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Web-Based Geographic Information Systems for Precision Agriculture in Sugarcane Farming: A Comprehensive Review

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ABSTRACT: This review focuses on the role of the web-based Geographic Information System (GIS) in sugarcane precision agriculture. Climate change, resource depletion, and market uncertainties have affected production; meaningfully, precision agriculture technologies can be solutions to reduce resource use and increase yield. The innovations, applicability, advantages, and challenges of web GIS platforms applied to sugarcane are reviewed and systematically analyzed in this paper based on literature spanning the years 2015 to 2024. The findings demonstrate that web GIS aids decision-making at the farm level by giving access to spatial data in real-time, as illustrated by the cases reducing fertilizers by 25% and improving water-use efficiency by 15-20%. Machine learning enhances these capabilities: yield predictions up to R-squared = 0.82, while disease detection achieves 95% accuracy using UAV imagery. This notwithstanding, barriers to adoption still prevail, such as high initial investment, technicality, and connectivity limitations in the rural landscape. Future research should, therefore, target user-interface functions, AI integration, and higher accessibility to cascade benefits widely across the globe. This review explains how web-based GIS can elevate sugarcane farming toward sustainability and efficiency.

KEYWORDS: Web-based GIS, Precision Agriculture, Sugarcane Farming, Machine Learning, Remote Sensing, Sustainable Agriculture

I. INTRODUCTION

Sugarcane, an important crop in the tropics and subtropics, suffers from significant production constraints such as climate change, resource scarcity, and market fluctuations. Conventional farming has been practiced for applying inputs uniformly in fields without accounting for spatial variability; this directly leads to inefficient practices of over-fertilizing regions and under-fertilizing others. Considerations of the already weak environmental stability have been made worse by previous input prices and environmental degradation brought on by nutrient runoff and water waste. Therefore, precision agriculture offered a solution to farmers' concerns by employing cutting-edge technical tools to reduce field unpredictability and maximize resource management and usage. GIS has given rise to a foundation for spatial analysis and mapping, allowing for site-specific management even as sophisticated techniques continue to develop and be used. The historical switch from conventional desktop GIS to web-based GIS is an important milestone in developing innovations that made spatial data available online in space and time so that they are integrated into a real-time decision-making process along with stakeholder consultation (Zhang et al., 2024).

Compared to conventional precision agriculture, web-based GIS supplements its capabilities by providing cloud-based platforms to transform data from numerous data sources, including remote sensing, field sensors, and historical documents (Shrivastav & Lal, 2020). Such data integration will assist farmers in obtaining better information concerning their fields' conditions to make better decisions regarding sugarcane production that is environmentally friendly and economically feasible.

This review explores the current situation regarding web-based GIS applications in sugarcane farming and the corresponding benefits and constraints. It will also accentuate the integration of machine learning technologies and encourage proposed future research approaches. Following this synthesis of findings from recent research and case implementations, the paper aims to advance the understanding of how web-based GIS could convert sugarcane farming into a more sustainable and efficient business.

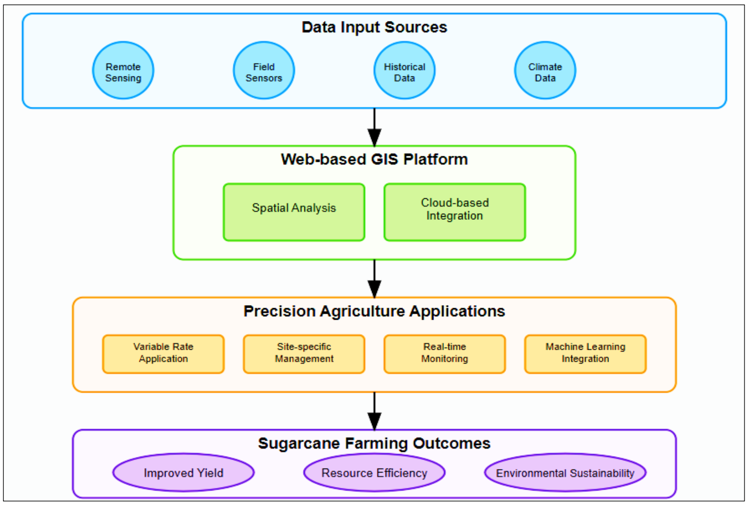

Figure 1: Conceptual framework of web-based GIS for precision agriculture in sugarcane farming

II. MATERIALS AND METHODS

It was synchronous within the parameters of a systematic literature review to find out how this online GIS has been utilized in sugarcane precision agricultural consulting practice. This proved challenging for many vital aspects of the review methodology.

A. Literature Search and Selection

The literature search encompassed peer-reviewed research papers, technical reports, and case studies from 2015 to 2024, with a focus on recently published reports since 2020 documenting existing technological advancements. The principal databases searched included ResearchGate, Springer, IEEE Xplore, ScienceDirect, and Google Scholar. Besides, industry reports from agencies and institutes such as USDA ARS, Sugar Research Australia, and the International Society of Sugar Cane Technologists were also consulted.

The keywords for the searches included combinations of "web-based GIS," "precision agriculture," "sugarcane farming," "spatial decision support systems," machine learning, remote sensing, and smart farming. The studies were considered when web-based GIS applications in sugarcane precision agriculture were involved, the benefits or challenges of implementation were discussed, and case studies or applications using machine learning were given within that context.

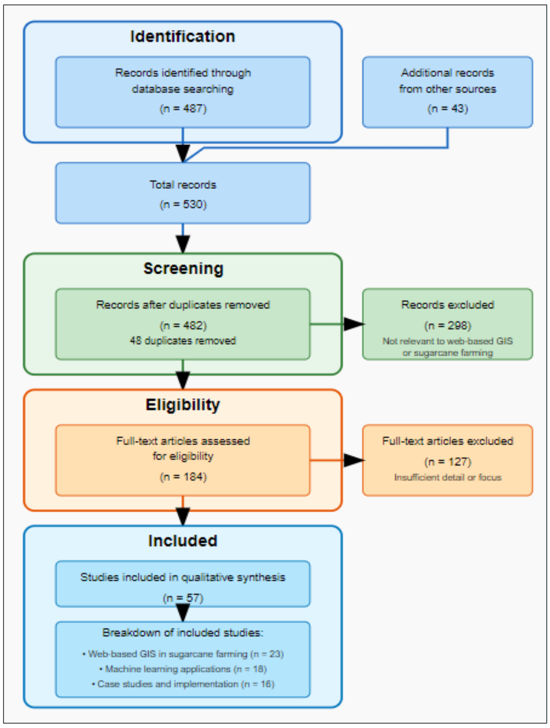

Figure 2: Flowchart of the literature search and selection process

B. Analysis Framework

Web GIS involves case studies and live platforms and applications that assess and comprehend resources in sugarcane agriculture. Machine learning combined with web GIS is emphasized in the context of enhancing decision-making and optimizing resources for farm productivity maximization. The study also discusses the advantages and challenges in implementing these technologies, with measurable parameters focusing on percentage improvements in resource use efficiency, improved yield forecasts, and accuracy measures of the predictive models. Ways and means of determining the cost and benefits of these technologies were also studied to see how economically profitable it is to adopt them. After investigating existing deployments, the study also ventured into future emerging research areas and trends, such as fast developments of remote sensing technology, real-time data processing, and smart decision-support systems. Synthesizing lessons from different studies, this research guides stakeholders interested in web-based GIS and machine learning applications for precision agriculture within the sugarcane sector.

III. RESULTS AND DISCUSSION

A. Overview of Precision Agriculture in Sugarcane Farming

From crude GPS-based guidance systems, sugarcane precision farming has evolved into a more sophisticated and integrated platform for field variability management in input optimization. Very important ones are GPS, Remote sensors (satellite and UAV), proximal sensors, variable-rate technology (VRT) and yield monitoring systems. Sugarcane precision farming has evolved from rudimentary GPS-based guidance systems to full-and-integrated platforms for managing variability field and input optimization. Key technologies in sugarcane precision agriculture include GPS, remote sensing (satellite and UAV), proximal sensors, variable rate technology (VRT) and yield monitoring systems.

Recent studies have proven substantial benefits to precision methods. Variable-rate application of fertilizers in Australian sugarcane operations led to a decrease of 25% in fertilizer use (Bramley et al., 2023). Santos et al. (2024) reported a 15-20% increase in water use efficiency due to precision irrigation in Brazilian sugarcane operations. The web GIS represents one of the most central hubs in precision agriculture today. It integrates many information sources and allows real-time analytical investigations. The field sensor data, satellite and drone evaluation imagery, real-time weather data, and historical records are integrated into coherent management systems accessible to farmers and other stakeholders.

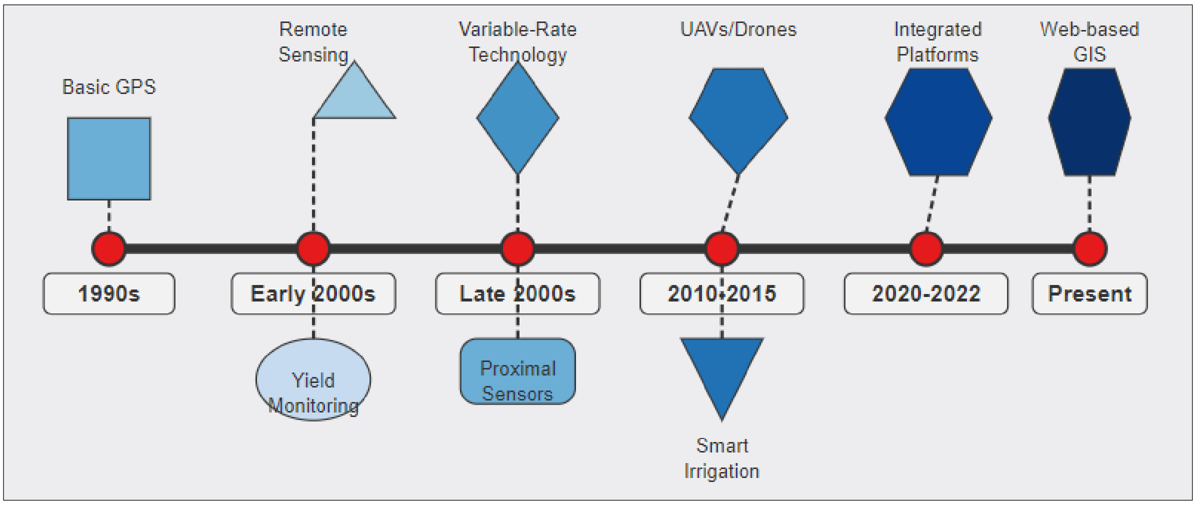

Figure 3: Evolution of Precision Agriculture in Sugarcane Farming

B. Role of GIS in Precision Agriculture

GIS is the backbone of precision agriculture and militating critical farm management and decision-making functions. It spatially maps variability across the fields to analyze differences in soil properties, crop health, and environmental conditions. Enhanced use of fertilizers, pesticides, and other inputs improves yield and reduces waste through targeted soil and crop management practices made possible by GIS through site-specific applications. Moreover, GIS is a necessary tool for yield monitoring and forecasting, which predicts production outcomes of recorded historical data, weather patterns, and real-time field conditions. The GIS system also manages pests and diseases by identifying risk areas and monitoring outbreaks for timely intervention and mitigation strategies. It facilitates the application of GIS in water management through the mapping of irrigation and drainage, as well as groundwater monitoring, all in an attempt to optimize the distribution of resources for field efficiency.

Web-based GIS enhances the above benefits dramatically: access to spatial information becomes democratized and available to farmers, agronomists, and others without regard to geographical bounds (Shrivastav & Lal, 2020). Unlike traditional desktop GIS approaches requiring special software installation and local data storage, web-based GIS facilitates real-time collaboration and easy remote access using internet-connected devices like cell phones and tablets. Most importantly, such accessibility guarantees that information aligns with the time needed to make on-ground decisions, where the farmers visualize field data and update records while still in the field. It may also capitalize on many cloud computing resources for advanced processing and high efficiency in predictive analytics and machine learning applications. Consequently, these technologies can be harnessed to enable farmers to make timely, accurate, and relevant data-based decisions to improve precision agriculture regarding yield, sustainability, and profitability.

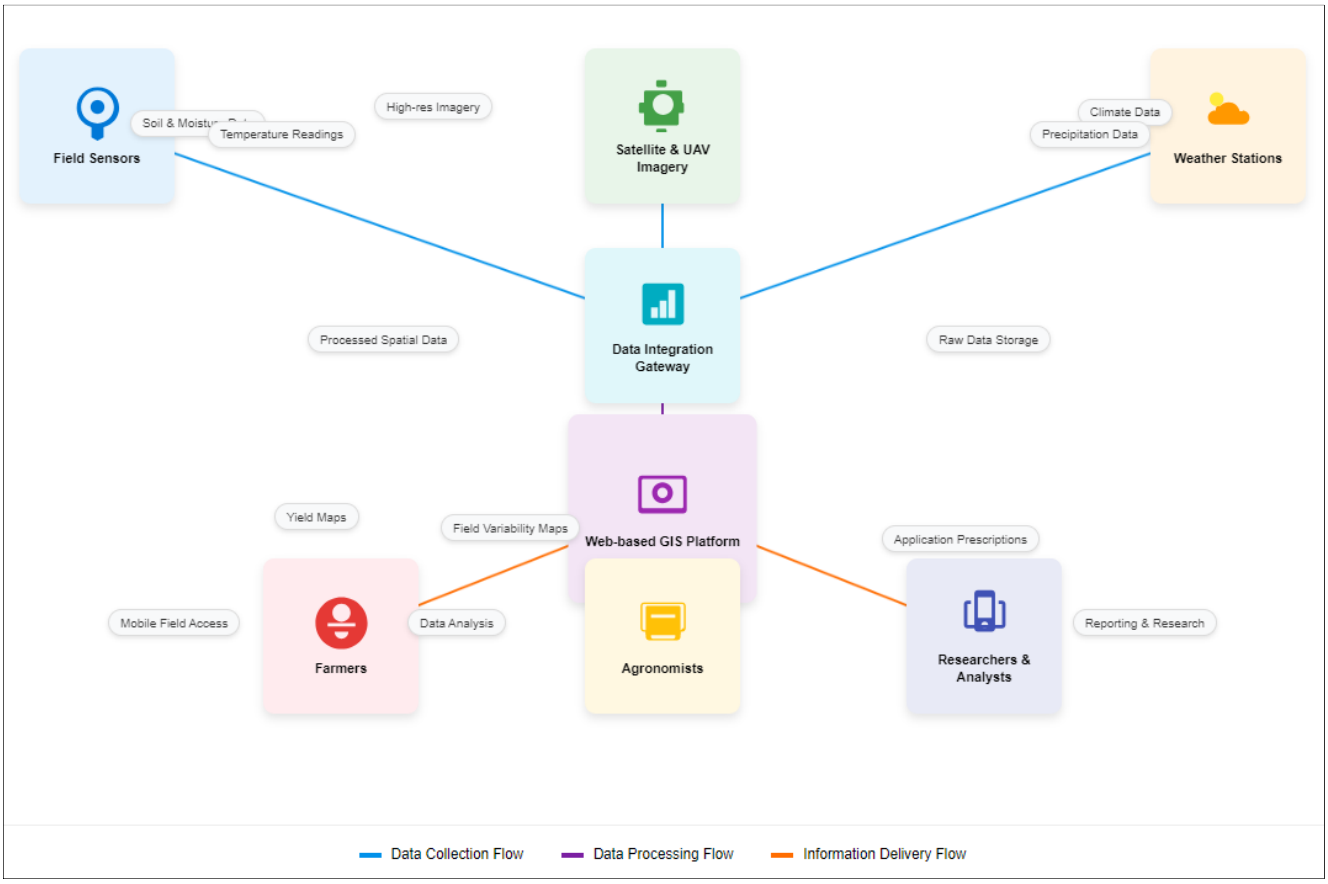

Figure 4: Web-based GIS for Precision Agriculture: System Architecture

C. Web-Based GIS Platforms: Case Studies and Applications

The following are prominent web-based GIS platforms applied for sugarcane farming:

- **SugarGIS (India):** SugarGIS, created in 2015, deals with crop health and variety selection by remote sensing via satellites plus ground information. The emphasis of this app is on some research and developmental services with new machine learning capabilities. SugarGIS is a desktop-oriented web application mostly used for manipulating satellite data, with some manual validation, while some basic functions are offered to mobile users (Shrivastav & Lal, 2020). A GIS application, Copla-GIS (Brazil), was developed in 2018 by 99GEO in partnership with Coplacana and utilizes GIS Cloud for mobile data collection and visualization. It is a mobile-first application that offers advanced field mobility and real-time updates. Integrating drone imagery, soil sensors, and equipment data to optimize field operations is made possible with a subscription-based model targeting field managers and technicians (Santos et al., 2024).
- **SugarMaps (Australia):** Australian Sugar Technology Services developed SugarMaps, a regulation and management tool for sugarcane growers, in 2020. This cloud-native platform with progressive web app characteristics supports data visualization for yields, pest incidence, and soil samples, while real-time monitoring uses IoT sensor integration. Advanced predictive analytics are offered on a tiered subscription basis, with free access in the basic tier for growers, agronomists, and mill operators (Bramley et al., 2023).

- **CaneSense (Thailand):** Launched in 2022, CaneSense is an agricultural platform that covers climate-resilient farming and water management with an augmented reality interface for visualization. This system collects relevant data through powerful sensor networks, edge computing, climate models, irrigation systems, and water quality sensors. CaneSense uses portals for stakeholder-enhanced collaboration on a pay-per-use model, integrating climate adaptation modeling with regional partnerships (Nattapong et al., 2023).
- **AgriField-360 (USA):** The most recent instance launched in 2023 was AgriField-360. It has provided a full-spectrum farm management platform for carbon tracking with a responsive web interface and voice command. Satellite, drone, sensor, and machinery data sources integrate with API to farm machinery, carbon markets, and supply chain tracking. The mobile platform offers predictive alerts and enterprise collaboration on a role-based permission system. An integrated supply chain wholesaler engaged in a value-based price model related to farm outcomes via a full AI suite and digital twin capability is the aim of the AgriField-360 platform(Chen & Rodriguez, 2023).

Table 1: Comparison of Major Web-Based GIS Platforms for Sugarcane Farming

Feature	SugarGIS (India)	Copla-GIS (Brazil)	SugarMaps (Australia)	CaneSense (Thailand)	AgriField-360 (United States)
Year Introduced	2015	2018	2020	2022	2023
Primary Focus	Crop health and variety selection	Field operation optimization	Productivity zone management with real-time analytics	Climate-resilient farming and water management	Full-spectrum farm management with carbon tracking
User Interface	Desktop-oriented web interface	Mobile-first approach	Cloud-native with progressive web app capabilities	Cross-platform with AR visualization	Responsive design with voice command capabilities
Data Collection	Primarily satellite data with manual validation	Field app with offline capability	Automated IoT integration with manual validation	Advanced sensor network with edge computing	Multi-source data fusion (satellites, drones, sensors, machinery)
Integration Capabilities	Satellite imagery, weather forecasts, mill data	Drone imagery, soil sensors, machinery	IoT sensors, drone data, mill records, weather stations	Climate models, irrigation systems, water quality sensors	Farm equipment APIs, carbon markets, supply chain tracking
Mobile Functionality	Basic	Advanced	Advanced with offline capabilities	Advanced with augmented reality	Comprehensive with predictive alerts
Real-time Collaboration	Limited	High	High	Advanced with stakeholder portals	Enterprise-level with role-based permissions
Cost Structure	Government subsidized	Subscription-based	Tiered subscription with free basic tier	Pay-per-use with regional partnerships	Value-based pricing tied to farm outcomes
Machine Learning Features	Emerging capabilities	Advanced analytics	Advanced predictive analytics	Climate adaptation modeling	Full AI suite with digital twin capabilities
Target Users	Researchers and extension officers	Field managers and technicians	Growers, agronomists, and mill operators	Water resource managers and farm planners	Integrated supply chain stakeholders
Key Strength	Large-scale regional analysis	Field mobility and real-time updates	Real-time analytics and IoT integration	Water optimization and climate resilience	Carbon footprint reduction and market integration

Due to technological advancement and expanding capabilities, these platforms are evolving. The oldest platform, SugarGIS out of 2015, provides some basic functionalities mostly used for research applications, while the most recently launched one, AgriField-360, launched in 2023, offers complete farm management with advanced AI integration and sustainability component features. This progression indicates the maturity of web-based GIS technology and the increased integration with other digital agricultural tools.

D. Integration of Machine Learning with Web-Based GIS

One major achievement in precision agriculture for sugarcane lies in merging machine learning algorithms with web-based GIS. Machine learning augments these platforms' analytics with predictive, pattern recognition, and automated decision support. A few current studies reveal some successful applications:

1. **Yield prediction:** Li et al.'s (2023) study used ensemble machine learning methods to fuse climate data, soil properties, and historical yields; R-squared values as high as 0.82 were obtained.
2. **Disease detection:** Liu et al. (2024) reported a detection accuracy of 95% for the sugarcane yellow leaf disease using deep learning algorithms on UAV-based multispectral images.
3. **Resource optimization:** Ekanayake et al. (2022) reported water savings of 22% using machine learning irrigation scheduling guided by spatial data.

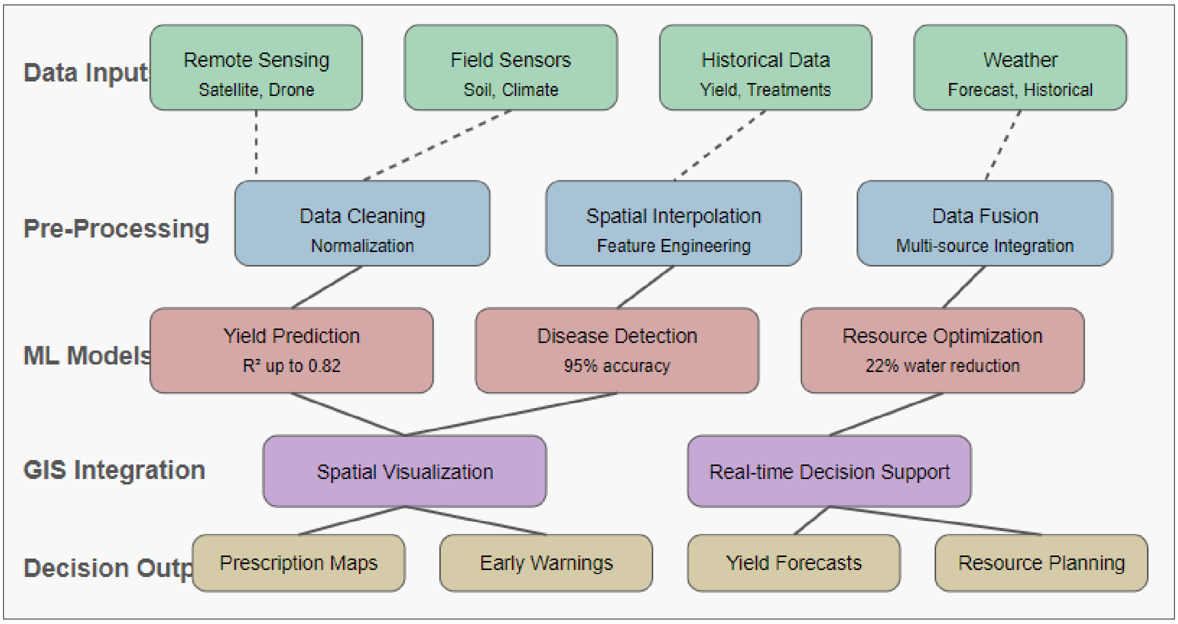

Figure 5: ML-GIS Integration for Precision Sugarcane Agriculture

Figure 5 clearly shows the five-layer architecture of your ML-GIS integration system for precision agriculture, with all text properly positioned within their respective shapes.

Table 2: Machine Learning Applications in Web-Based GIS For Sugarcane Farming

Application	ML Algorithm	Data Sources	Key Performance Metrics	Reference
Yield Prediction	Ensemble Machine Learning	Climate data, soil properties, historical yields	$R^2 = 0.82$	Li et al., 2023
Real-time Yield Estimation	Support Vector Regression	Harvester engine parameters, spatial coordinates	RMSE = 6.8 tons/ha	Felipe Maldaner et al., 2024
Biomass Estimation	Artificial Neural Networks	Satellite imagery, vegetation indices	r = 0.85	Abdel-Rahman & Ahmed, 2022
Disease Detection	Convolutional Neural Networks	UAV multispectral imagery	Accuracy = 95%	Liu et al., 2024
Irrigation Optimization	Gradient Boosting	Soil moisture, weather data, ET rates	Water savings = 22%	Ekanayake et al., 2022

Weed Classification	K-Nearest Neighbors	Drone imagery, spectral signatures	Precision = 90%	Zhang et al., 2024
Variety Performance	Decision Trees	Spatial yield data, soil types, climate	Accuracy = 85%	Bramley et al., 2023
Harvest Scheduling	Genetic Algorithms	Maturity estimates, factory capacity, transport	ROI increase = 9.2%	Santos et al., 2024

Table 2 shows that applying machine learning to precision agriculture has greatly improved various aspects of sugarcane farming. The machine learning models for predicting yields using ensemble learning scored high accuracy (R2=0.82), while real-time estimation of yields with support vector regression reduced errors (RMSE=6.8 tons/ha). Biomass estimation using artificial neural networks strongly correlated with actual values (r=0.85). Disease detection has been done with 95% accuracy using UAV multispectral imagery through convolutional neural networks. Gradient boosting-based irrigation optimization led to a water savings of 22%, and weed classification by K-nearest neighbors achieved 90% precision. Decision trees were effective in evaluating variety performance (85% accuracy), whereas genetic algorithms optimized harvest scheduling to increase ROI by 9.2%. These studies demonstrate how machine learning can enhance decision-making, resource efficiency, and productivity in sugar cane cultivation. The application of machine learning in precision agriculture is shown in Table 2, wherein it has proven to improve various aspects of sugarcane farming. Its predictions from the machine learning models employing ensemble learning approaches scored high accuracy values (R2=0.82), and real-time yield estimation through support vector regression cut back the errors (RMSE=6.8 tons/ha). The biomass estimation through artificial neural networks strongly correlates with actual values (r=0.85). Disease detection has been achieved with 95% accuracy using a UAV multispectral image-trained convolutional neural network. Gradient boosting-based irrigation optimization achieved a 22% saving in water, while weed classification through K-nearest neighbors achieved 90% precision. Decision trees appraised variety performance at 85% reliability, while harvest scheduling efficiency with genetic algorithms increased by 9.2% ROI. These studies prove how the learning machine could increasingly improve decision-making, resource efficiency, and productivity in harvesting sugar canes.

This is supported statistically by Table 2, within which the application of machine learning to precision agriculture has proven its worth through improvements across all possible aspects of sugarcane farming. Prediction by machine learning models using ensemble learning raised high accuracy rates (R2=0.82), while real-time yield estimation through support vector regression reduced errors (RMSE=6.8 tons/ha). Biomass estimation through artificial neural networks showed quite an impressive correlation with actual values (r=0.85). Disease detection has been done with 95% accuracy using UAV multispectral imagery through convolutional neural networks. Gradient boosting-based irrigation optimization led to a water savings of 22%, and weed classification by K-nearest neighbors achieved 90% precision. The Decision Trees were fairly effective in evaluating variety performance (Appx.85% accuracy), while the genetic algorithms optimized harvest scheduling so that ROI increased by 9.2%. These studies prove machine learning can improve sugarcane farming's decision-making, resource efficiency, and productivity.

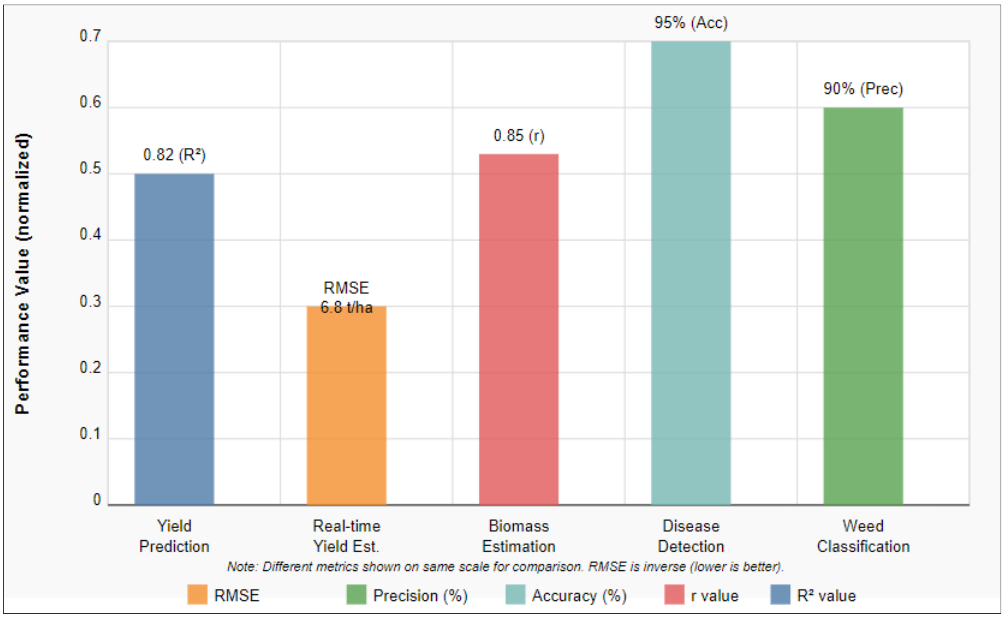

Figure 6: Performance Metrics of Different Machine Learning Applications in Sugarcane Farming

Figure 6 shows that Disease Detection has the highest performance metric (95% accuracy), followed by Weed Classification (90% precision) and Biomass Estimation (r = 0.85). The real-time yield estimation uses RMSE, which cannot be directly compared with the other metrics on the same scale.

E. Benefits and Challenges

Web-based Geographic Information Systems (GIS) is significantly pushing forward accuracy in sugarcane agriculture. This network-based technology contributes perks to some acts, such as effectiveness, sustainability, and decision-making. This network-based technology adds value to various activities, including efficiency, sustainability, and decision-making. One major benefit is the instant access to real-time data, forcing farmers to decide on the current situation in the field immediately. A contribution of web-based GIS towards efficient resource management, less wasted resources, and reduced environmental footprints is by facilitating the targeted application of inputs such as fertilizers and pesticides. The acquired spatial information can further assist in farm-management decisions by providing historical analyses to compare the previously executed management strategies between seasons. All of these lead to sustainable exploitation of resources, hence helping to diminish environmental footprints.

Nonetheless, several factors may hinder the acceptance of web-based GIS in sugarcane farming. From these, the most prominent are initial costs, as setting up these systems requires hardware, software, and training investments. Web-based GIS is technically too complicated for some farmers to operate efficiently because it requires specialized knowledge. Security also comes in a broad area of concern because the farmers do not want to share information derived from sensitive farm data online. Further, linking these web-based GIS inputs with legacy systems is not straightforward. Connectivity problems are further barriers to farmers who live in rural areas and require an Internet connection to exchange real-time data. Sensor data and data from remote sensing can be erroneous or have missing pieces, affecting data quality in their use. These challenges must be addressed to realize the maximum installability of web-based GIS towards precision agriculture.

F. Future Directions

In sugarcane farming, future research and development of web-based GIS should make efforts to overcome the existing limitations and increase the capability of providing better service to farmers and stakeholders. One important area will be the improvement of user interfaces and easier design that could lower the adoption barriers, especially for farmers who do not have adequate technical background. There are new technologies like natural language processing, which can control devices with voices and can simplify mobile interfaces for human interaction. Field usability could receive a boost from them. Another promising direction would be greater AI integration with federated learning schemes to allow data sharing while ensuring privacy in its insights. AI will also provide assistants that personalize the recommendations that farmers need concerning their data, requirements, and objectives. Connectivity remains a significant challenge, as rural connectivity continues to be challenging; thus, future avenues must focus on low-bandwidth applications, offline functionality, and emerging satellite networks for seamless access. Xu et al. (2023) provide recent evidence pointing to the fact that satellite internet technologies present a legitimate opportunity to sustain connectivity in agricultural areas.

But again, minimizing the cost of uptake is equally important if tiered models of service, supported by governments or open-source alternatives, are to be considered for easier adoption. As Maldaner et al. (2024) pointed out, this cooperative model could also have small-scale farmers benefiting from economies of scale. By addressing key issues in the areas above, web-based GIS will likely take a great leap toward increasing efficiency, sustainability, and profitability in sugarcane farming.

IV. CONCLUSIONS

Web-based GIS is a very effective tool for infusing higher precision in sugarcane farming. This review has shown that with these platforms, it is possible to achieve substantial benefits in resource management, documented benefits including savings of up to 22% for water and 25% for fertilizers. Machine learning is an ultra-level advanced feature for such abilities, improving yield prognostics over R-squared values of 0.82 and disease recognition with 95% accuracy.

However, much remains to be done regarding high implementation costs, technical complexity, and connectivity limitations. All these challenges remain higher hurdles for smallholder farmers and those in developing areas, which can aggravate the digital divide in agriculture.

Future research will focus on making most web-based GIS applications more accessible, user-friendly, and affordable while at the same time continuing to widen the frontier of AI-inclusivity for more analytical capabilities. With these, web-based GIS would enable far greater sustainability, efficiency, and productivity of sugar cane farming practices worldwide.

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