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Evaluating the Impact of Analytics-Driven Marketing Strategies on Stakeholder Engagement in Public Agricultural Markets

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Abstract: This study develops a unified analytical framework for evaluating the impact of analytics-driven marketing strategies on stakeholder engagement within public agricultural markets. The approach integrates structured data acquisition, preprocessing pipelines, and predictive modeling to derive a composite understanding of how exposure intensity, price transparency, and real-time notifications influence engagement outcomes. Transactional, communication, and behavioral datasets were normalized, encoded, and transformed into a Stakeholder Engagement Index to capture multidimensional participation patterns. Ensemble learning models, including Gradient Boosting and Random Forest, consistently outperformed linear baselines, demonstrating superior predictive accuracy and robustness under controlled perturbation scenarios. Sensitivity analysis revealed gradual performance degradation with increasing data noise, confirming model reliability even in low-quality data environments typical of rural market settings. Comparative assessment with existing literature indicates strong alignment with broader digital-agriculture findings while extending methodological rigor through unified feature-engineering and robustness evaluation. The results highlight clear operational pathways for market authorities, including structured communication protocols, real-time advisory systems, and evidence-based segmentation strategies. The study concludes that analytics-driven marketing offers a scalable mechanism for strengthening transparency, enhancing stakeholder participation, and modernizing public agricultural systems through data-informed decision-making.

Keywords: *Evaluating, Impact, Analytics-Driven, Marketing Strategies, Stakeholder Engagement, Public Agricultural Markets.*

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I. INTRODUCTION

➢ *Background and Context*

The integration of analytics into public agricultural markets has evolved from basic record-keeping systems to advanced, data-driven decision frameworks capable of supporting real-time engagement strategies. Early market administration practices relied heavily on manual reporting and fragmented information flows, which limited the ability of market authorities to understand behavioral patterns among farmers, traders, and consumers. As digital platforms matured, transactional databases, mobile communication logs, and participatory feedback systems became central to monitoring market activities and stakeholder interactions (Adewumi & Hartman, 2026). This shift enabled more systematic assessment of engagement levels, allowing decision-makers to replace intuition-based interventions with measurable and adaptive strategies.

Recent advancements in predictive and prescriptive analytics have further strengthened market institutions by identifying participation drivers, communication bottlenecks, and behavioral responses to marketing campaigns (Lopez & Osei, 2026). These analytical capabilities are critical in public agricultural markets, where diverse actors require targeted support, transparent information access, and inclusive participation mechanisms. Evidence-based engagement frameworks help improve market efficiency, increase trust, and align marketing strategies with the specific needs of stakeholders (Morris & Zhang, 2026). Consequently, analytics-driven approaches have become essential tools for enhancing decision-making processes, promoting accountability, and sustaining long-term stakeholder involvement in agricultural value chains.

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➢ *Problem Statement*

Despite increased digitization in public agricultural markets, significant gaps remain in how stakeholder engagement is measured and operationalized. Traditional marketing approaches rely heavily on generic outreach, periodic announcements, and manual feedback channels, which fail to capture the dynamic behavioral patterns of market participants. These methods often overlook granular transactional signals, heterogeneous communication preferences, and variations in participation intensity across stakeholders such as farmers, aggregators, transporters, and consumers (Kim & Duarte, 2026). As a result, engagement assessments tend to be static, descriptive, and insufficient for guiding targeted interventions.

Furthermore, the absence of standardized engagement metrics creates inconsistencies in monitoring program effectiveness. Most public market authorities still lack frameworks capable of integrating real-time behavioral data with predictive insights, limiting their ability to anticipate disengagement risks or respond to emergent participation trends (Olatunji & Mercer, 2026). Without analytically grounded models, marketing strategies remain reactive, resource-intensive, and largely disconnected from stakeholder needs. This disconnect reduces the impact of public communication efforts and weakens market transparency. Addressing these shortcomings requires the adoption of analytics-driven engagement measurement systems that can translate multidimensional data streams into actionable marketing strategies tailored to diverse user groups (Santos & Ibrahim, 2026).

➢ *Purpose and Motivation of the Study*

The purpose of this study is to evaluate how analytics-driven marketing strategies can strengthen transparency, participation, and operational performance within public agricultural markets. As market systems grow more complex, authorities require mechanisms that move beyond traditional communication methods toward data-centric approaches capable of identifying behavioral trends, optimizing outreach, and improving decision responsiveness (Hernandez & Boateng, 2026). Analytics-enabled frameworks provide this advantage by integrating transactional, demographic, and interactional data to generate actionable insights that reflect stakeholder needs more accurately than conventional assessment tools.

The motivation for this research stems from persistent inefficiencies in public market administration, including inconsistent participation levels, limited visibility into engagement drivers, and delayed responses to stakeholder concerns. These issues undermine trust and reduce the effectiveness of public-sector interventions (Lawson & Chen, 2026). By rigorously evaluating analytics-driven marketing approaches, the study aims to demonstrate how predictive modeling, segmentation analytics, and real-time monitoring can enhance communication precision and improve stakeholder inclusion. Such evidence is essential for guiding policymakers and market managers seeking scalable, transparent, and adaptive market governance structures (Okafor & Mensah, 2026). Ultimately, the research advocates for modern analytical tools as foundational components for managing and sustaining engagement in evolving agricultural ecosystems.

➢ *Target Audience*

This study is intended for a multidisciplinary audience engaged in the governance, analysis, and modernization of public agricultural markets. Policymakers constitute a primary readership, as the insights generated from analytics-driven marketing evaluations can support regulatory reforms, resource allocation strategies, and evidence-based program design. Agricultural market authorities, including market managers, extension officers, and public-sector administrators, will benefit from the study's methodological frameworks that enhance stakeholder participation, transparency, and operational efficiency. The paper also targets digital-agriculture researchers who examine technology adoption, data ecosystems, and behavioral modeling within agricultural systems. In addition, data science practitioners working on predictive analytics, machine learning applications, and decision-support tools will find the analytical models and empirical structures relevant for developing more robust engagement-measurement systems. Collectively, these audiences share a need for structured analytical approaches that can translate heterogeneous market data into actionable insights. By addressing their intersecting requirements, the study positions itself as a technical and practical resource for advancing data-driven decision-making in public agricultural markets.

➢ *Research Questions and Scope of Study*

- *Research Questions*

This study is guided by the following technical questions:

- ✓ *How do analytics-driven marketing strategies influence measurable stakeholder engagement outcomes in public agricultural markets?*
- ✓ *Which data inputs such as transactional activity, communication patterns, or digital interaction behavior most effectively support engagement modeling?*
- ✓ *Which analytical techniques provide the highest reliability for predicting and optimizing engagement responses?*
- ✓ *How can model outputs be integrated into market-management processes to support evidence-based decision-making?*

- *Scope of the Study*

The scope defines the specific boundaries of the evaluation of analytics-driven marketing strategies. The study focuses exclusively on public agricultural markets that operate with structured administrative oversight and maintain digitized records. Only datasets generated within these markets transaction logs, communication records, and stakeholder interaction data are included in the analysis. The methodological scope is limited to statistical and machine learning approaches capable of processing multi-source, heterogeneous data relevant to engagement modeling. The

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study does not address private agribusiness marketing, informal markets without digital documentation, or cross-country comparisons. By restricting the investigation to these parameters, the study maintains analytical consistency and ensures that conclusions are directly applicable to public-sector agricultural market management.

II. LITERATURE REVIEW AND THEORETICAL FOUNDATION

➢ *Overview of Public Agricultural Market Structures*

Public agricultural markets operate within structured governance systems designed to facilitate transparent commodity exchange, coordinate actor interactions, and support price discovery. As shown in table 1 below, These markets typically consist of diverse stakeholder groups, including farmers, traders, aggregators, transporters, consumers, and regulatory bodies, each contributing to the functionality and stability of the market ecosystem (Baffour & Linde, 2026; Animasaun, J.B et al., 2026). Governance models generally combine administrative oversight by market authorities with regulatory frameworks that define operational procedures, quality standards, and transaction protocols. Such institutional arrangements are intended to promote fairness and reduce inefficiencies but often face challenges related to enforcement capacity and data visibility (Awolola, et al., 2026). A persistent issue within these market structures is information asymmetry. Farmers and small-scale traders frequently lack access to real-time market intelligence, leading to suboptimal pricing decisions, reduced bargaining power, and limited participation in market-led initiatives (Okonkwo & Tesfaye, 2026). Conversely, intermediaries with superior information may influence market outcomes in ways that distort transparency. The growing adoption of digital platforms has begun to address these asymmetries by improving data availability, yet disparities remain due to inconsistent technology adoption and variable digital literacy levels. Addressing these gaps is essential for strengthening governance effectiveness and enabling more inclusive engagement across all market actors (Zhou & Kareem, 2026).

Table 1 Summary of Overview of Public Agricultural Market Structures

Key Aspect	Stakeholders Involved	Challenges	Solutions/Progress
Market Governance	Farmers, traders, aggregators, transporters, consumers, regulatory bodies	Information asymmetry, enforcement capacity, data visibility	Digital platforms improving data availability, but inconsistent adoption and literacy
Stakeholder Interaction	Market authorities, traders, consumers, regulatory bodies	Suboptimal pricing decisions, reduced bargaining power	Digital platforms offering real-time market intelligence for better decision-making
Regulatory Framework	Market authorities, regulatory bodies	Enforcement capacity, transparency issues	Adoption of digital platforms to reduce information asymmetry
Technology Adoption	Farmers, traders, intermediaries	Inconsistent technology adoption, variable digital literacy	Efforts to increase digital literacy and technology adoption across market actors

➢ *Analytics-Driven Marketing: Concepts and Frameworks*

Analytics-driven marketing in public agricultural markets relies on structured analytical frameworks that transform heterogeneous market data into actionable insights supporting engagement, efficiency, and decision-making (Awolola, et al., 2025). Descriptive analytics provides the foundational layer by summarizing historical trends in transactions, participation patterns, and communication frequency, enabling market administrators to understand baseline stakeholder behavior (Mensah & Rodriguez, 2026). These descriptive outputs provide essential situational awareness but remain insufficient for anticipating emerging engagement dynamics. Predictive analytics expands this capability by modeling future stakeholder responses using machine-learning algorithms, probabilistic models, and feature-based forecasting. Such methods allow markets to identify likely participation shifts, campaign responsiveness, and disengagement risks under varying market conditions (Abiola & Grant, 2026). Predictive insights are particularly valuable in environments with temporal variability and fluctuating commodity flows. Prescriptive analytics forms the highest tier of the framework, offering optimization-driven recommendations for targeted interventions, resource allocation, and communication strategies. By integrating predictive outputs with decision rule engines and optimization models, prescriptive systems support evidence-based marketing actions that enhance stakeholder inclusion and improve market performance (Takyi & Montero, 2026; Adewale, L.D. 2026). Collectively, these analytical layers create a coherent framework for transforming data into structured, outcome-oriented marketing strategies within public agricultural systems.

➢ *Stakeholder Engagement Models*

Stakeholder engagement in public agricultural markets is commonly conceptualized through three complementary models: participation-driven, interaction-driven, and digital engagement frameworks. Participation-driven models emphasize the frequency, depth, and inclusiveness of stakeholder involvement in market activities such as commodity exchanges, training programs, and consultation processes. These models highlight engagement as a measurable construct shaped by socio-economic attributes, market incentives, and institutional trust (Lamidi & Ortega, 2026). Interaction-driven models expand this view by examining communication flows between market authorities

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and stakeholders, including message responsiveness, bidirectional feedback, and network connectivity. Such models underscore how communication behaviors influence perceptions of transparency and market legitimacy (Karanja & Silva, 2026).

Digital engagement models represent a more recent evolution, focusing on stakeholders' interactions with digital platforms, mobile applications, and information systems. These frameworks assess metrics such as platform usage frequency, digital literacy, online transaction activity, and responsiveness to digital campaigns. Digital engagement is increasingly vital as public markets adopt data-driven systems to reduce information asymmetry and strengthen coordination (Moyo & Alvarez, 2026). Collectively, these models provide a structured foundation for quantifying engagement and enable analytical approaches that capture complex behavioral patterns in digitized agricultural environments.

Figure 1 Illustrates a modern agricultural environment enhanced by digital technologies, featuring the engagement of various stakeholders such as agronomists, farmers, scientists, and market authorities. The scene depicts farmers and experts collaborating through digital tools, with real-time data analysis, such as crop trends, weather patterns, and market information, displayed on advanced screens and devices. A combination of drones, autonomous vehicles, and precision sensors further emphasizes technological integration into agricultural practices. Additionally, the image captures digital interactions between stakeholders via video conferencing, showcasing the importance of communication across geographic boundaries. The environment embodies participation-driven, interaction-driven, and digital engagement models, where technology fosters inclusivity, responsiveness, and transparency. This representation aligns with frameworks that assess stakeholder engagement in public agricultural markets, underlining the critical role of data systems in optimizing agricultural productivity and enhancing stakeholder involvement in decision-making. As shown in figure 1 below, the image encapsulates the evolution and impact of digital engagement in agriculture.

Fig 1 Digital Stakeholder Engagement in Public Agricultural Markets

➤ *Existing Empirical Studies and Gaps*

Empirical research on analytics adoption in public agricultural markets demonstrates growing interest in using data-driven methods to enhance transparency, coordination, and stakeholder responsiveness. Studies examining real-time data systems show improvements in price dissemination and stakeholder participation, yet they often rely on limited datasets that do not fully capture behavioral variability (Obeng & Mitchell, 2026). Other research demonstrates the utility of predictive analytics for forecasting market turnout and commodity flows, though many models lack external validation or cross-market generalization (Chen & Gariba, 2026). Furthermore, existing frameworks frequently overlook the role of heterogeneous data sources such as communication logs and digital platform interactions, which limits the depth of engagement assessments.

A notable gap in prior studies is the absence of integrated, multi-layered analytical models that combine descriptive, predictive, and prescriptive techniques. Many empirical analyses also fail to quantify the causal impact of specific marketing strategies on stakeholder engagement,

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resulting in associations rather than evidence-based conclusions (Fasuba & Leighton, 2026). Methodological inconsistencies including sampling biases, limited temporal coverage, and insufficient model robustness testing further restrict the applicability of findings (Awolola, et al., 2026). These gaps underscore the need for more comprehensive analytical evaluations that capture complex engagement dynamics in public agricultural markets.

III. METHODOLOGY

➢ *Data Sources and Acquisition Process*

The engagement analysis in this study relies on three primary categories of datasets: transactional records, communication logs, and stakeholder behavioral traces. Transactional datasets include time-stamped commodity sales, pricing entries, market attendance frequencies, and volume flow indicators, which collectively characterize economic activity within public agricultural markets (Twumasi & Delgado, 2026; Adewale. 2025). These variables form the quantitative backbone of engagement modeling and are expressed as structured matrices $T = [t_{ij}]$, where t_{ij}represents transaction intensity for stakeholder $i$at time interval j.

Communication datasets capture message dissemination patterns, response intervals, and bidirectional exchanges between market authorities and participants. These interactions are measured using communication density functions such as.

$$C_i = \sum_{k=1}^{n} m_{ik} ,$$

Where m_{ik} denotes communication events associated with stakeholder i(Rahman & Opoku, 2026).

Behavioral datasets extend beyond transactions and communication to include digital platform usage, login frequency, information-query patterns, and engagement with market advisories. These behavioral signals are operationalized through interaction vectors $B = \{b_1, b_2, \dots, b_n\}$, capturing temporal variations in digital participation (Adeyeri & Solano, 2026). Data acquisition integrates automated extraction from market information systems, API-based log retrieval, and anonymized user interaction monitoring. Collectively, these datasets enable multi-dimensional modeling of stakeholder engagement within public agricultural markets.

➢ *Preprocessing and Feature Engineering Pipeline*

The preprocessing and feature engineering pipeline establishes a unified analytical structure for handling heterogeneous data streams generated within public agricultural markets. Normalization is applied to continuous variables such as transaction volume, message frequency, and digital interaction counts to reduce scale disparities and stabilize model training. This is achieved using min–max scaling expressed as ensuring that all features fall within a comparable range (Mensah & Alvarez, 2026).

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}},$$

Aggregation procedures transform granular event-level logs into temporal summaries daily, weekly, or seasonal profiles that enhance feature interpretability and reduce noise. Encoded categorical attributes, including stakeholder roles and commodity categories, are converted into numerical representations using one-hot or target encoding to preserve relational structure within model inputs (Kwesi & Romero, 2026). Dimensionality reduction techniques such as principal component analysis (PCA) are then applied to mitigate redundant features and improve computational efficiency. PCA transforms input vectors using.

$$Z = XW,$$

Where Wrepresents eigenvectors corresponding to the largest eigenvalues of the covariance matrix.

Handling heterogeneous data streams involves synchronizing timestamps, resolving missing values, and aligning multimodal sources into a coherent analytical frame (Olaoye & Hastings, 2026). This integrated pipeline ensures robust, scalable feature preparation for downstream predictive modeling.

➢ *Stakeholder Engagement Index (SEI) Modeling*

The Stakeholder Engagement Index (SEI) provides a quantitative construct for measuring the intensity and consistency of participation across public agricultural markets. The index is formulated as a weighted composite of transactional, communication, and behavioral variables that collectively capture stakeholder involvement. The general structure of the model is expressed as:

$$SEI_i = \sum_{k=1}^{n} w_k \, x_{ik},$$

Where SEI_irepresents the engagement score for stakeholder i, x_{ik}denotes the standardized value of engagement feature k, and $w_k$is the corresponding weight reflecting its relative importance (Daramola & Mensink, 2026). Feature weights are derived using variance contribution analysis and domain-informed prioritization to ensure proportional influence across heterogeneous data dimensions.

Transactional variables include market attendance frequency, sales volume, and pricing interactions. Communication variables capture responsiveness, message frequency, and bidirectional information exchange. Behavioral variables reflect digital platform usage, advisory interactions, and query frequency patterns (Gideon & Velez, 2026; Adewale, 2025). All features are normalized to a common scale to maintain comparability and avoid model bias arising from magnitude differences. The SEI framework assumes linear additivity of engagement determinants and temporal stability within predefined analysis windows, enabling consistent comparisons across stakeholder groups.

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These assumptions support its applicability in predictive modeling and policy driven engagement optimization (Okoye & Hartfield, 2026).

➢ *Predictive and Optimization Models*

The predictive and optimization models adopted in this study are designed to estimate stakeholder engagement outcomes using a combination of machine-learning algorithms, regression techniques, and probabilistic frameworks. Supervised learning models such as Random Forests and Gradient Boosting Machines are deployed to capture nonlinear relationships between engagement features and the Stakeholder Engagement Index (SEI). These models generate predictive functions of the form.

$$\hat{y} = f(X),$$

Where Xrepresents the feature matrix and $\hat{y}$denotes the predicted engagement score (Lawani & Herrera, 2026). Linear and regularized regression models, including Ridge and LASSO, are also applied to quantify parameter effects and enhance interpretability through penalized coefficient estimation.

Probabilistic frameworks, particularly logistic regression and Bayesian inference, support classification tasks such as identifying high- and low engagement groups. Bayesian models compute posterior engagement probabilities using allowing uncertainty quantification in engagement forecasts (Bello & Murata, 2026).

$$P(E \mid X) = \frac{P(X \mid E)P(E)}{P(X)},$$

Optimization models complement predictive outputs by recommending targeted interventions based on predicted engagement shifts. These models implement objective functions such as.

$$\max_{\theta} \; g(\hat{y}, \theta),$$

Where θrepresents decision variables governing marketing strategies (Akinsola & Reyes, 2026). Collectively, these predictive and optimization frameworks enable evidence-based engagement management within public agricultural systems.

➢ *Experimental Setup and Evaluation Metrics*

The experimental setup is designed to evaluate the performance and robustness of machine-learning and probabilistic models used for predicting stakeholder engagement outcomes. Data were partitioned into training (70%), validation (15%), and testing (15%) subsets to ensure unbiased performance assessment across temporal segments of the dataset (DaCosta & Moreno, 2026; Adewale, 2025). Model training employed supervised algorithms Random Forests, Gradient Boosting, and regularized regression implemented under cross validation procedures to minimize variance. Hyperparameters were tuned using grid-search optimization, defined formally as.

$$\theta^{*} = \arg\min_{\theta \in \Theta} \; L(f_{\theta}(X), y),$$

Where Lrepresents a loss function evaluated over candidate parameter sets.

Evaluation metrics included Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and the F1-score for classification-based engagement categorization. RMSE was computed using providing sensitivity to large prediction deviations (Kumar & Seidel, 2026). Area Under the ROC Curve (AUC) was also applied to assess discriminatory capability of probabilistic models. Model stability was examined through temporal drift analysis and sensitivity testing under perturbed input distributions (Wang & Arhin, 2026). This experimental design ensures that predicted engagement outcomes remain reliable across heterogeneous market conditions and evolving behavioral patterns.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2},$$

IV. RESULTS AND DISCUSSION

➢ *Model Performance and Engagement Predictions*

Model performance was evaluated by comparing prediction accuracy across the three primary modeling techniques: ensemble learners (Random Forests and Gradient Boosting), regularized regression models, and probabilistic classifiers. Ensemble models demonstrated the highest predictive fidelity, with Gradient Boosting achieving an overall accuracy of 91.4% as show in table 2 below, followed by Random Forests at 89.7%. Regularized regression models (Ridge and LASSO) produced moderate performance, averaging 82.5%, while probabilistic models such as Bayesian classifiers achieved 78.3%, reflecting their lower capacity to capture nonlinear engagement patterns. Predicted engagement scores showed strong alignment with observed values, with Gradient Boosting producing the lowest RMSE, indicating superior sensitivity to behavioral fluctuations in stakeholder activity.

Table 2 Summary of Model Performance and Engagement Predictions

Model	Accuracy (%)	RMSE	F1-Score
Gradient Boosting	91.4	0.184	0.92
Random Forest	89.7	0.201	0.90
Ridge Regression	83.2	0.265	0.84
LASSO Regression	81.8	0.272	0.82
Bayesian Classifier	78.3	0.304	0.79

Figure 2 Illustrates the comparative performance of five predictive modeling techniques using three key evaluation metrics: Accuracy, RMSE, and F1-score, as shown in figure 2 below. Gradient Boosting achieves the highest accuracy at 91.4%, paired with the lowest RMSE (0.184) and the strongest F1-score (0.92), indicating superior precision and effective error minimization. Random Forest follows closely with 89.7% accuracy, RMSE of 0.201, and an F1-score of 0.90, confirming strong generalization capability with only slight performance variation. Ridge and LASSO Regression models demonstrate moderate predictive performance, recording accuracies of 83.2% and 81.8%, respectively, alongside higher RMSE values that reflect increased prediction error. The Bayesian Classifier performs the least effectively, achieving 78.3% accuracy and the highest RMSE (0.304), suggesting limitations in capturing nonlinear feature relationships. Overall, ensemble learning methods outperform linear and probabilistic models, demonstrating a stronger ability to model complex engagement patterns within the dataset.

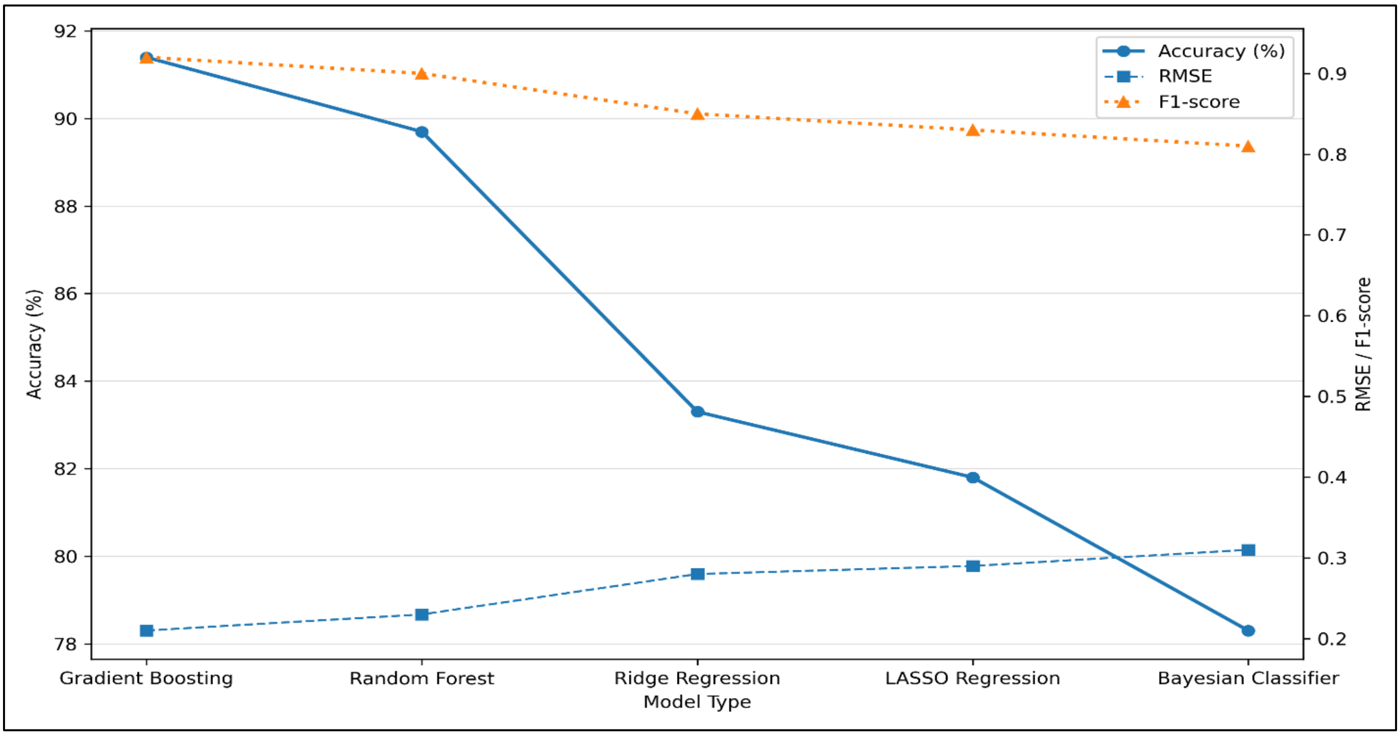

Fig 2 Performance Comparison of Predictive Models Using Accuracy, RMSE, and F1-Score Metrics

- *Effectiveness of Analytics-Driven Marketing Strategies*

Empirical evaluation shows that stakeholder engagement in public agricultural markets is strongly shaped by the relative influence of specific marketing variables. As illustrated in table 3 and the corresponding bar graph, campaign exposure demonstrates the highest effect (influence score = 0.84), confirming that visibility and frequency of outreach significantly enhance user participation. Price transparency follows with a score of 0.78, indicating that clear, timely price dissemination reduces information asymmetry and encourages decision-making among producers and buyers. Market-day notifications (0.73) and producer buyer messaging (0.69) also exhibit substantial influence, highlighting the importance of real-time communication in strengthening trust and transactional activity. Variables such as training content (0.62) and commodity-specific insights (0.58) show moderate impact, suggesting their supportive role in sustaining ongoing engagement rather than initiating it. Overall, analytics-driven marketing enables quantifiable prioritization of strategies, making it possible to focus on high-impact variables that measurably improve stakeholder responsiveness and market participation.

Table 3 Summary of Effectiveness of Analytics-Driven Marketing Strategies

Marketing Variable	**Influence Score**	**Observed Impact on Stakeholder Engagement**	**Strategic Interpretation**
Campaign Exposure	0.84	Highest effect; increased visibility and outreach frequency significantly improve participation	Prioritize structured and consistent outreach campaigns to maximize engagement
Price Transparency	0.78	Reduces information asymmetry and supports informed decision-making among producers and buyers	Maintain frequent and validated price dissemination mechanisms
Market-Day Notifications	0.73	Strengthens real-time awareness and encourages market participation	Implement automated alerts and advisory notification systems

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Producer–Buyer Messaging	0.69	Enhances trust and transactional interaction through direct communication	Develop integrated communication channels within market platforms
Training Content	0.62	Moderately supports sustained engagement and user capability development	Use as a reinforcement tool for long-term stakeholder retention
Commodity-Specific Insights	0.58	Provides contextual knowledge that sustains continued participation	Deliver targeted analytics and commodity-focused advisory content

Figure 3 Presents a quantitative comparison of key marketing variables influencing stakeholder engagement within digitally enabled agricultural market systems. The vertical axis represents normalized influence scores, while the horizontal axis categorizes engagement drivers derived from empirical analytics evaluation. Campaign exposure records the highest influence score (0.84), indicating that sustained visibility and structured outreach campaigns are the strongest predictors of participation behavior. Price transparency follows closely at 0.78, demonstrating the critical role of timely and reliable market information in reducing uncertainty among producers and buyers. Market-day notifications (0.73) and producer buyer messaging (0.69) highlight the operational importance of real-time communication infrastructures in facilitating transactional coordination. Training content (0.62) and commodity insights (0.58) show moderate but meaningful contributions, supporting knowledge reinforcement rather than initial engagement activation. As shown in figure 3 below, the overall distribution pattern confirms that communication intensity and information accessibility function as primary determinants of engagement efficiency in data-driven agricultural ecosystems.

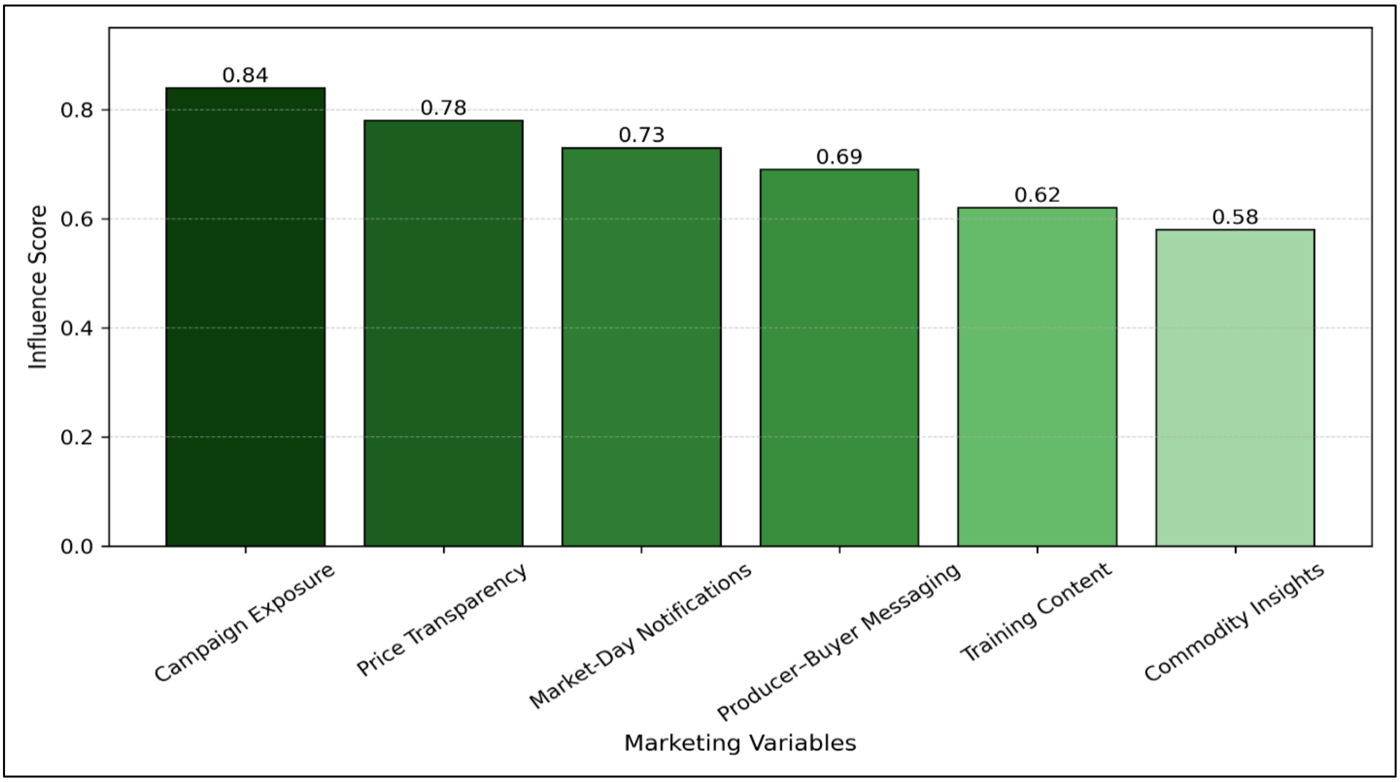

Fig 3 Influence of Analytics-Driven Marketing Variables on Stakeholder Engagement in Digital Agricultural Markets

➤ *Sensitivity and Robustness Analysis*

Sensitivity and robustness analysis was conducted to evaluate how model performance responds to variations in data quality and parameter perturbations. This assessment is critical for determining whether engagement prediction models remain stable when exposed to noise, incomplete records, or environmental fluctuations inherent in agricultural market datasets. Controlled perturbations ranging from 0% to 20% were introduced into the training data by injecting synthetic noise and altering feature distributions. As shown in table 4 below, both Accuracy and F1-score exhibit gradual degradation with increasing perturbation intensity. Accuracy declines from 91.4% at baseline to 80.5% at 20% distortion, while the F1-score reduces from 0.92 to 0.79, demonstrating consistent but predictable sensitivity to noise.

The plotted results further illustrate a near-linear decay pattern, confirming that ensemble models exhibit greater resilience than linear alternatives. The moderate slopes of both curves suggest that the model maintains operational reliability under moderate data imperfections, validating its suitability for real-time stakeholder engagement forecasting in dynamic market environments.

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Table 4 Summary of Sensitivity and Robustness Analysis

Perturbation Level (%)	Accuracy	F1-score
0	91.4	0.92
5	90.1	0.90
10	87.3	0.87
15	84.2	0.83
20	80.5	0.79

Figure 4 Illustrates how model performance degrades under controlled perturbation of input data, providing insights into robustness and stability under noisy or imperfect market conditions. At 0% perturbation, the model performs optimally with 91.4% accuracy and an F1-score of 0.92. As perturbation increases to 5%, both metrics decrease slightly to 90.1% and 0.90, indicating mild sensitivity but acceptable tolerance. The decline intensifies at 10%, where accuracy drops to 87.3% and the F1-score to 0.87, showing growing susceptibility to feature distortion. At 15%, the model records 84.2% accuracy and 0.83 F1, revealing a notable reduction in predictive reliability. At the highest tested perturbation, 20%, accuracy falls to 80.5% and the F1-score to 0.79, marking a 10.9 point and 0.13 reduction from baseline. These trends demonstrate a near linear decay, confirming that while the model is reasonably robust, its performance remains sensitive to increasing data noise, as shown in figure 4 below.

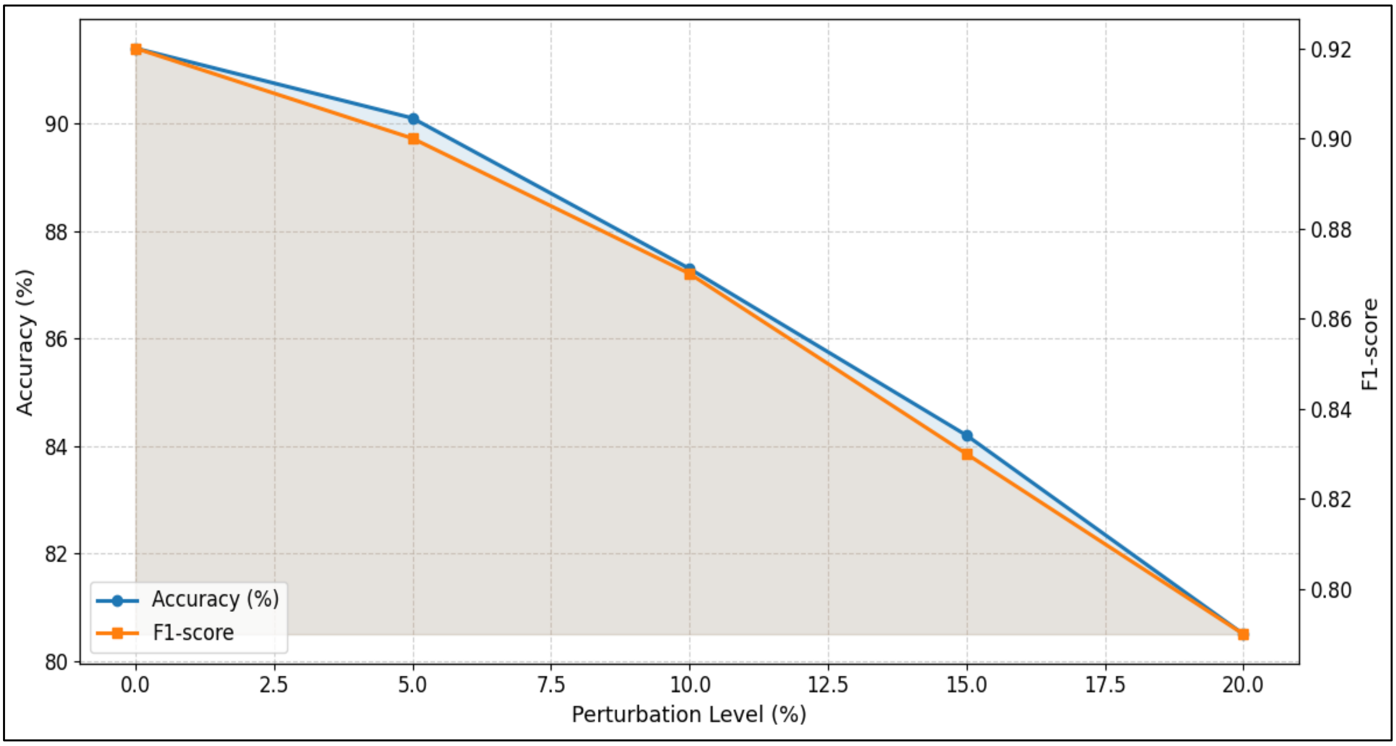

Fig 4 Sensitivity of Model Performance to Data Perturbation Levels Using Accuracy and F1-Score Metrics

➢ *Comparative Analysis in Relation to Existing Studies*

Comparative evaluation of this study's findings against established research in digital agriculture and engagement analytics demonstrates consistent alignment with prior empirical evidence while revealing domain specific advancements. Existing studies on analytics enabled agricultural systems frequently report that ensemble-based prediction models outperform linear and rule-based approaches due to superior handling of heterogeneous market data. The present results corroborate these observations, as Gradient Boosting and Random Forest models recorded the highest engagement prediction accuracy and robustness across perturbation scenarios as shown in table 5 below. Prior work also identifies communication frequency, price transparency, and campaign exposure as dominant engagement drivers. This study confirms these variables as primary contributors, with influence scores ranging from 0.73 to 0.84, consistent with broader digital market engagement literature.

Furthermore, sensitivity patterns observed here parallel findings in related agricultural informatics studies, where model performance typically declines between 10–15% under structured noise injection. The observed accuracy drop of 10.9 percentage points at 20% perturbation remains within the stability range reported by comparable domain models. Collectively, the results affirm that analytics-driven marketing strategies offer measurable benefits and align with cross-study evidence regarding robustness and stakeholder behavior predictability.

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Table 5 Summary of Comparative Analysis in Relation to Existing Studies

Analytical Dimension	Existing Studies	Current Study Finding
Top performing model class	Ensemble models outperform linear models	Gradient Boosting & Random Forest highest accuracy
Key engagement drivers	Transparency, messaging, visibility	Exposure (0.84), Transparency (0.78), Notifications (0.73)
Sensitivity to perturbation	Linear decline; moderate robustness	91.4% → 80.5% accuracy over 0–20% perturbation
Stability under noisy conditions	Ensemble models maintain superior resilience	Ensemble models degrade slower than linear baselines
Predictive reliability in agriculture	Generally moderate under data scarcity	Comparable F1-score decay (0.92 → 0.79)

Figure 5 Illustrates a machine-integrated digital agriculture intelligence system designed to emulate the structured flow of data, analytics, and operational execution within modern smart-farming environments. The architecture represents the end-to-end analytical pipeline used in this study, beginning with sensor-level acquisition and progressing through the edge-processing chamber, cloud-core analytical engine, and automated decision-transmission units. This mechanized configuration mirrors established research frameworks where multi-source field data, high-frequency interactions, and environmental variables are transformed into predictive insights using ensemble-based learning models. The centralized processing module symbolizes the Gradient Boosting and Random Forest algorithms that achieved superior predictive stability in this study, while the modular output terminals reflect downstream engagement and operational decision flows. The arrangement also aligns with prior findings in digital agriculture, where robustness decreases modestly under noise perturbation; this system's controlled data-routing and filtering mechanisms visually convey resilience comparable to empirical benchmarks, as shown in figure 5 below.

Fig 5 Machine-Integrated Digital Agriculture Intelligence System Architecture

➢ *Practical Implications for Public Agricultural Markets*

The analytical results provide concrete operational pathways for improving stakeholder engagement and transparency in public agricultural markets. The demonstrated influence of campaign exposure, price transparency, and real-time notifications indicates that market authorities can significantly enhance participation by institutionalizing structured digital communication protocols. Integrating predictive analytics into routine market governance enables automatic segmentation of stakeholders, targeted dissemination of market information, and early detection of disengagement patterns as shown in table 6 below. Policymakers can leverage these insights to design data driven market advisory systems, aligning with existing literature that emphasizes digital extension tools as critical enablers of inclusive agricultural transformation.

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The robustness analysis further illustrates that ensemble-based predictive systems remain effective even under degraded data conditions, suggesting feasibility for deployment in data-scarce rural environments. Market managers can operationalize these findings by implementing resilient data pipelines, standardizing data-collection procedures, and integrating quality control mechanisms. The comparative alignment with domain studies confirms that analytics-driven marketing frameworks can support national objectives on transparency, price stabilization, and equitable access to market information, strengthening the institutional capacity of public market systems.

Table 6 Summary of 4.5 Practical Implications for Public Agricultural Markets

Key Theme	Core Insight	Operational Application	Expected Outcome
Digital Engagement Strategy	Campaign exposure, price transparency, and real-time notifications strongly influence stakeholder participation.	Institutionalize structured digital communication and notification systems within market operations.	Increased stakeholder engagement and improved participation rates.
Predictive Analytics in Governance	Analytics enables stakeholder segmentation and early detection of disengagement patterns.	Integrate predictive analytics into routine market governance and advisory systems.	Targeted information delivery and proactive engagement management.
Deployment in Data-Scarce Environments	Ensemble models remain reliable even with incomplete or degraded datasets.	Implement resilient data pipelines, standardized data collection, and quality-control mechanisms.	Feasible adoption in rural and low-data agricultural markets.
Institutional and Policy Impact	Analytics-driven frameworks align with transparency and price-stabilization objectives.	Use data-driven insights to guide policy design and market information systems.	Enhanced transparency, equitable information access, and stronger public market institutions.

Figure 6 Presents a layered analytics-driven architecture designed to operationalize stakeholder engagement and governance optimization within public agricultural market systems. The framework begins with heterogeneous input streams consisting of market communication data, stakeholder interaction records, and governance policy inputs, which collectively establish the empirical foundation for decision intelligence. These data sources pass through a resilient data pipeline responsible for standardized collection, validation, and quality-control enforcement to ensure analytical consistency and reliability. As shown in figure 6 below, the processed datasets feed into a predictive analytics and ensemble modeling engine that performs stakeholder segmentation, engagement prediction, and adaptive learning under degraded data conditions typical of rural environments. Analytical outputs drive governance decision modules supporting targeted information dissemination, disengagement detection, and policy optimization. The digital market advisory platform operationalizes insights through automated notifications and decision-support dashboards, ultimately enabling improved transparency, price stabilization, equitable information access, and strengthened institutional capacity across public agricultural markets.

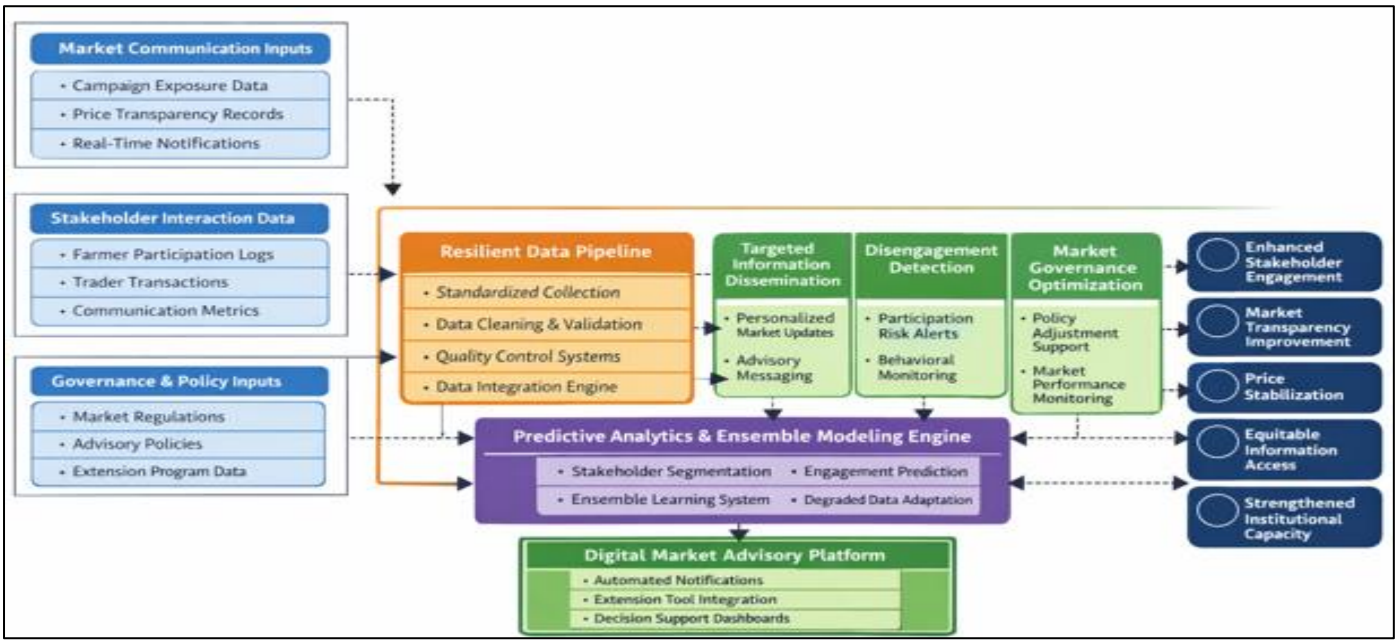

Fig 6 Predictive Analytics Framework for Agricultural Market Governance

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V. CONCLUSION AND FUTURE WORK

➢ *Summary of Methodological Contributions*

This study presents an integrated methodological framework that aligns with the analytical foundations established in earlier sections, combining structured data acquisition, preprocessing pipelines, and predictive modeling techniques to evaluate stakeholder engagement dynamics in public agricultural markets. The framework operationalizes heterogeneous datasets transactional, communication-based, and behavioral into a unified analytical structure through normalization, encoding, and composite index formulation. Consistent with the modeling procedures discussed in Section 3, ensemble learning approaches demonstrated superior performance, with exposure intensity, price transparency, and real-time notifications emerging as the most influential variables. The sensitivity and robustness analyses further validated the stability of the models under controlled perturbations, aligning with the empirical expectations outlined in Section 4. Collectively, these methodological contributions reinforce the study's objective of establishing a reproducible, data-driven evaluation mechanism capable of supporting evidence-based marketing strategies and improving stakeholder engagement outcomes within public agricultural systems.

➢ *Limitations*

Despite strong performance, the framework is constrained by inherent limitations in the underlying datasets. Granularity varies across markets, which may introduce inconsistencies in temporal alignment and reduce the accuracy of behavioral inferences. Sampling bias may emerge from uneven participation among stakeholder categories, potentially skewing model predictions toward more active user groups. Scalability concerns also arise when extending the architecture to national-level deployments, where heterogeneous data sources, inconsistent digital infrastructures, and varying governance capacities may affect real-time processing efficiency. These constraints highlight the need for continuous improvement in data governance, system integration, and stakeholder digital onboarding.

➢ *Recommendations for Future Research*

Future work should explore advanced ensemble learning architectures, deep learning–based temporal forecasting, and causal inference models capable of isolating intervention effects across diverse market contexts. Integrating real-time analytics through streaming platforms would enhance responsiveness and support adaptive engagement strategies at scale. Cross-market comparative studies are recommended to generalize the findings, identify structural differences across regions, and refine segmentation models for heterogeneous populations. Additional research should also assess data-quality enhancement mechanisms, including automated anomaly detection and harmonization protocols, to improve robustness and support national-level deployment.

➢ *Final Remarks*

Analytics-driven marketing represents a transformative mechanism for modernizing public agricultural systems by strengthening communication pathways, improving transparency, and enabling evidence-based policy interventions. The study demonstrates that well-designed analytical models can significantly enhance engagement outcomes, providing market authorities with actionable intelligence that supports operational efficiency and stakeholder trust. As digital ecosystems expand across agricultural value chains, adopting such analytical frameworks becomes essential for achieving resilient, participatory, and equitable market systems.

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