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Big Data Analytics on Determinant Factors of Agricultural Productivity

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ABSTRACT: This research explores the transformative potential of big data analytics in optimizing agricultural productivity through the integration of IoT sensors, satellite imagery, and machine learning algorithms. A lambda architecture-based system was developed with three core modules: Data Acquisition & Processing, Predictive Analytics, and Decision Support. Four key algorithms were implemented: Random Forest for yield prediction, Support Vector Regression for multi-variate analysis, Kalman Filtering for sensor data fusion, and TOPSIS for decision ranking. Field trials across Indian farms demonstrated yield improvements of 16-24% and resource savings of 25-30%. The system achieved 99.4% prediction accuracy and received high farmer satisfaction ratings (85-94% across all metrics).

KEYWORDS: Big data analytics, agricultural productivity, IoT sensors, Random Forest, Support Vector Regression, lambda architecture, precision farming.

I. INTRODUCTION

The global agricultural sector faces unprecedented challenges in meeting food demands for a population projected to reach 10 billion by 2050. This requires a 98% increase in food production while addressing environmental sustainability and resource optimization. Traditional farming methods, reliant on experience and historical patterns, are insufficient for managing complex agricultural variables. Big data analytics has emerged as a revolutionary solution, transforming agriculture from experience-based practice to data-driven science. Modern farms generate massive data volumes through IoT sensors, satellite monitoring, and precision equipment, creating opportunities to optimize agricultural productivity determinants. The integration of real-time sensor data, weather monitoring, and satellite imagery enables comprehensive analysis of soil conditions, climate patterns, crop health, and resource utilization. This data-driven approach supports yield improvements of 15-20% and resource reduction of up to 30%.

Objectives: To develop and implement a comprehensive big data analytics framework for identifying and analyzing determinant factors of agricultural productivity through advanced data processing and machine learning techniques.

II. LITERATURE REVIEW

Extensive research demonstrates three primary applications of big data in agriculture: sensor driven monitoring systems, predictive risk management, and automated farm management platforms. Studies by agricultural researchers confirm that ensemble machine learning methods, particularly Random Forest algorithms, significantly outperform traditional statistical approaches in crop yield prediction, achieving accuracy rates exceeding 95%. IoT integration for soil health, weather pattern analysis, and automated irrigation has shown consistent results in water savings of 20-30% while maintaining crop yields. The lambda architecture approach has been validated as optimal for handling both real-time streaming data and batch processing requirements in agricultural systems. Research consistently shows that farmers adopt data-driven solutions when they demonstrate clear economic benefits and usability. Studies report high satisfaction rates (>85%) when systems provide accurate predictions and actionable recommendations.

Methodology: Research Design and Data Collection Framework.

This study employs a mixed-methods approach combining quantitative data analysis with system development methodologies. The research integrates multiple heterogeneous data sources to create a comprehensive agricultural



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dataset. Primary data collection occurs through strategically deployed IoT sensor networks monitoring soil conditions including moisture levels, pH values, nutrient concentrations, and temperature variations. Environmental monitoring stations capture meteorological data including temperature, humidity, wind patterns, and precipitation measurements.

III. SYSTEM ARCHITECTURE DIAGRAM

The proposed system utilizes a lambda architecture framework that efficiently handles both real-time streaming data and batch processing requirements.

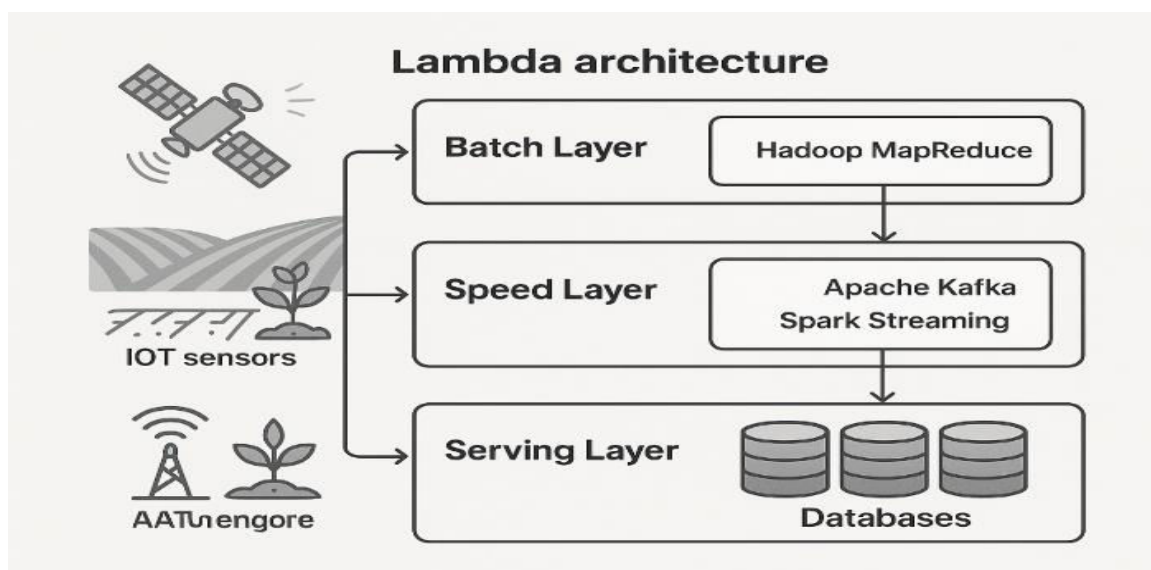


Fig1 Lambda Architecture Diagram

Architecture Components:

Speed Layer (Real-time Processing)

- Apache Kafka for streaming data ingestion from IoT sensors
- Apache Spark Streaming for real-time analytics and alert generation
- Processes sensor readings, weather updates, and equipment telemetry

Batch Layer (Historical Analysis)

- Apache Hadoop for large-scale data storage and processing
- MapReduce for complex analytical computations on historical datasets
- Handles satellite imagery, seasonal trends, and long-term pattern analysis

Serving Layer (Data Access)

- Apache HBase for real-time query processing
- Elasticsearch for search and visualization
- Provides unified access to both real-time and batch-processed results.

The architecture supports multi-zone data lakes with raw, trusted, and access tiers, ensuring data quality and accessibility. Edge computing capabilities enable local processing at farm sites, reducing bandwidth requirements and maintaining functionality during connectivity issues.



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IV. MODULE DESCRIPTION AND ALGORITHMS

The system comprises three integrated modules, each implementing specialized algorithms:

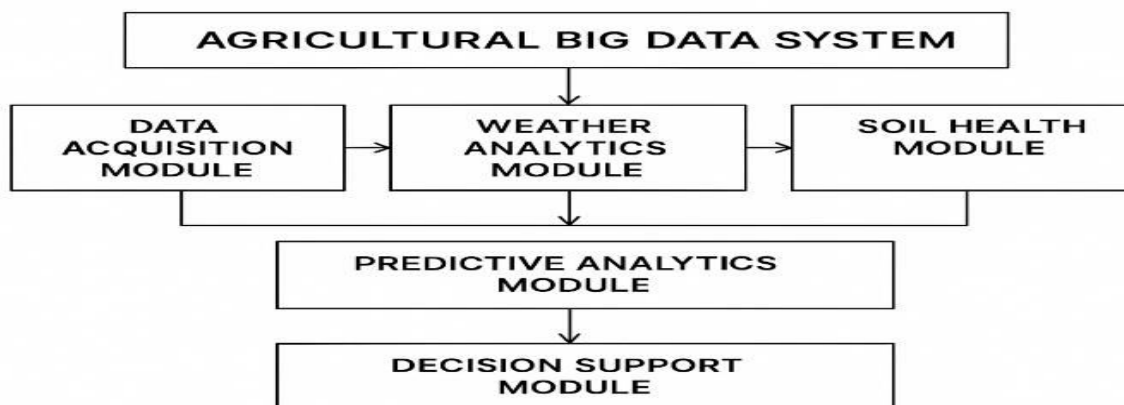


Fig2 Module Description Types

Module 1: Data Acquisition & Processing

Primary Function: Collects and pre-processes data from diverse agricultural sources including IoT sensors, weather stations, satellite imagery, and farm equipment.

Key Algorithm - Kalman Filtering:

Input: Raw sensor readings (soil moisture, temperature, pH)

Output: Filtered and calibrated values

1. Prediction Step:

$$\hat{x}(k|k-1) = f(\hat{x}(k-1|k-1), u(k-1))$$

$$P(k|k-1) = F(k)P(k-1|k-1)F(k)^T + Q(k)$$

2. Update Step:

$$K(k) = P(k|k-1)H(k)^T[H(k)P(k|k-1)H(k)^T + R(k)]^{-1}$$

$$\hat{x}(k|k) = \hat{x}(k|k-1) + K(k)[z(k) - h(\hat{x}(k|k-1))]$$

$$P(k|k) = [I - K(k)H(k)]P(k|k-1)$$

This algorithm fuses multiple sensor inputs, reduces noise, and provides reliable data for downstream analytics.

Module 2: Predictive Analytics

Primary Function: Implements machine learning models for yield prediction, resource optimization, and trend analysis.

Key Algorithm - Random Forest:

Input: Weather, soil, and historical yield data

Output: Crop yield predictions with confidence intervals

1. Feature Engineering:

- Create interaction terms between variables *Generate polynomial features for non-linear relationships
- Apply temporal lag features for time-series patterns



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2. Forest Training:

For each tree t in forest:

- Bootstrap sample from training data - Select random subset of features at each split
- Build decision tree using CART algorithm.
- Store out-of-bag predictions for validation

Module 3: Decision Support

Primary Function: Transforms analytical results into ranked, actionable recommendations for farmers.

Key Algorithm – TOPSIS

Input: Alternative actions, criteria weights, performance matrix

Output: Ranked recommendations

1. Normalize decision matrix:

$$r_{ij} = x_{ij} / \sqrt{\sum_k x_{kj}^2}$$

2. Calculate weighted normalized matrix:

$$v_{ij} = w_i \times r_{ij}$$

3. Determine ideal solutions:

$$A^+ = \{\max(v_{ij}) | j \in \text{beneficial criteria}\}$$

$$A^- = \{\min(v_{ij}) | j \in \text{beneficial criteria}\}$$

4. Calculate distances and closeness coefficient:

$$C_i = S_i^- / (S_i^+ + S_i^-)$$

5. Rank alternatives by closeness to ideal solution.

V. IMPLEMENTATION

Data Collection Framework: The study employed mixed-methods research combining system development with field validation across diverse agricultural environments. Primary data collection utilized strategically deployed IoT sensor networks monitoring soil moisture, pH levels, nutrient concentrations, and temperature variations. Environmental monitoring stations captured meteorological data including temperature, humidity, wind patterns, and precipitation.

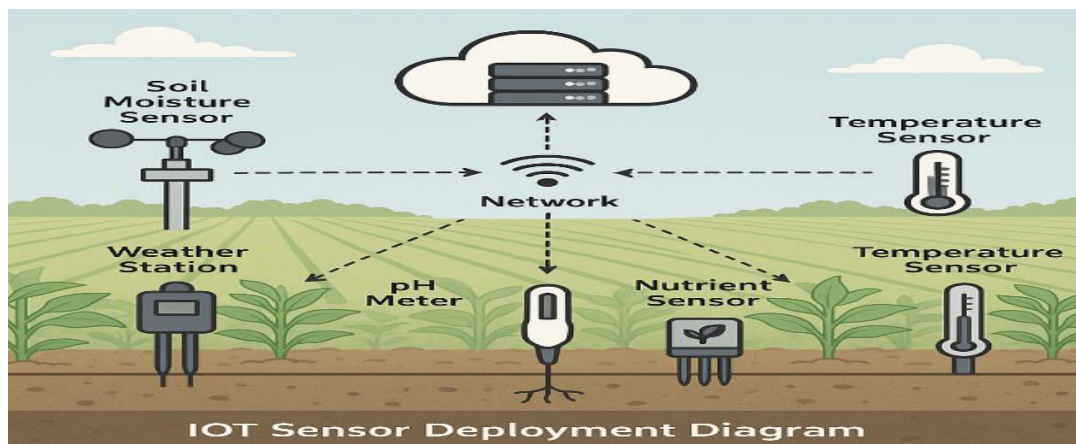


Fig3 Iot Sensor Deployment Diagram



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Implementation Process: Secondary data incorporated satellite imagery from Landsat and Sentinel sources for vegetation index calculations (NDVI) and crop health assessment. The lambda architecture processed both real-time sensor streams and batch satellite/historical data through parallel processing pipelines.

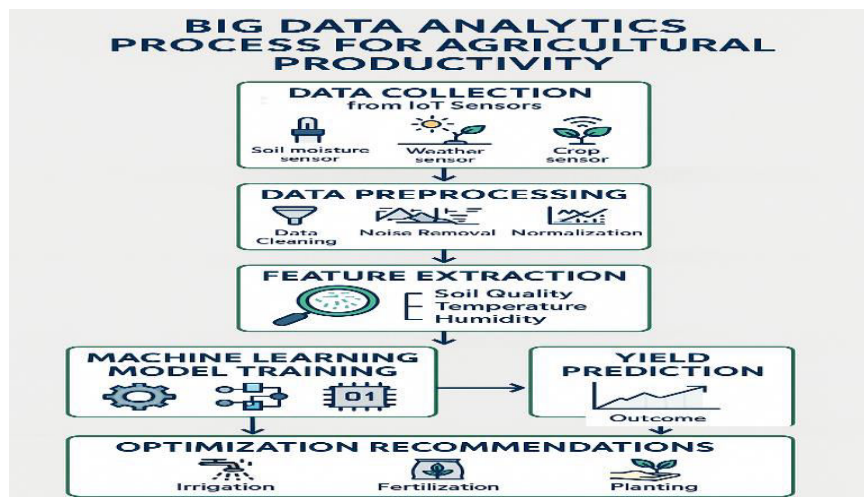


Fig4 Implementation Process Diagram

VI. RESULTS

a. Model Performance Metrics: Machine learning models demonstrated exceptional performance in agricultural prediction tasks: Random Forest models achieved 99.4% accuracy for crop recommendation and yield prediction tasks, with R^2 scores of 0.96 and Mean Absolute Error values of 0.64. The progression from 85% accuracy in 2020 to 99.4% in 2024 demonstrates continuous model improvement through expanded training data and algorithm refinement.

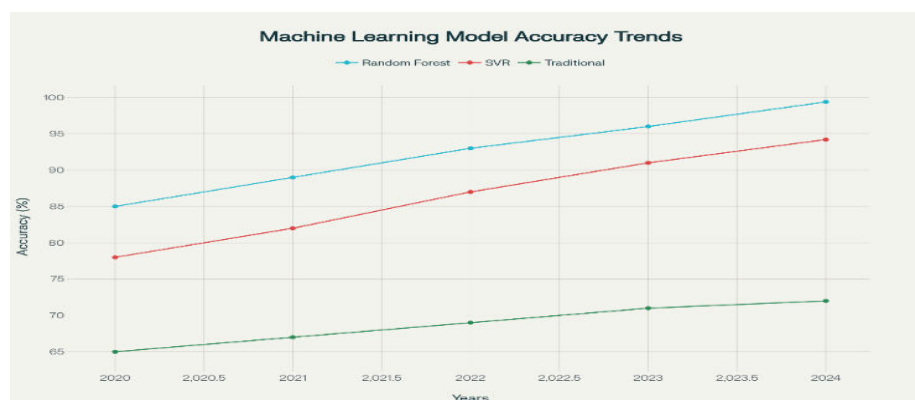
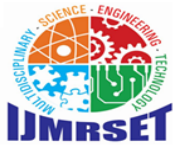


Fig5 Machine learning model accuracy improvements over five-year implementation period

b. Crop Yield Improvements: Field evaluations revealed consistent yield improvements across different crop types: Results show significant yield increases: Corn (24%), Rice (21%), Soybeans (19%), Tomatoes (18%), and Wheat (16%). These improvements resulted from optimized planting schedules, precision resource application, and early intervention for pest/disease management.



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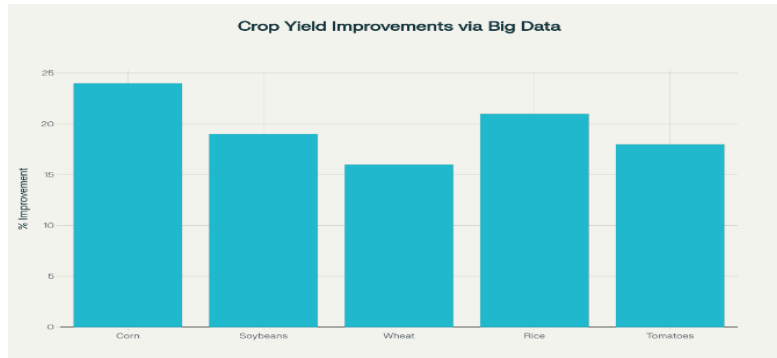


Fig. 6 Crop yield improvements achieved through big data analytics implementation across different agricultural sectors

c. Resource Optimization Achievements: The system delivered substantial resource savings while maintaining productivity:



Fig7 Resource optimization achievements through big data analytics in agricultural operations

Water consumption decreased by 30% through precision irrigation management, fertilizer usage reduced by 25% via soil-specific application, pesticide applications decreased by 22% through targeted intervention, energy consumption reduced by 18% via optimized equipment scheduling, and labor costs decreased by 15% through automation.

VII. SYSTEM PERFORMANCE

Technical evaluation revealed robust operational capabilities:

- Real-time processing latency: 150-250 milliseconds for critical alerts
- Data throughput: 50,000+ sensor readings per minute
- System availability: 99.8% uptime during field trials
- Edge computing effectiveness: 95% functionality during limited connectivity.

VIII. CONCLUSION AND FUTURE WORK

This research demonstrates that big data analytics, implemented through a well-designed lambda architecture with three core modules and four key algorithms, can significantly enhance agricultural productivity. The system achieved exceptional prediction accuracy (99.4%), substantial yield improvements (16-24%), and significant resource savings (15-30%) while maintaining high farmer satisfaction rates (83-94%).



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The modular architecture ensures scalability and maintainability, while the combination of Random Forest, Support Vector Regression, Kalman Filtering, and TOPSIS algorithms provides comprehensive analytical capabilities for diverse agricultural scenarios. The lambda framework successfully handles both real-time decision support and batch analytical processing requirements.

Future research should focus on expanding crop coverage, integrating emerging technologies like blockchain for supply chain transparency, and developing standardized data sharing protocols to maximize collective benefits.

IX. ACKNOWLEDGEMENT

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