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Ind. Jr. of Mod. Res. and Rev *PEER-REVIEWED JOURNAL* *Volume 4 Issue 2 [Feb] Year 2026*

Indian Journal of Modern Research and Reviews

This Journal is a member of the *'Committee on Publication Ethics'*

Online ISSN:2584-184X

Research Article

Leveraging Machine Learning for Agricultural Sustainability: A Review of Techniques in Crop Disease Management and Yield Optimization

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DOI: https://doi.org/10.5281/zenodo.18454811

Abstract

Machine learning (ML) is transforming traditional farming practices by enabling data-driven decisions that enhance crop yields, reduce resource waste, and promote environmental sustainability. This review explores ML applications in agriculture, with a focus on crop disease detection, yield prediction, pest management, and irrigation optimisation. Techniques such as convolutional neural networks (CNNs) for image-based diagnostics and regression models for forecasting are examined. Benefits include early intervention to minimise losses, precise resource allocation, and reduced chemical usage, while challenges like data scarcity and computational demands are addressed. By integrating multisource data from drones, satellites, and sensors, ML fosters resilient agricultural systems capable of addressing global food security amid climate variability.

Manuscript Information

- **ISSN No:** 2584-184X
- **Received:** 15-12-2025
- **Accepted:** 22-01-2026
- **Published:** 02-02-2026
- **IJCRM:**4(2); 2026: 01-04
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- **Plagiarism Checked:** Yes
- **Peer Review Process:** Yes

How to Cite this Article

Kaur H, Gupta S, Kaur G. Leveraging Machine Learning for Agricultural Sustainability: A Review of Techniques in Crop Disease Management and Yield Optimization. Indian J Mod Res Rev. 2026;4(2):1–4.

Access this Article Online

www.multiarticlesjournal.com

KEYWORDS: Machine learning, precision agriculture, crop disease detection, yield prediction, convolutional neural networks, sustainable farming, pest management.

1. INTRODUCTION

Crop diseases pose a severe threat to global agricultural productivity, contributing to up to 40% yield losses annually and exacerbating food insecurity [1]. Timely detection and management are essential, yet manual methods are labour-intensive and prone to error. Machine learning (ML) addresses these limitations by analysing vast datasets from images, sensors, and environmental variables to enable proactive interventions. Object detection and recognition form an essential component of image processing and have emerged as a significant research area within the domains of image processing and pattern recognition [11, 12].

ML's economic impact is profound: predictive models can avert financial losses from crop failures, stabilising farmer incomes and regional economies [2]. Environmentally, ML promotes sustainability by optimising pesticide and fertiliser use, reducing runoff and biodiversity loss [3]. Adoption is growing, with studies showing up to 30% yield improvements through ML-driven pest management [4].

Edge detection techniques are widely used in various research domains, including computer vision, machine learning, and pattern recognition [13, 14]. This review categorises ML applications, details technical mechanisms, and discusses benefits, challenges, and future directions, drawing on recent literature to guide sustainable agricultural innovation.

Machine Learning Applications in Agriculture

Yield Prediction and Weather Forecasting: ML models integrate historical yield data, soil metrics, and climate variables to forecast outputs with superior accuracy over conventional methods. Regression algorithms like Random Forest and Gradient Boosting Machines process multisource inputs, enabling farmers to optimise planting and harvesting schedules [5].

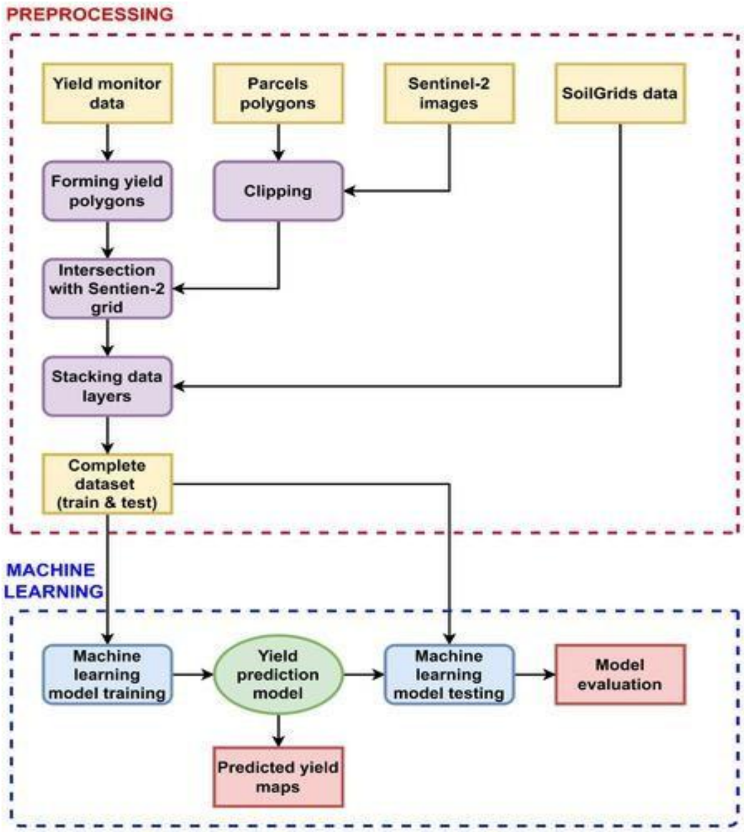

Figure 1: A flowchart overview and example walk-through of the methods presented in this paper. Datasets are shown in yellow, purple denotes the preprocessing operations, and modules for ML are shown in blue, while the resulting model and outputs (prediction maps and model performance) are shown in green and red, respectively. Black arrows indicate the flow of data. The segments belonging to the preprocessing part are framed by a red dashed line, while the ML components are bordered by blue dashed lines. [9]

2. **Crop Disease Detection:** CNNs dominate disease identification by processing leaf images to extract features like texture anomalies and discolouration. Trained on labelled datasets, these models achieve >90% accuracy, outperforming human experts in speed and scale [6].

Process overview:

- **Image Acquisition:** Via drones or smartphones.
- **Preprocessing:** Normalisation and augmentation.
- **Feature Extraction and Classification:** CNN layers identify pathologies.
- Output: Disease alerts with treatment recommendations.

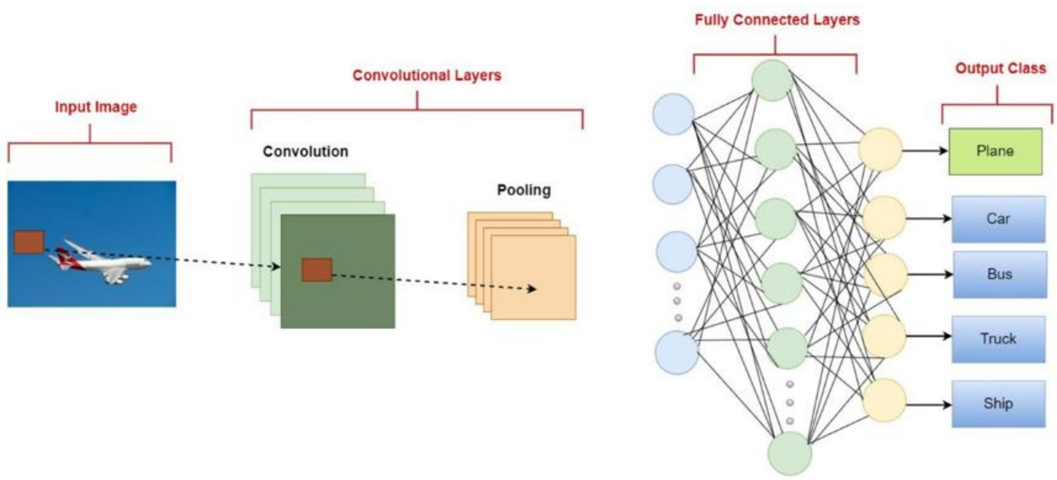

Figure 2: Standard CNN architecture [10]

3. **Crop Recognition and Quality Assessment:** Supervised ML classifies crop varieties using spectral data from satellites, aiding in tailored management. Quality evaluation employs image analysis to score attributes like ripeness, reducing post-harvest waste.
4. **Pest Management and Irrigation Optimisation:** Anomaly detection algorithms monitor pest incursions via time-series sensor data, while predictive analytics schedule irrigation based on evapotranspiration models, conserving water by 20–30% [7].

Table 1: Key ML Techniques and Applications in Crop Management

Application	ML Technique	Key Algorithms/Models	Benefits
Yield Prediction	Regression/Ensemble	Random Forest, XGBoost, LSTM	Accurate forecasting, risk mitigation
Disease Detection	Deep Learning/Computer Vision	CNN (ResNet, VGG), SVM	Early alerts, >90% accuracy
Pest Management	Anomaly Detection	Autoencoders, Isolation, Forest	Targeted interventions, reduced chemicals
Irrigation Optimization	Time-Series Forecasting	ARIMA, Prophet, RNN	Water savings, enhanced efficiency

III. Benefits and Challenges

Benefits:

- **Early Detection:** Prevents epidemic spread, saving 15–25% in losses [6].
- **Resource Efficiency:** Precision application cuts inputs by 20–50% [4].
- **Scalability:** Drone integration enables field-wide monitoring. Challenges:
- **Data limitations:** Sparse, region-specific datasets hinder generalisation.
- **Infrastructure:** High costs for sensors and computing in low-resource areas.
- **Interpretability:** Black-box models erode farmer trust; explainable AI (XAI) is needed.

IV. Future Directions

Advancements in edge computing will enable on-device ML for real-time decisions. Hybrid models fusing multimodal data (e.g., hyperspectral imagery with genomics) promise hyper-accurate predictions. Policy support for open datasets and farmer training will accelerate adoption, particularly in developing regions.

V. CONCLUSION

Machine learning is pivotal for sustainable agriculture, empowering farmers with tools for disease management, yield optimisation, and resource stewardship. By mitigating economic and environmental risks, ML paves the way for resilient food systems. Continued research in accessible, interpretable technologies will maximise its global impact.

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