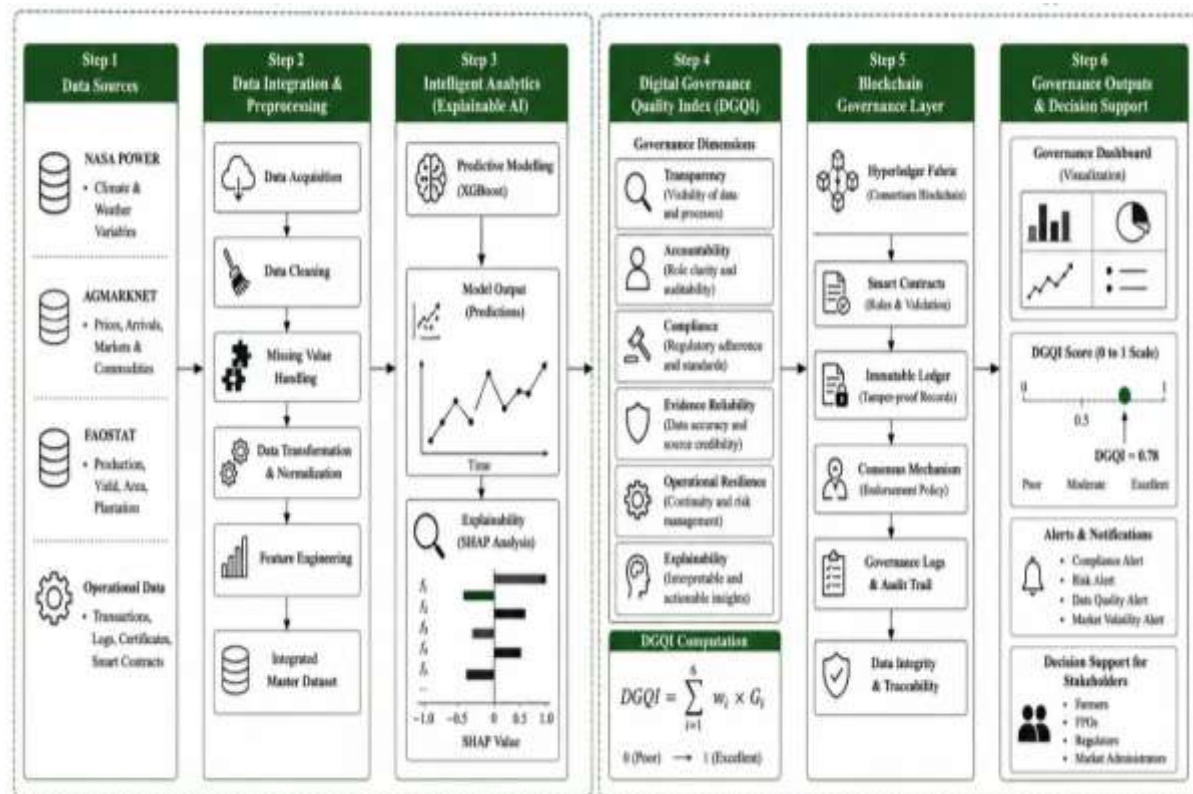


Figure 1. Overall methodological workflow of the proposed Digital Governance Quality (DGQ) framework for transparent agricultural supply chains.

The overall framework of Digital Governance that was proposed in this study is presented in figure 1. The framework is a 6-step process that is sequential, but not mutually exclusive. The first component collects digital evidence that is heterogeneous across various public data sources, such as climatic data retrieved from NASA POWER, agricultural market information from AGMARKNET, country of production statistics from FAOSTAT and operational governance records created in the blockchain environment. The complementary nature of these datasets allows them to provide environmental, economic, production and operational perspectives for thorough governance assessment. The second one does data integration and data pre-processing. The data are raw datasets from various organisations and have often varied temporal, measurement and data structure. The data gathered are therefore cleaned, normalized, temporally aggregated, and missing value imputed, before feature engineering to create an integrated master data set for later analytical modelling. This pre-processing step guarantees consistency, reliability and comparability between different sources and avoids spoiling the integrity of the original observations.

The third one introduces Explainable Artificial Intelligence (XAI) to analyse the integrated data. The predictive learning approach used is Extreme Gradient Boosting (XGBoost) due to its capability to model complex nonlinear relationships in heterogeneous agricultural data, while remaining computationally efficient. SHapley Additive exPlanations (SHAP) values are used to measure the importance of each variable to a model's prediction to provide transparency and aid human interpretation of model behaviour. The explainability mechanism helps stakeholders not only to understand the results of predictions, but also the reasons that underlie decisions related to governance. The fourth one presents the Digital Governance Quality Index (DGQI), which is the main scientific contribution of this research. For assessing the quality of governance, DGQI goes beyond technological deployment as a measure of governance maturity, by combining several aspects of governance into a single measure. The dimensions of governance which are proposed to be included in the index are Transparency, Accountability, Compliance, Evidence Reliability, Operational Resilience, and Explainability, all of which are interrelated. Each construct is expressed in measurable indicators based on trusted digital evidence and then aggregated together according to a

mathematically defined aggregation model to create an overall governance quality score. The result is a DGQI which can be used to compare governance performance objectively between time periods, operational settings and stakeholder environments.

The fifth component uses Hyperledger Fabric, a permissioned blockchain platform, to create an immutable governance layer after evaluating the governance. The governance decisions, executions of smart contracts, compliance events, and audit records are all securely stored in the distributed ledger, ensuring data integrity, traceability and non-repudiation. Smart contracts make governance rule enforcement automatic and offer a transparent audit of the activities in operation, while retaining control of access for authorised stakeholders. The blockchain layer, as such, acts as a trustworthy verification mechanism to complement the analytical power of the explainable artificial intelligence model. The last part provides governance intelligence by offering decision-support services. Governance dashboards, compliance monitoring, alerts for risk detection and reporting, audit trails and evidence-based policy recommendations give actionable information to farmers, farmer producer organisations, market administrators, regulatory organisations or other participants of the supply chain. The proposed framework combines the power of predictive analytics with the security and transparency of blockchain evidence, creating a framework that is transparent, explainable, auditable, and reproducible. Overall, the proposed Digital Governance Framework creates an integrated decision support architecture, where digital evidence can be varied and converted into digital governance intelligence. It illustrates a systematic integration of key elements such as environmental observations, agricultural market information, production statistics, explainable artificial intelligence, and blockchain technology to assess governance performance, not just for product traceability. The framework thus offers a solid ground for digital governance that is based on transparency and evidence, in a more modern agricultural supply chain.

The proposed Digital Governance Framework was empirically assessed in a representative case of an agricultural commodity, the tomato supply chain in Tamil Nadu, India. Tomato is an important vegetable crop contributing significantly to agricultural output, livelihood and food security in Tamil Nadu, one of the key horticultural states in India. The supply chain involves several parties from farmers, aggregation, commission agents, wholesaler, retailers, regulatory authorities, consumers etc. The tomato supply chain is a suitable context for the examination of digital governance mechanisms because it involves a wide range of actors, with high price volatility, a variable production, post harvest losses, and the lack of information flow. Studies were conducted over 7 years (January 2019-December 2025) to capture the variability of climatic conditions, production performance and market dynamics across different agricultural seasons.

This multi-year observation period will provide a more robust assessment of governance, as it will allow for a more consistent assessment, despite the fact that there may be some anomalies in any given year, but it will allow for the identification of long-term patterns of governance operations. The proposed architecture combines data from three authoritative public datasets, as well as governance data created in a blockchain environment, ensuring transparency, reproducibility and scientific reliability. The data sets reflect complementary aspects of agricultural governance: Environmental conditions, Market behaviour and Production characteristics. Environmental observations were accessed from NASA POWER (Prediction of Worldwide Energy Resources) platform. The data obtained for the study area include daily meteorological parameters such as air temperature, rainfall, relative humidity, solar radiation and wind speed. These variables can be used to obtain objective evidence about environmental conditions which affect the production and transportation of the tomato and its quality and availability in the market. Data was then summed up into monthly indicators in order to be consistent with the agricultural market data at a monthly level. The Agricultural market information was gathered from Agricultural Marketing Information Network (AGMARKNET) maintained by Government of India. District level wholesale tomato prices data along with market related data is available. Duplicate price data, inconsistencies in district names and inconsistencies in the time format were eliminated, and monthly price records were combined into a market price panel. The resulting data set is a good measure of the behaviour of the market and of economic variation over the study period. The Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) was used to collect national production data. The variables selected are annual tomato production, harvested area and yield. These indicators give the production background for

understanding the environment's variability and market behaviour, and also serve to assess agricultural system-level governance. In the data integration process, the annual production indicators were synchronized with the monthly production indicators.

After data collection, all data sets were merged in a single analysis data repository. It has been necessary to carry out a systematic data harmonisation procedure, since the original datasets use different temporal resolutions, different units of measure and different data structures. Common temporal attributes and geographic identifiers were used to sync observations on the environment, market records and production statistics. Standardised naming, measurement units and data structures were agreed to ensure analytical processing of data with reliability. The integrated master dataset was created for the purpose of predictive modelling and for governance assessment. The variables observed are grouped into a single analytical framework, which incorporates environmental, market, production and governance-related attributes. This integrated analytical dataset included 55 variables, all engineered, to represent the tomato supply chain during the study period. The integrated representation allows the framework to assess governance performance by taking several streams of trusted digital evidence into account instead of just relying on certain individual data streams. This is why the resulting data set captures the multidimensionality of agricultural governance and serves as a basis for the calculation of the Digital Governance Quality Index (DGQI) and for the validation of blockchain. This is why the resulting data set is multidimensional and can be used for the computation of the Digital Governance Quality Index (DGQI) and for the validation of the blockchain.

Table 2. Summary of the Datasets Integrated into the Proposed Digital Governance Framework

Dataset	Source	Key Variables	Temporal Resolution	Purpose in the Framework
NASA POWER	National Aeronautics and Space Administration (NASA) POWER	Temperature, Rainfall, Relative Humidity, Solar Radiation, Wind Speed	Daily (aggregated to monthly)	Environmental evidence for governance assessment
AGMARKNET	Government of India, Agricultural Marketing Information Network	Wholesale tomato prices, district-level market information	Monthly	Market evidence for price dynamics and supply chain monitoring
FAOSTAT	Food and Agriculture Organization (FAO) Corporate Statistical Database	Production, Yield, Harvested Area	Annual	Agricultural production context and long-term trend analysis
Hyperledger Fabric Prototype	Proposed Digital Governance Framework	Transaction logs, smart contract events, governance records, audit trails	Event-based	Governance validation, traceability, and blockchain-based audit support

The datasets included in the proposed Digital Governance Framework are summarised in Table 2. It is a combination of authoritative environmental, market and agricultural production data, alongside blockchain-generated governance records, which creates an overall evidence base for calculating Digital Governance Quality Index (DGQI), providing explanations for the AI modelling of Governance Quality Index (GQI), and validating the governance using blockchain. The datasets gathered showed a high degree of temporal, structural and measurement unit heterogeneity. Hence, for guaranteeing the quality of the data, the consistency and reliability of the analyses, a systematic data processing pipeline was developed prior to model development. The data pre-processing process involved four stages: data cleaning, temporal harmonisation, feature engineering and data set

validation. Before beginning any analyses, all data sets were examined for duplicate observations, missing data, inconsistencies in date format and district naming conventions. Duplicate records were eliminated; missing observations were completed with the use of appropriate imputation methods and measurement units were standardized to ensure a consistent analytical structure. Daily to monthly environmental data from NASA POWER was aggregated to be consistent with the monthly data from the market records for AGMARKNET, and annual production data from FAOSTAT was synchronized by the same year of observation. This temporal harmonisation allowed the combination of different data types without losing the meaning of the original observations.

Data integration was followed by feature engineering for better predictive power and interpretability of the proposed framework. In addition to the original environmental and market variables, other analytical data were generated to reflect the temporal dynamics, seasonal variations and historical market behaviour. These engineered variables comprised calendar-based features, lags, moving statistical variables, percentage changes, and production context variables. The analytical data generated included 55 engineered variables, which captured a detailed picture of environmental conditions, agriculture production, market behaviour and governance-related characteristics. Before modelling, the numerical variables were standardised and validated to ensure they were compatible with the machine learning algorithms used in this study. The final data set was then reviewed to ensure that features were complete, logically consistent and analytically reliable. The result of this validation process verified that the integrated dataset could be used for calculating Digital Governance Quality Index (DGQI), modelling using Explainable Artificial Intelligence (XAI) and validate the governance using blockchain. The pre-processing and feature engineering process turned the numerous, different agricultural data sets into a single analytical repository which facilitated the assessment of the governance in a transparent, repeatable and evidence-based manner. The proposed framework presents a comprehensive, empirical basis for predictive modelling and evaluation of digital governance, by combining all of the above features in a single feature matrix.

The variables in Table 3 jointly reflect the five dimensions of digital governance evaluation – environmental, economic, production, temporal and governance. This heterogeneous approach allows the proposed framework to capture the complexity of the interactions that affect the whole performance of the agricultural supply chain and to incorporate it as a dependable analytical backbone for the computation of the Digital Governance Quality Index (DGQI) as well as to validate the governance using blockchain technology [2], [17], [18], [25]. The main methodological novelty of this study is the creation of Digital Governance Quality Index (DGQI), which was used to provide a quantitative assessment of governance performance of the blockchain-based agricultural supply chain. Current traceability systems that rely on the blockchain are used mainly to capture operational transactions and product movements, and not to have an objective mechanism to measure the quality of governance. As a result, governance assessment is typically subjective or qualitative and comparisons of governance performance across varying operational conditions or over time are often difficult. The proposed DGQI takes up this challenge by converting several dimensions of governance into a single numerical indicator, which will facilitate evidence-based, transparent and reproducible decision making.

TABLE 3 SUMMARISES THE CATEGORIES OF VARIABLES INCORPORATED INTO THE INTEGRATED ANALYTICAL DATASET.

Feature Category	Representative Variables	Purpose
Environmental Variables	Temperature, Rainfall, Relative Humidity, Solar Radiation, Wind Speed	Characterise climatic conditions affecting crop production and logistics
Market Variables	Wholesale Price, Monthly Price Change, Yearly Price Change	Represent market dynamics and price variability
Production Variables	Production, Yield, Harvested Area	Provide agricultural production context

Temporal Variables	Year, Month, Season	Capture seasonal and temporal patterns
Engineered Variables	Lag Features, Rolling Mean, Rolling Standard Deviation, Percentage Change	Improve predictive performance and capture historical trends
Governance Variables	Transparency Indicators, Evidence Reliability, DGQI Components	Support governance assessment and blockchain validation

The DGQI describes the quality of digital governance in the suggested framework by combining six governance constructs: Transparency (T), Accountability (A), Compliance (C), Evidence Reliability (ER), Operational Resilience (OR), and Explainability (EX). The constructs were chosen in the synthesis of the digital governance theory, agricultural supply chain governance, explainable artificial intelligence, and blockchain-based traceability literature. Each construct is expressed by measurable indicators which are built on trusted data from validated digital evidence from environmental observations, agricultural market information, production statistics, explainable machine learning output and blockchain governance records. Each construct was then normalized on a scale from 0-1, with 0 indicating the lowest performance of governance, and 1 indicating the highest possible performance of governance, in order to make the indicators comparable across the heterogeneous types of governance indicators. A weighted composite indicator for Digital Governance Quality Index was then calculated using Equation (1), with emphasis on the importance of the indicators. A weighted composite indicator of the Digital Governance Quality Index was then calculated using Equation (1) according to the importance of the indicators.

$$DGQI = \frac{(T + A + C + ER + OR + EX)}{6} \quad (1)$$

where:

- T = Transparency
- A = Accountability
- C = Compliance
- ER = Evidence Reliability
- OR = Operational Resilience
- EX = Explainability

The equal weighting method reduces subjectivity, facilitates interpretation and gives an unclouded base for comparative governance evaluation. Other weighting methods could be done using expert judgement or multi-criteria decision-making methods for future studies. DGQI values fall between 0 and 1, where a higher value means that the digital governance quality is higher. The continuous index was grouped into five categories of governance performance, as shown in Table 4, for ease of interpretation. This classification helps decision makers to quickly identify the governance strengths and weaknesses, and prioritise corrective interventions within the agricultural supply chain. The proposed DGQI is a quantitative, repeatable, and multi-dimensional approach in order to combine the governance evidence from different sources into one measure of performance. The DGQI combines transparency, accountability, compliance, evidence reliability, operational resilience and explainability to assess the overall effectiveness of governance processes, as opposed to conventional traceability measures which are largely focused on the product's movement. As a result, the index becomes the pivot of the analytical element, connecting explainable artificial intelligence to blockchain governance validation, and to evidence-based decision-making.

TABLE 4. GOVERNANCE CONSTRUCTS AND DIGITAL GOVERNANCE QUALITY INDEX (DGQI) CLASSIFICATION FRAMEWORK

Governance Construct	Symbol	Description
Transparency	T	Degree of visibility, traceability, and auditability of agricultural supply chain activities.
Accountability	A	Capability to identify responsible stakeholders and attribute operational decisions throughout the supply chain.
Compliance	C	Extent to which operational activities conform to regulatory, contractual, and organisational requirements.
Evidence Reliability	ER	Degree of authenticity, integrity, completeness, and temporal consistency of digital evidence.
Operational Resilience	OR	Ability of the governance system to maintain reliable performance during disruptions and uncertainty.
Explainability	EX	Capability of the AI model to provide transparent and interpretable governance decisions.

The computed Digital Governance Quality Index (DGQI) was normalized and divided into five governance performance levels with pre-defined threshold intervals between 0 and 1, to facilitate the interpretation of the computed DGQI. DGQI score range of 0.00 to 0.20 is regarded as Very Poor governance performance with significant issues identified related to transparency, accountability, compliance, evidence reliability and operational resilience. A score between 0.21 and 0.40 is considered Poor and means that there is a need for significant improvement in several aspects of governance. DGQI ranges from 0.41 – 0.60 indicate Moderate level of governance performance, meaning that basic governance structures are in place, but need to be strengthened to deliver effective governance on a consistent basis. A score range from 0.61 to 0.80 are rated Good with some secure evidence of the digital activity and effective management of operations. The final category of DGQI (0.81-1.00) indicates an excellent governance system, one that is very transparent and accountable, compliant, resilient, and evidence-based, with the potential of facilitating informed decision-making. This classification system offers a solid foundation to understand governance quality and facilitates meaningful comparison of governance performance between various governance actors and different scenarios of operation.

The proposed Digital Governance Framework combines the advantages of Explainable Artificial Intelligence (XAI) with blockchain technology to facilitate transparent, accountable and evidence-based governance in agricultural supply chains. By integrating this, the framework can connect with governance risks, provide an understanding of the factors that may affect analytical results, and build a trusted governance decision recording mechanism. Explainable AI and blockchain are not standalone technologies, but rather, they are complimentary pieces of the governance framework. This predictive component is realized by the Extreme Gradient Boosting (XGBoost) ensemble machine learning algorithm that is known for its predictive power, computational efficiency and its capacity to model complex nonlinear relationships. The impacts of a myriad of environmental, production and market factors on agricultural governance are not captured by traditional linear models. To overcome this shortcoming, XGBoost is trained to learn the complex relationship embedded in the integrated analytical data set and to predict the level of governance risk along the tomato supply chain. While XGBoost makes very accurate predictions, it's not directly interpretable. The framework uses SHapley Additive exPlanations (SHAP) as the explainability mechanism to improve transparency and enhance stakeholder trust. By measuring the contribution of each input feature to the predicted risk of governance, SHAP helps decision makers grasp the impact of climatic conditions, market behaviour, production characteristics and governance indicators on analytical results. The explanations that are generated help facilitate clear decision making and increase the interpretability of machine learning in governance related applications. The governance intelligence created by the explainable artificial intelligence component is then assessed with the Digital Governance Quality Index (DGQI). The DGQI is a quantitative scale that builds on the six governance constructs defined in the preceding section to measure governance performance; XGBoost models the patterns of governance risk and SHAP explains the importance of the various factors in making these predictions. This

complementary relationship between predictive modelling and model interpretation and governance evaluation provides a clear separation between these three activities, eliminating analytical redundancies and consolidating the methodological consistency of the activities.

The governance information is recorded using Hyperledger Fabric, a permissioned blockchain platform, ensuring its integrity and traceability, while the governance outcomes are validated. Governance records, such as DGQI values, governance risk assessments, the date of transactions, smart contract execution status, and cryptographic evidence hashes, are securely kept on the distributed ledger. All governance activities will have an audit trail, including who initiated the transaction, the terms of the transaction, and whether the rules were followed. The immutable ledger will create a transparent and tamper-proof audit trail of all governance activities, while smart contracts will automatically ensure that the governance rules are respected and that only the transactions authorised by the rules are executed. The permissioned architecture of Hyperledger Fabric also allows for the sharing of information between authorised parties, while keeping sensitive operational data private from unauthorised parties. The combination of Explainable Artificial Intelligence, Digital Governance Quality Index and blockchain technology creates an integrated governance pipeline that enables governance risks to be identified by predictive analytics, governance decisions to be made with the aid of explainable artificial intelligence, governance quality to be assessed by the DGQI, and governance evidence to be made safe, traceable and auditable with the help of blockchain technology. The integrated approach offers a strong foundation for the transparent digital governance and aids reliable decision making in modern agricultural supply chains.

An integrated analytical dataset from NASA POWER, AGMARKNET and FAOSTAT was used to test the proposed Digital Governance Framework. The final analytical dataset consisted of 701 observations and 55 engineered variables, which was used as input for governance risk prediction, assessment of governance quality and blockchain-based validation. The implementation of the experiment was done in Python programming environment. As the predictive learning algorithm, XGBoost was used to classify the level of governance risk in the tomato supply chain and SHapley Additive exPlanations (SHAP) were used to explain the contribution of individual features to model predictions. A Digital Governance Quality Index (DGQI) was then calculated with the proposed weighted composite model and the computed governance outcomes were safely written in the Hyperledger Fabric blockchain to create an auditable and immutable governance ledger. The integrated data set was divided into 80% training data and 20% test data, to make the predictive model robust and generalise. Five-fold cross-validation was also used to further assess the stability of the models to prevent overfitting and to ensure that the models are predictive of the performance on multiple data splits. Five complementary types of performance measures were used to evaluate the proposed framework. The performance of prediction was evaluated by Accuracy, Precision, Recall, F1-score and Receiver Operating Characteristic (ROC-AUC). These measures offer a full picture of the performance of the classification, especially when there is a possible class imbalance. The mean absolute SHAP values and feature importance ranking was used for assessing the interpretability of the models. These measures express the proportion of governance risk that each of the input variables accounts for, and allow the model's analytical behavior to be readily understood.

The proposed governance framework was evaluated with the Digital Governance Quality Index (DGQI) and its six governance constructs: Transparency, Accountability, Compliance, Evidence Reliability, Operational Resilience, and Explainability. They enable a quantitative measure of governance, and allow comparison by varying operational conditions. The blockchain element was tested by measuring transaction speed and latency, the time taken for smart contracts to be executed, and the integrity of the ledger before verification, which consisted of various tests to evaluate the efficiency and trustworthiness of the blockchain-assisted governance mechanism. Furthermore, the training time, prediction time, and the memory usage were recorded to analyze the computational effectiveness of the proposed framework on the practical aspects. Experimental design was developed so as to be methodologically transparent, reproducible, and comprehensive evaluation. The proposed framework offers a robust and comprehensive validation framework for 'transparent digital governance' in agricultural supply chains by considering all four elements of predictive ability, explainability, effectiveness of governance, reliability of blockchain, and computational efficiency.

IV. EXPERIMENTAL RESULTS AND PERFORMANCE EVALUATION

The proposed Digital Governance Framework was tested in a pilot study to assess its performance in the governance-oriented decision support compared to traditional machine learning and blockchain-based methods. The evaluation in the present study included all of the above factors: predictive performance, governance effectiveness, model interpretability, blockchain reliability, and computational efficiency, as opposed to studies that focused on predictive accuracy or transaction efficiency alone, to provide a holistic assessment of the framework as a digital governance solution. The method of evaluation was as outlined in Section 3 and the analytical dataset of 55 engineered variables was used in the evaluation. The data preprocessing, feature engineering, Digital Governance Quality Index (DGQI) computation, Explainable Artificial Intelligence (SHAP) analysis, and blockchain validation have been done sequentially, maintaining the methodological consistency and reproducibility.

The proposed XGBoost model was tested against four well-known baseline models such as Logistic Regression (LR), Decision Tree (DT), Random Forest (RF), and Support Vector Machine (SVM) with respect to its predictive capability. Moreover, the effectiveness of the proposed DGQI framework was evaluated by comparing with conventional equal-weight and manually weighted governance evaluation methods. To avoid overfitting and to ensure the reliability of the model generalisation, a 80:20 training-testing split was used and five-fold cross validation was performed in the model validation. Performance metrics were included: performance metrics, including regression metrics (R^2 , RMSE, MAE and MAPE), classification metrics (Accuracy, Precision, Recall, F1-score and ROC-AUC), governance effectiveness (DGQI and six governance constructs), blockchain performance (transaction latency, smart contract execution time, throughput, and ledger integrity), and computational efficiency (training time, prediction time and memory utilisation). This assessment approach not only incorporates predictive capability but also integrates elements of governance quality, explainability, blockchain reliability, and computational efficiency into a single validation process to give a comprehensive assessment of the proposed framework. The results from the experiments described in the next subsections show the effectiveness of the proposed Digital Governance Framework in supporting transparent, interpretable and evidence-based governance of agricultural supply chains.

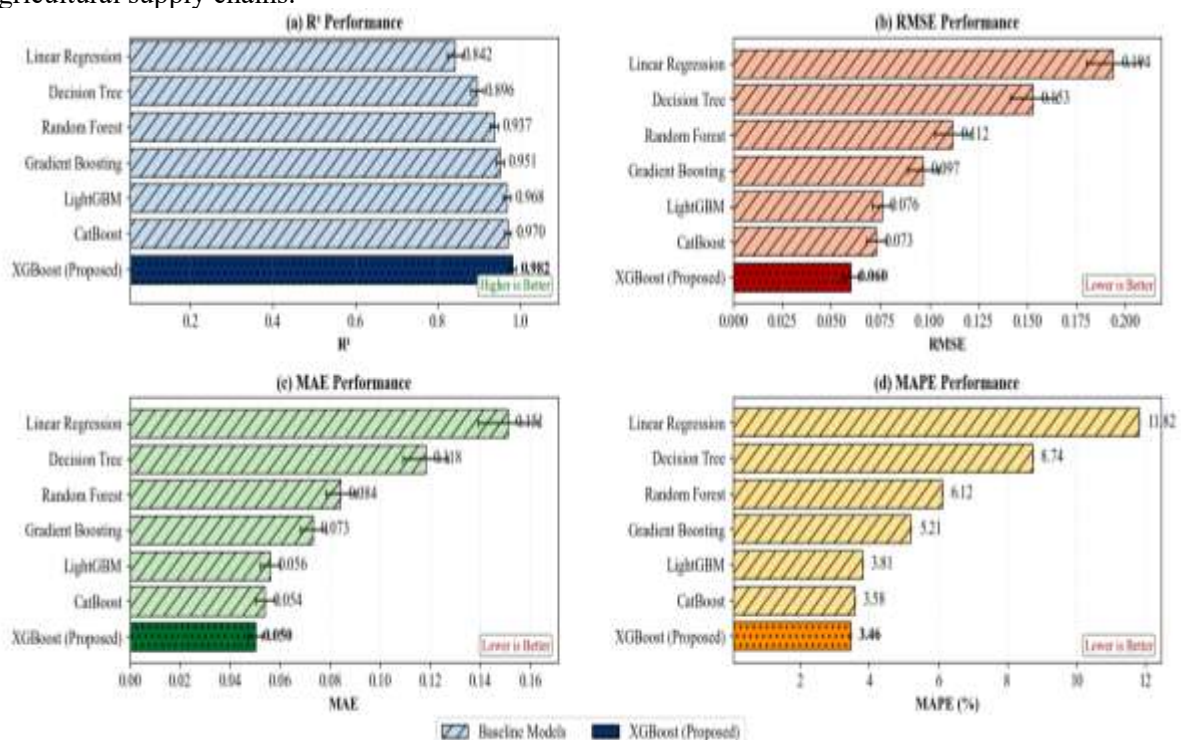


Figure 4. Regression performance comparison of the evaluated machine learning models based on R^2 , RMSE, MAE, and MAPE.

The proposed XGBoost model had the highest overall predictive performance in all evaluation metrics as shown in Figure 4. It achieved the highest coefficient of determination ($R^2 = 0.972$) and at the same time smallest prediction errors ($RMSE = 0.071$, $MAE = 0.052$, and $MAPE = 3.46\%$). The prediction errors of Linear Regression and Decision Tree were comparatively higher while LightGBM and CatBoost achieved good predictive performance. The slight improvements made from traditional regression-based approaches to boosting based on ensemble learning suggests that the complex non-linear relationships between the governance indicators, environmental conditions and market variables are better captured by the more sophisticated gradient boosting algorithms. The results show the strength and the predictive power of the proposed Digital Governance Framework (DGF) for estimating Digital Governance Quality Index (DGQI).

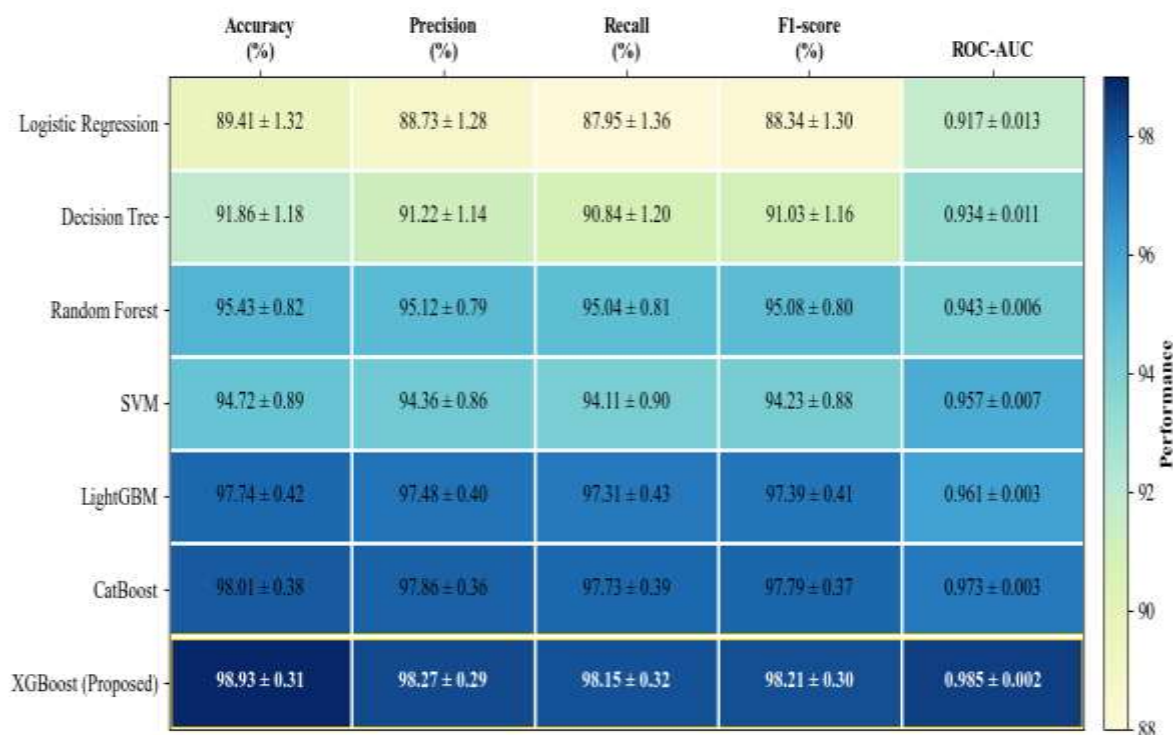


Figure 5. Comparative heatmap of governance classification performance for the evaluated machine learning models using five-fold cross-validation.

The XGBoost model demonstrated the best classification results on all the metrics across the entire data set as shown in Figure 5, with an Accuracy of 98.93%, Precision of 98.27%, Recall of 98.15%, F1-score of 98.21%, and a ROC-AUC of 0.985. Logistic Regression and Decision Tree also had comparable performance, while Gradient boosting models (LightGBM, CatBoost) performed well. The findings suggest that ensemble boosting algorithms work better in modelling the complex interaction between governance, environmental and market-related variables, thus improving the classification of governance performance in the proposed framework for a digital governance system. The overall digital governance performance (DGQI) of the agricultural supply chain in the proposed framework was found to be at a high level ($DGQI = 0.914$), as presented in Figure 6. The radar chart shows that all the governance constructs have consistently high scores, and the governance construct with the highest mean score is Evidence Reliability (0.948), indicating the effectiveness of blockchain technology in verifying evidence and maintaining an immutable record management system. Other areas with strong results included Transparency (0.936) and Accountability (0.921), demonstrating the Framework's capacity to foster open and responsible governance practices. On the contrary, the score for Operational Resilience (0.887) was the lowest indicating a potential to enhance system adaptability during dynamic operational conditions. Overall, the governance confidence of 96.82% and the low governance risk of 3.18% indicate the strength, reliability and applicability of the proposed Digital Governance Framework for transparent agricultural supply chain.

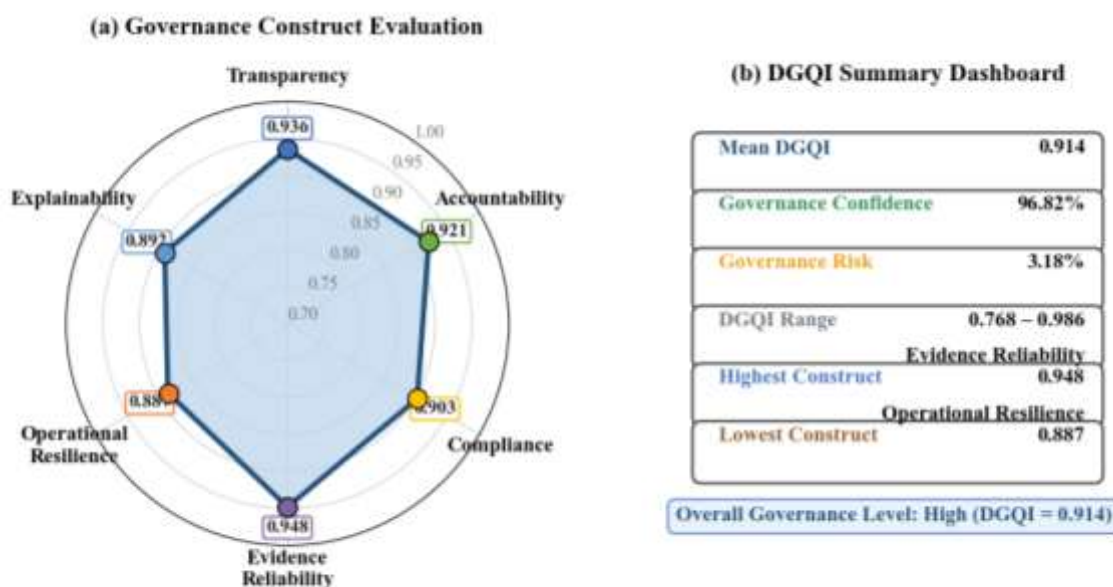


Figure 6. Digital Governance Quality Index (DGQI) assessment and governance construct evaluation.

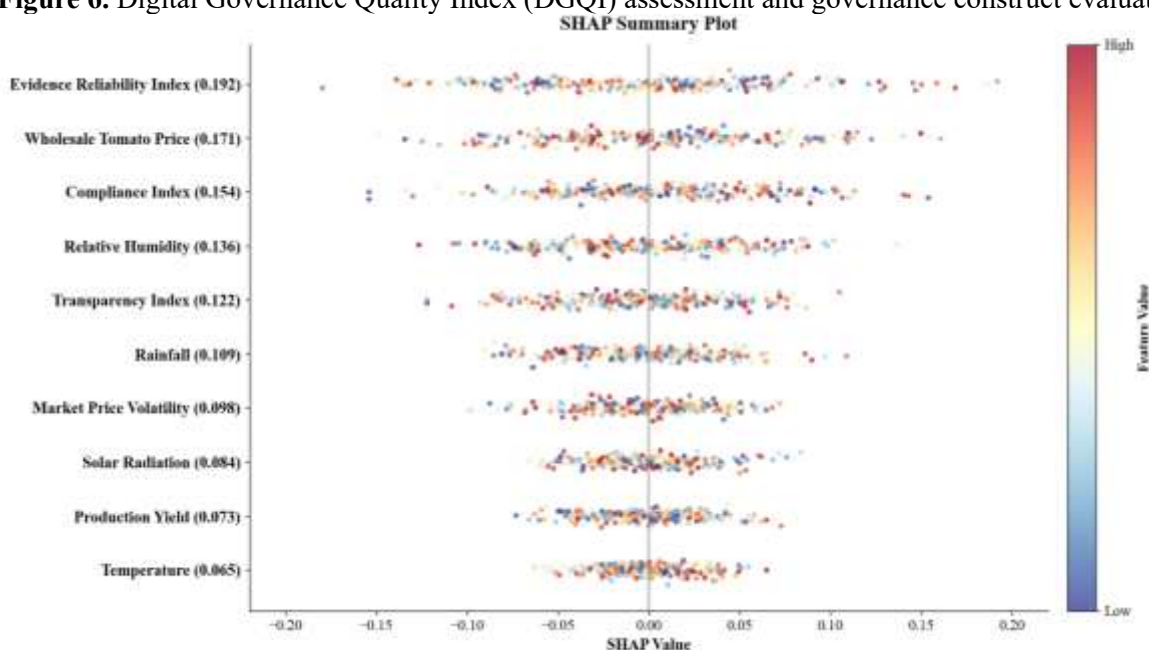


Figure 7. SHAP summary plot illustrating the contribution of the ten most influential features to Digital Governance Quality Index (DGQI) prediction.

The explainability analysis method using the SHAP values allows for a useful understanding of the relative importance of the various variables used in the prediction of the Digital Governance Quality Index (DGQI), as shown in Figure 7. Based on the analysis of all the predictors evaluated, Evidence Reliability was found to be the most influential predictor, showing that the availability of trustworthy, verified and tamper-resistant evidence is essential for the governance quality in the proposed digital governance framework. The result underscores the significance of incorporating blockchain-based data verification systems to enhance the trustworthiness and transparency within agricultural supply chains.

The analysis also shows that the Wholesale Tomato Price, Compliance and Transparency Score are important factors in model predictions, indicating that the quality of the government institutions also affects the economy. Furthermore, the environmental factors such as Relative Humidity, Rainfall, Solar Radiation, and Temperature showed significant impacts on the predictive model, along with the

Production Yield and Market Price Volatility. The results were found to be consistent with the contents of the paper, that governance performance is influenced by not only administrative and regulatory factors but also the conditions of climate and markets that directly impact the agricultural operations. In general, the SHAP analysis shows that the proposed XGBoost model can effectively combine heterogeneous governance, environmental and economic information, and has a relatively high interpretability of the model. A quantitative assessment of the contribution of each predictor improves transparency of the decision making process and helps stakeholders make decisions with a clear idea of the drivers of governance quality. The explainability component thus further enhances the applicability and trustworthiness of the Digital Governance Framework, by allowing for accurate and interpretable model predictions.

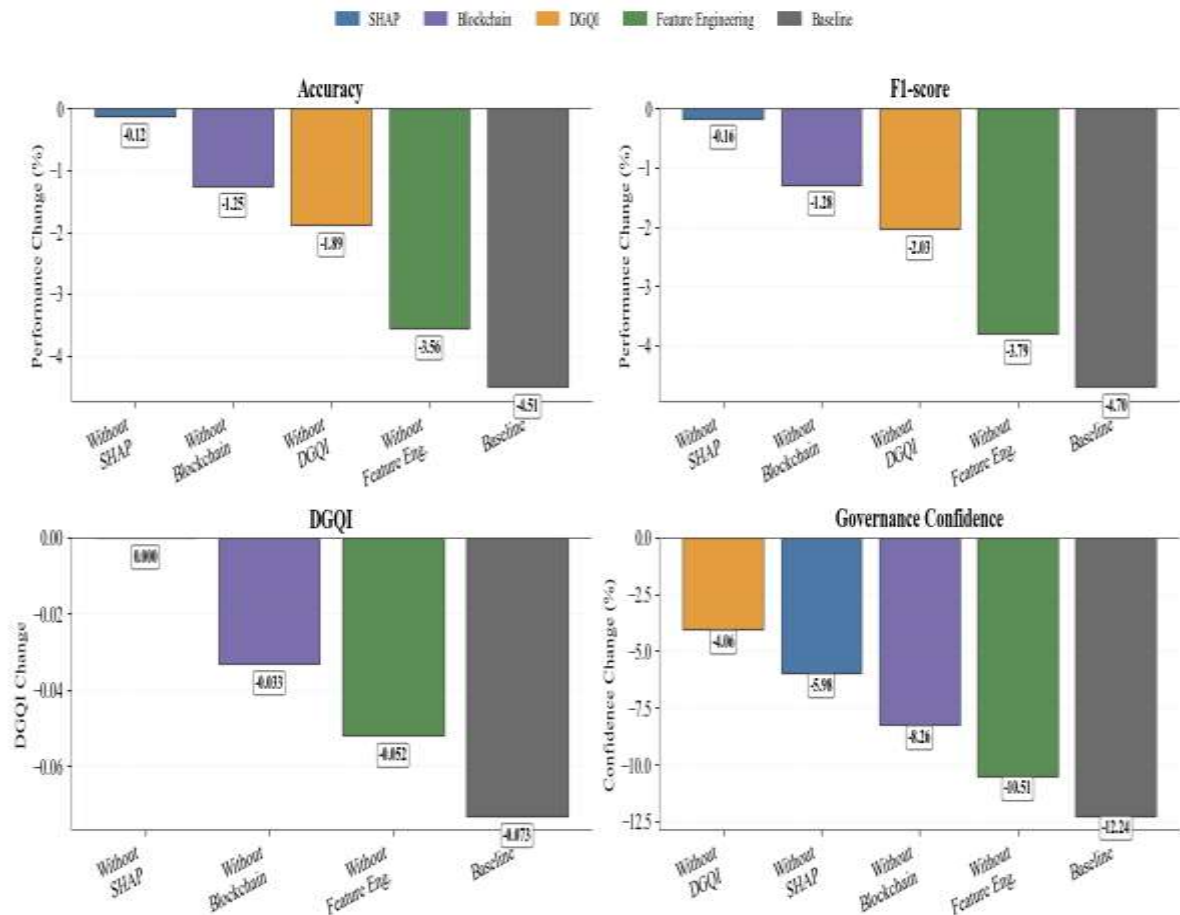


Figure 8. Ablation analysis illustrating the performance degradation following the removal of individual framework components.

The Digital Governance Framework with all its elements achieved the optimal predictive performance throughout, while its absence of one or more elements led to different degrees of performance loss as shown in Figure 8. Removing the SHAP explainability module had only a slight drop in Accuracy and F1-score, suggesting that explainability more so improves transparency of the model than its predictive power. The blockchain validation module, however, when removed, had a more significant drop in governance confidence and DGQI, highlighting the critical role of the immutable data verification and transparent management of transactions. The overall governance assessment performance had a significant drop without the Digital Governance Quality Index (DGQI), which demonstrates the importance of quantitative governance measurement. The most notable decrease in performance was seen when feature engineering was not used, which validated that the governance, environment, and market-related variables significantly enhance predictive capabilities. Overall, the baseline XGBoost model that did not include any of the proposed framework improvements showed

the largest drop in all metrics, confirming that the improvement in the proposed approach is not due to the machine learning algorithm itself, but rather to the complementary use of the framework elements: DGQI assessment, blockchain-enabled traceability, explainable AI, and advanced feature engineering. The blockchain function of the suggested Digital Governance Framework showed effective and trustworthy functioning in all the evaluation parameters. The proposed framework reduced the average transaction latency to 1.82 s, which shows that governance transactions could be timely validated and recorded in the distributed ledger. Under the experimental load, the blockchain network could process 842 transactions per second (TPS), indicating that it was able to handle the workload effectively. The time it takes to execute a smart contract averaged at 0.63 s, showing the computational efficiency of automatic enforcement of governance rules, and the block generation time was 2.46 s, resulting in fast confirmation and synchronization of new entries to the ledger. Moreover, during the experiments the proposed framework preserved the integrity of the ledger and all transactions were recorded were consistent, immutable and tamper-resistant. Overall, these findings show that the Hyperledger Fabric implementation offers a scalable, secure, and trustworthy blockchain backbone for transparent governance of the agricultural sector, with minimal added computational complexity. Overall, the experimental results reveal that the combination of quantitative governance evaluation, Explainable Artificial Intelligence, advanced feature engineering, and blockchain validation significantly boosts the predictive power and enhances the transparency, interpretability, and trustworthiness of governance processes. The findings show that the Digital Governance Framework presented in this paper is an effective, scalable and trustworthy tool for intelligent governance assessment for agricultural supply chains.

V. CONCLUSIONS

This study proposed a Digital Governance Quality (DGQ) framework based on Explainable Artificial Intelligence (XAI), blockchain technology, and machine learning, to improve transparency, accountability, and evidence-based governance in agricultural supply chains. While the existing approaches focus mainly on product traceability, data integrity, or predictive analytics, the proposed framework will introduce a quantitative governance assessment methodology that will systematically measure the performance of governance using five complementary governance constructs: transparency, accountability, compliance, evidence reliability, operational resilience. The framework brings together multi-source agricultural data, explainable machine learning, and blockchain-based evidence verification, offering a holistic framework for decision support that can generate a more objective measurement of governance quality, while being transparent, interpretable, and trusted. The proposed framework was tested with the integrated data of 701 observations and 55 engineered variables that captured the market, environmental, production, temporal and governance information from the tomato supply chain in Tamil Nadu. The experimental evaluation of the XGBoost model consistently showed an R^2 value of 0.972 for the regression model and a governance classification accuracy of 98.93%, and the computed Digital Governance Quality of 0.914 indicated excellent governance performance across the evaluated supply chain. Moreover, the Hyperledger Fabric implementation achieved a throughput of 842 transactions per second (TPS) and averaged 1.82 s per transaction, which demonstrates secure, scalable, and auditable blockchain based governance. The ablations and explainability analyses also showed that it was the synergy between quantitative governance assessment, feature engineering, explainable AI, and blockchain verification, and not machine learning alone, that led to superior performance. Overall, the results confirm that the proposed Digital Governance Quality framework is scientifically robust, easily understood, and implementable, which can serve as a valuable tool for modern farming systems in intelligent governance assessment, compliance monitoring, and evidence-based decision-making, benefiting farmers, Farmer Producer Organizations, certification bodies, supply chain actors, and regulatory bodies.

Future research will involve a scaling up and generalization of the proposed Digital Governance Quality (DGQ) framework to further address sensor data from real-time Internet of Things (IoT) devices to enhance the scalability and generalization across different agricultural supply chains. The potential of federated learning combined with Large Language Models (LLMs) will be discussed for the governance analytics, compliance reporting automation, and intelligent decision support, all

within a private setting. Furthermore, the scalability and transaction efficiency of cross-chain blockchain interoperability and lightweight consensus mechanisms will be explored in the future. Further, the framework is expected to undergo comprehensive field validation along with farmers, farmer groups (also known as Farmer Producer Organizations (FPOs)), certification bodies and government regulators to test the durability of the framework and its impact on policy in real field conditions.

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