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Development of Precision Agriculture Techniques for Soybean Yield Improvement

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Abstract Precision agriculture (PA) has emerged as a transformative approach to optimizing crop production, particularly for high-value crops like soybean. With the growing demand for increased soybean yields to meet global food security needs, PA technologies offer promising solutions for enhancing productivity, sustainability, and environmental stewardship. This study examines the application of various precision agriculture techniques in soybean farming, focusing on the integration of GPS, GIS, remote sensing, soil sensors, variable rate technology (VRT), and automation to improve yield efficiency. A case study of a soybean farm in the Midwest highlights the successful implementation of these technologies, demonstrating significant improvements in yield and resource management. Additionally, the study explores the role of data analytics, decision support systems, and machine learning in optimizing farm management decisions. Economic and environmental impacts, including cost-benefit analysis and sustainability, are also discussed. The findings suggest that while the adoption of precision agriculture can lead to substantial economic gains and environmental benefits, challenges remain in widespread adoption. This research provides a comprehensive overview of the potential of precision agriculture to revolutionize soybean farming, while outlining future directions for further innovation and adoption in the sector.
Keywords Precision agriculture; Soybean; Yield improvement; GPS/GIS; Remote sensing; Sustainability

1 Introduction

Precision agriculture (PA) is an advanced farming practice that utilizes technology to optimize field-level management regarding crop farming. The integration of sensor-based decision tools, unmanned aerial vehicles (UAVs), and machine learning algorithms has revolutionized the way farmers manage their crops. These technologies enable the precise application of nutrients and water, thereby enhancing crop productivity and resource-use efficiency. For instance, sensor-based nutrient and irrigation management has been shown to significantly improve the physiological performance and yield of soybean crops by providing real-time assessments of crop health and needs (Sachin et al., 2023a). UAV platforms equipped with multi-sensor data collection capabilities have also been employed to accurately estimate crop yields, further aiding in the optimization of farming practices (Eugenio et al., 2020; Ren et al., 2023).

Soybean (*Glycine max* L.) is a critical crop in global agriculture due to its high protein content and versatility in food and industrial applications. It plays a vital role in food security and economic stability, particularly in regions where it is a major agricultural product. The continuous improvement of soybean yield is essential to meet the growing global food demand and address security concerns. Advances in precision agriculture techniques, such as the use of UAVs and machine learning for yield prediction, have shown promise in enhancing soybean production efficiency and sustainability (Vogel et al., 2021; Yoosefzadeh-Najafabadi et al., 2021). Moreover, understanding the physiological processes and environmental interactions that influence soybean yield can lead to more targeted and effective breeding programs (Smidt et al., 2016; Fathi et al., 2023; Wang, 2024).

This study attempts to explore the development and evaluation of precision agriculture techniques to improve soybean yield, discuss the integration of advanced technologies such as UAV-based multi-sensor data and machine learning algorithms, and provide an overview of how precision breeding technologies like genome editing can enhance soybean yield. The research focuses on investigating the effectiveness of sensor-based nutrient and irrigation management, integrating physiological principles with environmental data to optimize farm management, and identifying practical solutions to improve soybean productivity. Ultimately, this study aims to contribute to global food security and promote sustainable farming practices.

2 Precision Agriculture Technologies for Soybean

2.1 Overview of precision agriculture

Precision agriculture involves the use of advanced technologies to monitor and manage field variability in crops, aiming to optimize returns on inputs while preserving resources. This approach includes the use of GPS, GIS, remote sensing, and various sensors to collect data on soil and crop conditions, which can then be used to make informed decisions about planting, fertilizing, and irrigating crops (Hedley, 2015; Smidt et al., 2016). The goal is to enhance crop productivity and resource-use efficiency, ensuring sustainable agricultural practices (Figure 1).

Figure 1 Precision tillage of soybean crops (Photo credit: Yuting Zhong)

2.2 GPS and GIS technologies in soybean farming

GPS and GIS technologies are fundamental to precision agriculture, providing accurate location data and spatial analysis capabilities. These technologies enable farmers to create detailed maps of their fields, showing variations in soil properties, crop health, and yield. This spatial information allows for site-specific management practices, such as variable rate seeding and fertilization, which can optimize input use and improve crop yields (Hedley, 2015; Smidt et al., 2016). The integration of GPS with variable rate technology (VRT) has enabled precise application of inputs, reducing waste and increasing efficiency.

2.3 Remote sensing and drones for yield monitoring

Remote sensing technologies, including the use of drones, have revolutionized yield monitoring in soybean farming. Drones equipped with multispectral and hyperspectral sensors can capture high-resolution images of fields, providing valuable data on crop health and growth stages. This data can be used to estimate yields accurately and identify areas needing attention (Eugenio et al., 2020; Skakun et al., 2021; Ren et al., 2023). Machine learning algorithms further enhance the predictive power of remote sensing data, allowing for more precise yield estimations and better decision-making (Maimaitijiang et al., 2020).

2.4 Soil sensors and variable rate technology (VRT)

Soil sensors play a crucial role in precision agriculture by providing real-time data on soil moisture, nutrient levels, and other critical parameters. This information is essential for implementing variable rate technology (VRT), which adjusts the application rates of water, fertilizers, and other inputs based on the specific needs of different field zones (Hedley, 2015; Sachin et al., 2023a). VRT helps in optimizing input use, improving crop health, and increasing yields while minimizing environmental impact.

2.5 Automation and robotics in soybean production

Automation and robotics are emerging technologies in precision agriculture, offering the potential to further enhance efficiency and productivity in soybean farming. Automated systems can perform tasks such as planting, weeding, and harvesting with high precision and consistency. Robotics can also be integrated with other precision agriculture tools, such as GPS and sensors, to perform site-specific management practices autonomously. These technologies reduce labor costs and increase operational efficiency, contributing to higher yields and better resource management (Hedley, 2015; Smidt et al., 2016).

Precision agriculture technologies, including GPS, GIS, remote sensing, soil sensors, and automation, are transforming soybean farming by enabling more precise and efficient management of inputs. These technologies help optimize resource use, improve crop health, and increase yields, contributing to sustainable agricultural practices. The integration of these advanced tools into soybean production systems holds great promise for the future of agriculture.

3 Genetic and Environmental Interactions in Soybean Yield

3.1 Genetic improvement in soybean varieties

Genetic improvement in soybean varieties has been a cornerstone of agricultural advancements, aiming to enhance yield potential and stability. Plant breeders have successfully released varieties with improved yield potential through performance-based selection, even without a complete understanding of the molecular mechanisms involved (Vogel et al., 2021). Recent studies have utilized machine learning and genetic optimization algorithms to model and optimize soybean yield by analyzing key yield component traits such as the number of nodes and pods per plant (Yoosefzadeh-Najafabadi et al., 2021). Additionally, genome-wide association studies (GWAS) and genomic selection (GS) have identified specific single nucleotide polymorphisms (SNPs) associated with yield and related traits, providing valuable markers for breeding programs (Ravelombola et al., 2021). The integration of conventional and molecular breeding techniques, including CRISPR-based genome editing, has opened new avenues for soybean yield and quality improvement (Figure 2) (Gai et al., 2021).

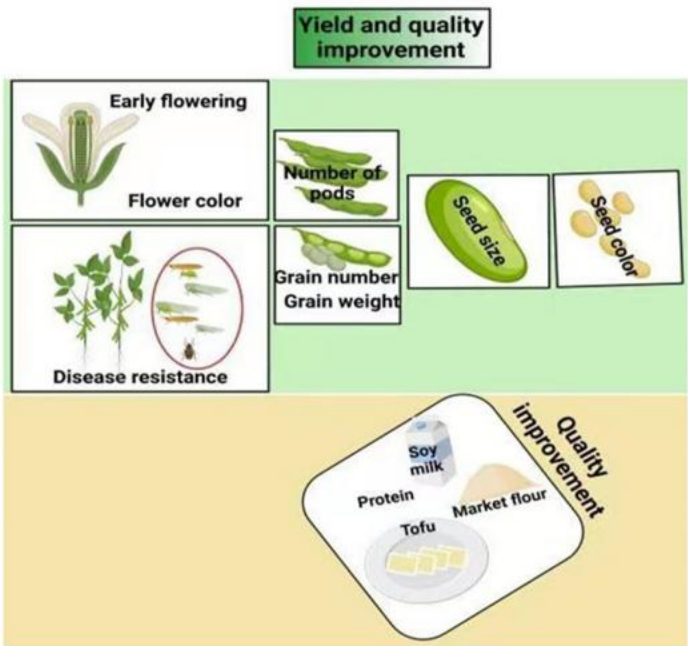


Figure 2 The main breeding targets in soybean are yield, quality improvement and diseases resistance (Adopted from Gai et al., 2021)

3.2 Environmental factors affecting soybean growth

Environmental factors play a significant role in soybean growth and yield. Factors such as water availability, nutrient management, and climatic conditions can greatly influence physiological processes and yield outcomes. Precision nutrient and irrigation management have been shown to enhance physiological performance, water productivity, and yield in soybean crops (Sachin et al., 2023a; Sachin et al., 2023b). The use of unmanned aerial vehicles (UAVs) and remote sensing data has improved the accuracy of yield estimation by incorporating environmental variables such as maturity group information and vegetation indices (Ren et al., 2023). Furthermore, understanding genotype-by-environment interactions is crucial for developing stable and high-yielding soybean cultivars. Studies have identified specific genomic regions associated with these interactions, providing insights into how different genotypes perform under varying environmental conditions (Xavier et al., 2017).

3.3 Integrating precision agriculture with genomic tools

Integrating precision agriculture with genomic tools offers a promising approach to soybean yield improvement. Precision agriculture techniques, such as sensor-based nutrient and irrigation management, can optimize resource use and enhance crop productivity (Sachin et al., 2023b). Combining these techniques with genomic tools like GWAS and GS allows for the identification of favorable alleles and the development of high-yielding, environmentally resilient soybean varieties (Ravelombola et al., 2021). Machine learning algorithms have also been employed to predict soybean yield by analyzing data from multiple sensors and growth stages, further enhancing the precision of yield estimation (Eugenio et al., 2020; Herrero-Huerta et al., 2020). The integration of these technologies enables a more comprehensive understanding of the factors influencing soybean yield and facilitates the development of targeted breeding strategies for yield improvement.

Genetic and environmental interactions significantly impact soybean yield, and advancements in both areas are crucial for yield improvement. Genetic improvements through conventional and molecular breeding techniques, coupled with precision agriculture practices, offer a holistic approach to enhancing soybean productivity. Integrating genomic tools with precision agriculture technologies provides a powerful framework for optimizing yield and developing resilient soybean varieties.

4 Case Study: Precision Agriculture in a Soybean Farm in the Midwest

4.1 Background of the farm

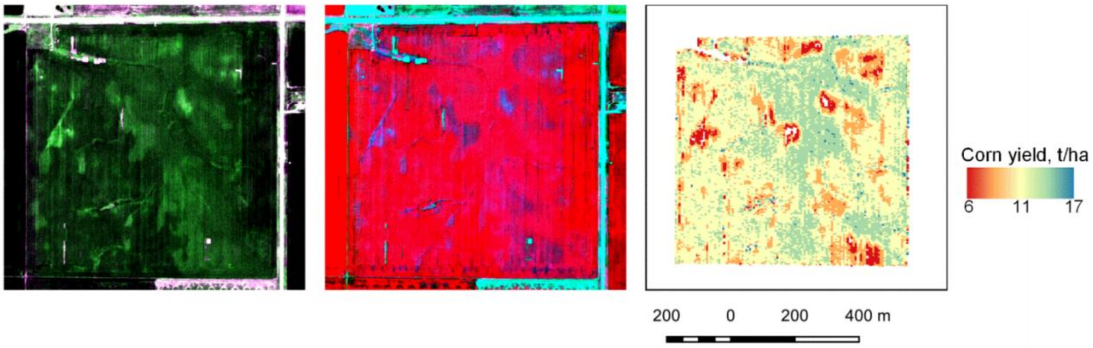
The soybean farm under study is located in the Midwest, a region known for its fertile soil and favorable climate for soybean cultivation. The farm spans approximately 500 hectares and has been operational for over two decades. Traditionally, the farm employed conventional farming practices, but in recent years, it has transitioned to precision agriculture techniques to enhance productivity and sustainability.

4.2 Application of GPS and VRT for soil and water management

The farm utilizes Global Positioning System (GPS) technology and Variable Rate Technology (VRT) to optimize soil and water management. GPS allows for precise mapping of field variability, enabling targeted interventions. VRT is used to adjust seeding rates, fertilizer application, and irrigation based on soil characteristics and crop needs. This approach has led to more efficient use of resources and improved crop performance (Hedley, 2015; Smidt et al., 2016).

4.3 Use of remote sensing for pest and disease detection

Remote sensing technologies, including multispectral and hyperspectral imaging from UAVs and satellites, are employed to monitor crop health and detect pest and disease outbreaks early. These technologies provide real-time data on vegetation indices such as NDVI, which are crucial for assessing plant health and stress levels. Early detection through remote sensing allows for timely and targeted pest and disease management, reducing crop losses and improving yield (Figure 3) (Zhang et al., 2015; Eugenio et al., 2020; Skakun et al., 2021).



(a) (b) (c)

Figure 3 Example of WorldView-3 (WV-3) images acquired over the Coles corn field on 2 July 2018 (Adopted from Skakun et al., 2021)

Image caption: True color composite red-green-blue (a); false color composite near infrared (NIR)-red-green (b); corn yields (c). ©2021 DigitalGlobe, Inc., a Maxar company, NextView License (Adopted from Skakun et al., 2021)

4.4 Yield improvements and economic benefits

The adoption of precision agriculture techniques has resulted in significant yield improvements and economic benefits for the farm. Sensor-based nutrient and irrigation management have enhanced physiological performance and water productivity, leading to higher grain yields. For instance, the integration of sprinkler irrigation with precision nutrient management recorded a grain yield increase of up to 35.4% compared to conventional practices (Sachin et al., 2023a). Additionally, the use of remote sensing and machine learning for yield prediction has optimized resource allocation, further boosting economic returns (Eugenio et al., 2020; Ren et al., 2023).

4.5 Challenges and lessons learned

Despite the benefits, the farm faced several challenges in implementing precision agriculture. These included the high initial costs of technology adoption, the need for technical expertise, and data management complexities. However, the long-term benefits, such as reduced temporal yield variation and increased yield stability, have outweighed these challenges. The farm has learned the importance of continuous monitoring and adaptation of precision agriculture practices to local conditions for sustained success (Yost et al., 2017; Monzon et al., 2018). In summary, the case study of the Midwest soybean farm demonstrates the transformative potential of precision agriculture in enhancing yield and economic viability while addressing environmental sustainability.

5 Data Analytics and Decision Support Systems

5.1 Role of big data in precision agriculture

Big data plays a crucial role in precision agriculture by enabling the collection, analysis, and interpretation of vast amounts of data from various sources such as remote sensing, UAVs, and ground sensors. This data can be used to monitor crop health, predict yields, and optimize resource use. For instance, UAV-based multimodal data fusion using RGB, multispectral, and thermal sensors has been shown to improve soybean yield prediction accuracy significantly, demonstrating the adaptability of big data to spatial variations and its potential for high-throughput phenotyping and crop field management (Maimaitijiang et al., 2020; Ren et al., 2023).

5.2 Machine learning and AI for yield prediction

Machine learning (ML) and artificial intelligence (AI) are pivotal in enhancing yield prediction models. Various ML techniques, such as Random Forest (RF), Support Vector Regression (SVR), and Deep Neural Networks (DNN), have been employed to predict soybean yields with high accuracy. For example, DNN-based models using UAV data have achieved an R^2 of 0.720 and a relative RMSE of 15.9%, indicating their robustness and adaptability across different soybean genotypes. Additionally, combining genotype information with UAV-based multi-sensor data using ML methods like Gaussian Process Regression (GPR) has further improved yield estimation accuracy (Maimaitijiang et al., 2020; Ren et al., 2023).

5.3 Decision support systems for farm management

Decision Support Systems (DSS) are integral to modern farm management, providing farmers with actionable insights derived from data analytics. These systems utilize sensor-based tools to assess crop health and optimize irrigation and nutrient management. For instance, sensor-based precision nutrient and irrigation management has been shown to enhance physiological performance, water productivity, and yield in soybean crops. The integration of DSS with precision agriculture practices can lead to significant improvements in crop productivity and resource-use efficiency (Sachin et al., 2023a).

5.4 Integration of weather forecasting and precision techniques

Integrating weather forecasting with precision agriculture techniques can significantly enhance yield prediction and farm management. Deep learning models that incorporate time-series weather data, such as the 3D-ResNet-BiLSTM model, have demonstrated superior performance in predicting soybean yields at the county level. These models leverage detailed remote sensing imagery and weather data to provide accurate yield predictions, supporting sustainable agriculture and food security (Fathi et al., 2023). Additionally, the use of weather variables in ML models, such as LSTM networks, has been shown to outperform traditional methods in predicting crop yields, offering valuable insights for plant breeders and farmers (Shook et al., 2020).

The integration of big data, machine learning, and decision support systems in precision agriculture offers significant potential for improving soybean yield predictions and farm management practices. By leveraging advanced data analytics and AI techniques, farmers can make more informed decisions, optimize resource use, and enhance crop productivity. The incorporation of weather forecasting further strengthens these models, providing a comprehensive approach to sustainable agriculture (Eugenio et al., 2020; Teodoro et al., 2021).

6 Economic and Environmental Impacts

6.1 Cost-benefit analysis of precision agriculture for soybeans

Precision agriculture (PA) techniques have shown significant potential in improving the economic viability of soybean farming. Studies indicate that PA systems can sustain profitability over long periods. For instance, a long-term study in central Missouri demonstrated that a precision agriculture system (PAS) maintained profits in 97% of the field without subsidies for cover crops or payments for enhanced environmental protection (Yost et al., 2019). Additionally, the integration of sensor-based nutrient and irrigation management has been found to enhance water productivity and yield, leading to better economic water productivity and water-use efficiency (Sachin et al., 2023b). The use of unmanned aerial vehicles (UAVs) and multispectral imagery for yield prediction has also been shown to improve the accuracy of yield estimates, which can help farmers make more informed decisions and optimize their input costs (Eugenio et al., 2020; Ren et al., 2023).

6.2 Environmental benefits: reducing input use and environmental footprint

Precision agriculture techniques contribute significantly to reducing the environmental footprint of soybean farming. By optimizing the use of inputs such as water, fertilizers, and pesticides, PA practices help in minimizing waste and environmental degradation. For example, the adoption of sensor-based irrigation and nutrient management systems has been shown to improve water productivity and reduce canopy temperature, which in turn enhances the physiological performance of soybean crops (Sachin et al., 2023a). Moreover, the use of UAVs and NDVI techniques in small Mediterranean farms has demonstrated ecological benefits by reducing the use of water and fertilizers, thus promoting sustainable agriculture (Loures et al., 2020). The implementation of PAS, which includes practices like no-till farming and cover cropping, has also been effective in addressing environmental concerns while maintaining crop yields (Yost et al., 2017; Yost et al., 2019).

6.3 Potential for sustainable soybean farming practices

The potential for sustainable soybean farming practices is greatly enhanced by the adoption of precision agriculture techniques. These practices not only improve yield stability and resilience to changing climate conditions but also promote sustainable resource use. For instance, the use of site-specific nutrient management and variable-rate technology (VRT) has been shown to optimize seeding rates and improve yield outcomes (Smidt et al., 2016). Additionally, integrating crop physiology principles into PA systems can bridge yield gaps and increase farmer profit while reducing risk (Monzon et al., 2018). The combination of rhizobium inoculation and phosphorus supplementation has also been found to significantly increase soybean yields in the savanna areas of Nigeria, highlighting the potential for sustainable yield improvements through precision agriculture (Jemo et al., 2023).

Precision agriculture techniques offer substantial economic and environmental benefits for soybean farming. By optimizing input use and improving yield prediction accuracy, these practices can enhance profitability and promote sustainable farming. The integration of advanced technologies such as UAVs, sensor-based irrigation, and nutrient management systems further underscores the potential for sustainable soybean farming practices.

7 Future Directions and Innovations

7.1 Emerging technologies in precision agriculture

Emerging technologies in precision agriculture are revolutionizing the way soybean yield is managed and improved. Sensor-based decision tools, for instance, have shown significant promise in enhancing the physiological performance and water productivity of soybean crops. These tools provide quick assessments of nutritional and physiological health, leading to better crop growth indices and yield improvements (Sachin et al., 2023b). Additionally, the integration of machine learning techniques with multispectral imagery from UAVs has proven effective in accurately predicting soybean yields, offering a robust tool for high-throughput phenotyping and crop field management (Eugenio et al., 2020; Maimaitijiang et al., 2020; Ren et al., 2023). The use of deep learning models, such as self-normalizing neural networks, further enhances yield prediction accuracy, making it a critical component of future precision agriculture practices (Shu, 2020).

7.2 The role of blockchain and IoT in agriculture

Blockchain and the Internet of Things (IoT) are poised to play transformative roles in agriculture. IoT systems, in particular, are expected to significantly increase farm yields by enabling precise monitoring and management of agricultural processes. These systems can track various parameters such as soil moisture, nutrient levels, and crop health in real-time, facilitating data-driven decision-making (Ruan et al., 2019). However, the large-scale application of IoT in agriculture faces challenges, including the need for substantial investment and the technical proficiency of farmers. Addressing these challenges through innovative financing and management solutions will be crucial for the widespread adoption of IoT in agriculture.

7.3 Challenges to widespread adoption of precision agriculture

Despite the promising advancements, several challenges hinder the widespread adoption of precision agriculture. One major challenge is the integration of various data sources and the effective use of this data to make informed decisions. While technologies like GPS and variable rate technology (VRT) have advanced, there is still a gap in the methods and knowledge required to utilize the vast amounts of data generated (Smidt et al., 2016). Additionally, the high initial costs and the need for technical expertise can be barriers for many farmers. Long-term studies have shown that while precision agriculture can reduce temporal yield variation and increase yield stability, the spatial yield variation remains largely unaffected, indicating the need for more refined techniques (Yost et al., 2017).

7.4 Prospects for future soybean yield improvement

The future of soybean yield improvement lies in the integration of advanced technologies and a deeper understanding of crop physiology. Precision breeding, leveraging genome editing and molecular knowledge, offers a promising avenue for developing soybean varieties with enhanced yield potential (Vogel et al., 2021). Furthermore, the use of UAVs and machine learning to monitor and predict crop performance can lead to more precise and efficient farming practices (Eugenio et al., 2020; Maimaitijiang et al., 2020; Ren et al., 2023). The adoption of sensor-based nutrient and irrigation management systems has already shown significant improvements in soybean yield and resource-use efficiency, suggesting that these technologies will play a crucial role in future agricultural practices (Sachin et al., 2023a). By addressing the current challenges and continuing to innovate, the prospects for soybean yield improvement are highly promising.

8 Concluding Remarks

The development of precision agriculture techniques for soybean yield improvement has shown significant promise across various studies. Sensor-based precision nutrient and irrigation management have been demonstrated to enhance physiological performance, water productivity, and yield of soybean crops. For instance, the adoption of sprinkler irrigation at 80% crop evapotranspiration (ETC) combined with precision nutrient management significantly improved photosynthetic characteristics and yield parameters. Additionally, the integration of unmanned aerial vehicle (UAV) platforms with machine learning algorithms has proven effective in accurately estimating soybean yield by combining maturity group information with multi-sensor data. Furthermore, the application of deep learning models, such as the 3D-ResNet-BiLSTM, has shown superior performance in predicting soybean yield at the county level, highlighting the potential of advanced computational techniques in precision agriculture.

The findings from these studies have several practical implications for soybean farmers. Firstly, the use of sensor-based decision tools for nutrient and irrigation management can lead to significant improvements in crop productivity and resource-use efficiency. For example, adopting sprinkler irrigation and precision nutrient management can enhance photosynthetic rates and water-use efficiency, ultimately leading to higher yields. Secondly, the integration of UAV-based remote sensing data with machine learning models can provide farmers with accurate and timely yield predictions, enabling better decision-making and resource allocation. Lastly, the implementation of precision agriculture systems that incorporate physiological principles of crop responses can improve whole-farm yield and profit, as demonstrated in case studies.

In conclusion, the advancement of precision agriculture techniques holds great potential for improving soybean yield and sustainability. The integration of sensor-based management, UAV technology, and machine learning models offers a comprehensive approach to optimizing crop production. Future research should focus on further refining these technologies and exploring their applicability across different agro-ecological regions. Additionally, there is a need for long-term studies to assess the sustainability and economic viability of precision agriculture practices. By continuing to bridge the gap between field-based physiological knowledge and advanced computational techniques, we can unlock new opportunities for enhancing crop productivity and ensuring food security.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Eugenio F., Grohs M., Venancio L., Schuh M., Bottega E., Ruoso R., Schons C., Mallmann C., Badin T., and Fernandes P., 2020, Estimation of soybean yield from machine learning techniques and multispectral RPAS imagery, Remote Sensing Applications: Society and Environment, 20: 100397. https://doi.org/10.1016/j.rsase.2020.100397

Fathi M., Shah-Hosseini R., and Moghimi, A., 2023, 3D-ResNet-BiLSTM model: a deep learning model for county-level soybean yield prediction with time-series Sentinel-1, Sentinel-2 imagery, and daymet data, Remote Sensing, 15(23): 5551. https://doi.org/10.3390/rs15235551

Gai, Y., Rasheed, A., Zhou, Z., Gardiner, J., Ilyas, M., Akram, M., Piwu, W., Gillani, S., Batool, M., and Jian, W., 2021, Role of conventional and molecular techniques in soybean yield and quality improvement: a critical review, Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 49(4): 12555-12555. https://doi.org/10.15835/nbha49412555

Hedley C., 2015, The role of precision agriculture for improved nutrient management on farms, Journal of the Science of Food and Agriculture, 95(1): 12-19. https://doi.org/10.1002/jsfa.6734

Herrero-Huerta M., Rodriguez-Gonzalvez P., and Rainey K., 2020, Yield prediction by machine learning from UAS-based mulit-sensor data fusion in soybean, Plant Methods, 16: 78.
https://doi.org/10.1186/s13007-020-00620-6

Jemo M., Devkota K., Epule T., Chfadi T., Moutiq R., Hafidi M., Silatsa F., and Jibrin J., 2023, Exploring the potential of mapped soil properties, rhizobium inoculation, and phosphorus supplementation for predicting soybean yield in the savanna areas of Nigeria, Frontiers in Plant Science, 14: 1120826.
https://doi.org/10.3389/fpls.2023.1120826

Loures L., Chamizo A., Ferreira P., Loures A., Castanho R., and Panagopoulos T., 2020, Assessing the effectiveness of precision agriculture management systems in mediterranean small farms, Sustainability, 12(9): 3765.
https://doi.org/10.3390/su12093765

Maimaitijiang M., Sagan V., Sidike P., Hartling S., Esposito F., and Fritschi F., 2020, Soybean yield prediction from UAV using multimodal data fusion and deep learning, Remote Sensing of Environment, 237: 111599.
https://doi.org/10.1016/j.rse.2019.111599

Monzon J., Calviño P., Sadras V., Zubiaurre J., and Andrade F., 2018, Precision agriculture based on crop physiological principles improves whole-farm yield and profit: a case study, European Journal of Agronomy, 99: 62-71.
https://doi.org/10.1016/J.EJA.2018.06.011

Ravelombola W., Qin J., Shi A., Song Q., Yuan J., Wang F., Chen P., Yan L., Feng Y., Zhao T., Meng Y., Guan K., Yang C., and Zhang M., 2021, Genome-wide association study and genomic selection for yield and related traits in soybean, PLoS ONE, 16(8): e0255761.
https://doi.org/10.1371/journal.pone.0255761

Ren P., Li H., Han S., Chen R., Yang G., Yang H., Feng H., and Zhao C., 2023, Estimation of soybean yield by combining maturity group information and unmanned aerial vehicle multi-sensor data using machine learning, Remote Sensing, 15(17): 4286.
https://doi.org/10.3390/rs15174286

Ruan J., Wang Y., Chan F., Hu X., Zhao M., Zhu F., Shi B., Shi Y., and Lin F., 2019, A life cycle framework of green iot-based agriculture and its finance, operation, and management issues, IEEE Communications Magazine, 57: 90-96.
https://doi.org/10.1109/MCOM.2019.1800332

Sachin K., Dass A., Dhar S., Rajanna G., Singh T., Sudhishri S., Sannagoudar M., Choudhary A., Kushwaha H., Praveen B., Prasad S., Sharma V., Pooniya V., Krishnan P., Khanna M., Singh R., Varatharajan T., Kumari K., Nithinkumar K., San A., and Devi A., 2023a, Sensor-based precision nutrient and irrigation management enhances the physiological performance, water productivity, and yield of soybean under system of crop intensification, Frontiers in Plant Science, 14: 1282217.
https://doi.org/10.3389/fpls.2023.1282217

Sachin K., Dass A., Dhar S., Rajanna G., Singh T., Sudhishri S., Kushwaha H., and Khanna M., 2023b, Precision nutrient and irrigation management influences the growth, rhizosphere characters and yield of soybean (*Glycine max*) under system of crop intensification, The Indian Journal of Agricultural Sciences, 93(8): 856-861.
https://doi.org/10.56093/ijas.v93i8.136822

Shook J., Gangopadhyay T., Wu L., Ganapathysubramanian B., Sarkar S., and Singh A., 2020, Crop yield prediction integrating genotype and weather variables using deep learning, PLoS ONE, 16(6): e0252402.
https://doi.org/10.1371/journal.pone.0252402

Shu K., 2020, Prediction of soybean yield using self-normalizing neural networks, Proceedings of the 2020 5th International Conference on Machine Learning Technologies, pp.51-55.
https://doi.org/10.1145/3409073.3409092

Skakun S., Kalecinski N., Brown M., Johnson D., Vermote E., Roger J., and Franch B., 2021, Assessing within-field corn and soybean yield variability from WorldView-3, Planet, Sentinel-2, and Landsat 8 satellite imagery, Remote. Sens., 13: 872.
https://doi.org/10.3390/rs13050872

Smidt E., Conley S., Zhu J., and Arriaga F., 2016, Identifying field attributes that predict soybean yield using random forest analysis, Agronomy Journal, 108: 637-646.
https://doi.org/10.2134/AGRONJ2015.0222

Teodoro P., Teodoro L., Baio F., Junior C., Santos R., Ramos A., Pinheiro M., Osco L., Gonçalves W., Carneiro A., Junior J., Pistori H., and Shiratsuchi L., 2021, Predicting days to maturity, plant height, and grain yield in soybean: a machine and deep learning approach using multispectral data, Remote. Sens., 13: 4632.
https://doi.org/10.3390/rs13224632

Vogel J., Liu W., Olhoft P., Crafts-Brandner S., Pennycooke J., and Christiansen N., 2021, Soybean yield formation physiology – a foundation for precision breeding based improvement, Frontiers in Plant Science, 12: 719706.
https://doi.org/10.3389/fpls.2021.719706

Wang Y., 2024, GWAS reveals progress in genes related to rice yield and quality, Rice Genomics and Genetics, 15(2): 48-57.
https://doi.org/10.5376/rgg.2024.15.0006

Xavier A., Jarquín D., Howard R., Ramasubramanian V., Specht J., Graef G., Beavis W., Diers B., Song Q., Cregan P., Nelson R., Nelson R., Mian R., Mian R., Shannon J., McHale L., Wang D., Schapaugh W., Lorenz A., Xu S., Muir W., and Rainey K., 2017, Genome-wide analysis of grain yield stability and environmental interactions in a multiparental soybean population, G3: Genes|Genomes|Genetics, 8: 519-529.
https://doi.org/10.1534/g3.117.300300

Yoosefzadeh-Najafabadi M., Tulpan D., and Eskandari M., 2021, Application of machine learning and genetic optimization algorithms for modeling and optimizing soybean yield using its component traits, PLoS ONE, 16(4): e0250665.
https://doi.org/10.1371/journal.pone.0250665

Yost M., Kitchen N., Sudduth K., Massey R., Sadler E., Drummond S., and Volkmann M., 2019, A long-term precision agriculture system sustains grain profitability, Precision Agriculture, 20: 1177-1198.
https://doi.org/10.1007/s11119-019-09649-7

Zhang M., Hendley P., Drost D., O'Neill M., and Ustin S., 2015, Corn and soybean yield indicators using remotely sensed vegetation index, Precision Agriculture, 1475-1481.
https://doi.org/10.2134/1999.PRECISIONAGPROC4.C49B