

Precision Farming Techniques for Sustainable Rice Production – A Review

A Ramya^{1*}; D.Sarath Kumar²; A. Upendra Rao³; S. Govinda Rao⁴;
B. Rajendra Kumar⁵; K. Hemalatha⁶

¹PG Student, Department of Agronomy, Agricultural College, Naira

^{2,6}Teaching Associate, Department of Agronomy, Agricultural College, Naira

³Senior Professor, Department of Agronomy, Agricultural College, Naira

⁴Assistant Professor, Department of Statistics and Computer Applications, Agricultural College, Naira

⁵Associate Professor, Department of Agronomy, Agricultural College, Naira

*Corresponding Author

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Abstract— Rice (*Oryza sativa* L.) is the primary staple food for a large proportion of the global population, particularly in Asia, where it accounts for nearly 90% of global rice production and consumption. In India, rice has been cultivated on about 46 million hectares. However, productivity and resource-use efficiency remain sub-optimal due to conventional practices characterised by excessive use of fertilisers, water, pesticides and labour, resulting in increased production costs and environmental degradation. Nitrogen use efficiency in rice rarely exceeds 30–40% under blanket fertiliser recommendations, leading to significant nutrient losses and pollution. Precision farming-based site-specific management offers a sustainable alternative by integrating data-driven tools for nutrient, water, weed and crop management. Site-specific nutrient management using tools such as Leaf Colour Chart, SPAD meter, Green Seeker, Nutrient Expert and Rice Crop Manager synchronises nutrient supply with crop demand, reducing nitrogen use by 15–30% while improving grain yield by 10–25%. Precision water management practices, including alternate wetting and drying, sensor-based irrigation and micro irrigation systems, achieve 20–40% savings in irrigation water without yield penalties, while improving water productivity and reducing methane emissions. Precision weed and disease management using sensors, remote sensing and uncrewed aerial vehicles enables early detection and site-specific interventions, resulting in 40–45% reductions in pesticide use with stable yields. Precision mechanisation technologies, such as laser land levelling, mechanised establishment, and autonomous harvesting, further enhance crop uniformity and operational efficiency. Despite adoption constraints related to cost, technical complexity, awareness, and fragmented landholdings, this review highlights precision farming as a sustainable pathway to enhance the productivity, profitability, and environmental sustainability of rice-based systems.

Keywords— Micro-irrigation, Site-specific nutrient management, LCC, SSNM, Productivity.

I. INTRODUCTION

Rice (*Oryza sativa* L.) is a vital food crop worldwide and a staple for more than half of the global population, with Asia as the dominant rice-consuming region. It supplies nearly one-fifth of the global dietary energy and plays an indispensable role in food security, livelihood support and poverty reduction, particularly among small and marginal farming communities (FAO, 2020; Sun et al., 2022). Asia accounts for nearly 90% of global rice production and consumption. At present, India is the world's largest rice producer, cultivating approximately 47 million hectares and producing nearly 158.5 million tonnes of paddy annually, with an average productivity of about 2.9 t ha⁻¹ (GOI, 2023; FAO, 2023). Despite this vast cultivation area, rice yields in several regions remain well below attainable levels due to inefficient resource use, climate-related stresses and escalating input costs. Consequently, achieving sustainable rice production has emerged as a significant global concern.

Traditional rice cultivation systems are predominantly based on continuous flooding, uniform fertiliser schedules, blanket pesticide applications and intensive reliance on manual labour. Such practices have led to inefficient utilization of water, nutrients and energy, resulting in environmental degradation and increased production costs. Flooded rice cultivation requires enormous volumes of water, often ranging from 3000 to 5000 litres to produce one kilogram of grain, which accelerates groundwater depletion and intensifies competition among agricultural, industrial, and domestic water users (IRRI, 2001; Kumar & Ladha, 2011). In addition, poor irrigation management contributes to 40–50% of nonproductive water losses through runoff and percolation, while prolonged flooding enhances methane emissions, raising concerns about the environmental sustainability of rice ecosystems (Belder et al., 2005; Wu et al., 2022).

Efficient nutrient management, particularly nitrogen (N), remains a critical factor influencing rice productivity. Nitrogen is the most limiting nutrient in rice cultivation and is essential for photosynthesis, vegetative growth, tiller formation and grain development (Yoshida et al., 2006; Djaman et al., 2018). However, nitrogen use efficiency in rice systems is typically low, seldom exceeding 30–40%, owing to significant losses through volatilisation, leaching, runoff, and denitrification (Cassman et al., 1998; Nachimuthu et al., 2007). The widespread adoption of blanket fertiliser recommendations fails to address field-level variability in soil fertility and crop demand, often leading to excessive fertiliser use, increased production costs, lodging, pest outbreaks and environmental pollution (Rahman et al., 2007; Djaman et al., 2018). These limitations highlight the importance of adopting need-based and site-specific nutrient management strategies.

In recent years, precision nutrient management tools such as the Leaf Colour Chart (LCC), SPAD chlorophyll meter, Green Seeker and Site-Specific Nutrient Management (SSNM) approaches have gained considerable attention. LCC and SPAD offer rapid, non-destructive and cost-effective methods for monitoring crop nitrogen status under field conditions, enabling better synchronisation between nitrogen supply and crop demand (Peng et al., 1993; Ghosh et al., 2016). Decision-support tools such as Nutrient Expert and Rice Crop Manager (RCM), based on SSNM principles, provide field-specific fertiliser recommendations that have been shown to improve nitrogen use efficiency by 20–30%, enhance grain yield and reduce nutrient losses and greenhouse gas emissions compared with conventional farmer practices (Gupta et al., 2016; Banayo et al., 2018).

The challenges of water scarcity, erratic rainfall patterns and declining groundwater levels have further increased the vulnerability of rice production systems, particularly under climate change scenarios (Mahajan et al., 2012; Chauhan et al., 2014). To mitigate these constraints, several water-saving rice production technologies have been introduced, including alternate wetting and drying (AWD), aerobic rice cultivation, direct-seeded rice (DSR) and micro-irrigation systems. AWD has been reported to reduce irrigation water use by 15–30% without compromising yield and, in some cases, to enhance water productivity compared with conventional continuous flooding (Feng et al., 2007; Tan et al., 2012). Likewise, DSR minimises labour and water requirements, shortens crop duration and lowers greenhouse gas emissions while sustaining yields when managed appropriately (Farooq et al., 2011; Kumar et al., 2018).

Weeds, pests, and diseases are additional significant constraints on rice productivity, especially under direct-seeded and reduced-flooding systems. Conventional uniform pesticide application often results in excessive chemical usage, higher production costs, environmental contamination and the development of pesticide resistance. Precision weed and pest management using UAV-based multispectral and thermal sensors enables early identification of weed infestations, nutrient stress, and disease hotspots, enabling targeted, variable-rate pesticide applications (Mahlein, 2016; Palakuru et al., 2020). Drone-assisted spraying further reduces chemical and water consumption, labour requirements and operator exposure while improving application efficiency and environmental safety (Huang et al., 2021).

Labour shortages and increasing wages have also become serious challenges in rice cultivation, particularly during peak transplanting periods. Manual transplanting is labour-intensive, time-consuming and physically demanding. Precision mechanization technologies such as machine transplanting and laser land levelling have therefore emerged as viable alternatives. Laser land levelling improves field uniformity, enhances irrigation efficiency, reduces water use by 15–30%, and promotes uniform crop establishment and nutrient distribution (Jat et al., 2006; Eid et al., 2014). Machine transplanting substantially reduces labour requirements by as much as 90%, ensuring timely crop establishment and improving overall productivity and profitability (Guru et al., 2018; Ramya et al., 2021).

Recent developments in robotics, automation and digital agriculture are further reshaping rice production systems. Technologies such as unmanned aerial vehicles (UAVs), autonomous sprayers, sensor-based nutrient and water management systems, and artificial intelligence-driven decision-support platforms enable real-time crop monitoring, precise input delivery, and data-driven farm management. These robotic and autonomous technologies improve operational efficiency, reduce human

drudgery, enhance resource-use efficiency, and support climate-resilient, environmentally sustainable rice production (Zhang and Kovacs, 2012; Mahlein, 2016; Wu et al., 2022).

In view of these challenges and opportunities, the integration of precision agriculture technologies encompassing precision water, nutrient, weed, pest, land and mechanization management is essential to overcome the limitations of conventional rice cultivation. This review synthesises recent advances in precision irrigation, site-specific nutrient management, crop establishment techniques, weed and pest management, mechanisation, robotics and digital agriculture in rice systems. It evaluates their potential to enhance productivity, resource-use efficiency, profitability, and environmental sustainability across diverse agro-ecological conditions.

II. COMPONENTS OF PRECISION FARMING

Precision farming in rice production is structured around an integrated set of advanced technologies that enable site-specific and data-driven crop management. These technologies facilitate the management of spatial and temporal variability in soil properties, crop growth and input utilization. The Global Positioning System (GPS) provides accurate geo-referencing of field operations, enabling precise mapping of field boundaries, soil heterogeneity and crop performance. Lee et al. (2023) reported that GPS-based navigation improves operational accuracy in mechanized activities, including harvesting, by minimizing overlap and reducing errors. The Geographic Information System (GIS) further strengthens decision-making by integrating data from field surveys, sensors and remote sensing platforms to generate spatial maps of soil fertility and yield variability. In rice-growing regions, GIS-based soil fertility mapping has been shown to identify intra-field nutrient variability and support location-specific fertiliser recommendations, thereby enhancing resource-use efficiency (Sudha Rani et al., 2014). Remote sensing technologies, including satellite imagery and UAV-based platforms, provide large-scale crop monitoring through vegetation indices and stress detection. Zhou et al. (2023) demonstrated that UAV-based multispectral imaging enables early detection of crop stress and improves yield prediction in rice systems.

Sensor technologies and variable input application further strengthen precision management. Optical sensors such as SPAD meters and Green Seeker are widely used to assess crop nitrogen status and guide fertiliser scheduling. Karthik et al. (2023) reported that sensor-based nitrogen management enhances nutrient-use efficiency and reduces fertiliser losses by synchronizing application with crop demand. Variable Rate Technology (VRT) enables differential application of fertilisers and pesticides within the same field by integrating sensor data, GPS and prescription maps. Krishna et al. (2024) demonstrated that UAV-based variable-rate spraying significantly reduces pesticide use while maintaining effective weed and disease control in rice. Yield monitoring systems integrated with GPS generate spatial yield maps during harvesting, allowing evaluation of field performance and delineation of management zones. Lee et al. (2023) further reported that such yield data supports feedback-based refinement of subsequent crop management strategies. Collectively, the integration of GPS, GIS, remote sensing, sensors, VRT and yield monitoring constitutes the technological foundation of precision rice farming, promoting improved productivity, resource-use efficiency and environmental sustainability.

III. PRECISION LAND LEVELLING AND MECHANIZATION IN RICE

Precision land levelling and mechanization play a vital role in improving resource-use efficiency and productivity in rice cultivation. Laser land levelling enhances field uniformity, optimizes water distribution and reduces irrigation losses, while machine transplanting and combine harvesting minimise labour requirements, ensure timely operations and improve overall crop establishment and profitability.

Laser land levelling has been shown to play a significant role in improving rice growth and yield performance, as reported by Ramya et al. (2021) when compared with conventional and unlevelled field conditions. Under laser-levelled fields, the authors observed improved crop vigour, reflected by higher tiller density (about 320 m⁻²) and greater dry matter accumulation (about 1127 g m⁻²). This enhanced vegetative growth subsequently resulted in superior grain yield (about 4.7 t ha⁻¹) along with increased straw yield (about 3.6 t ha⁻¹). The study clearly indicates that laser land levelling improves field uniformity and resource-use efficiency, thereby contributing to enhanced productivity and sustainability of rice production systems.

El-Soragaby et al. (2019), through a field experiment, reported an effective field capacity of about 0.35–0.65 ha h⁻¹ with total grain losses below 4% under optimized combine harvester operation. The study demonstrated that precision adjustment of operating parameters significantly reduced harvest losses and labour dependence, highlighting combine harvesting as a key precision farming technique for sustainable rice production.

IV. PRECISION NUTRIENT MANAGEMENT IN RICE

Precision nutrient management is a key component of precision farming aimed at improving nutrient use efficiency and productivity in rice systems. It focuses on synchronizing nutrient supply with crop demand by applying fertilisers at the right rate, right time and right place based on soil nutrient status and crop requirements. This approach reduces excess fertiliser use, enhances nutrient uptake and minimizes environmental risks.

The effectiveness of LCC-based nitrogen application under water-saving rice systems was demonstrated by Singh and Chakraborti (2019). LCC-guided nitrogen management reduced nitrogen usage by 50% while achieving nearly 73% higher agronomic nitrogen use efficiency, indicating its potential as a low-cost and farmer-friendly tool. Optimizing nitrogen dose and timing has been shown to improve productivity in semi-dry rice systems. Jhansi Lakshmi Bai et al. (2013) reported higher grain yield (about 4.7 t ha⁻¹) with nitrogen application at about 120 kg ha⁻¹ using split scheduling. The study confirms that split or LCC-based nitrogen application improves nutrient use efficiency and profitability.

SPAD-guided nitrogen application has been shown to optimize nitrogen use and improve yield stability in rice. Venkatesh Babu et al. (2022) reported that optimum nitrogen application (about 120 kg N ha⁻¹) resulted in higher grain yield (about 5.8 t ha⁻¹), while excessive nitrogen reduced productivity. In direct-seeded rice, Karthik et al. (2023) recorded higher nitrogen uptake (about 95–97 kg ha⁻¹) under SPAD-guided fixed and adjustable nitrogen management strategies. These findings highlight SPAD as an effective tool for improving nitrogen uptake without adverse effects on soil properties.

Sensor-guided nitrogen management using Green Seeker has proven effective in improving rice yield and nitrogen efficiency. Sahoo et al. (2022) reported higher grain yield (about 5.7 t ha⁻¹) and improved economic returns under Green Seeker-based nitrogen application compared with blanket fertiliser practices. Billa et al. (2020) observed higher grain yield (about 5.4 t ha⁻¹) under NDVI-guided nitrogen management, along with improved post-harvest soil nitrogen status. These studies demonstrate that Green Seeker effectively synchronizes nitrogen supply with crop demand.

Targeted yield-based fertiliser application using STCR has significantly enhanced rice productivity. Srivastava et al. (2016) reported higher grain yield (about 5.8 t ha⁻¹) under STCR-based fertilization combined with organic manure compared with blanket fertiliser application. The study demonstrates improved fertiliser use efficiency through soil test-based nutrient targeting.

Balanced nutrient management based on nutrient omission studies has been effective in identifying yield-limiting nutrients. Majumder et al. (2024) reported higher grain yield (about 4.9 t ha⁻¹) and improved nutrient uptake with balanced NPK application supplemented with zinc and sulphur. The findings emphasize the importance of correcting secondary and micronutrient deficiencies for sustainable rice production.

Nutrient Expert-guided fertiliser recommendations have shown clear advantages over conventional practices. Sireesha et al. (2022) observed higher grain yield (about 6.3 t ha⁻¹) and improved nutrient uptake under Nutrient Expert-based fertilization compared with recommended dose and farmers' practice. The study highlights Nutrient Expert as an effective SSNM tool for balanced fertilization and yield enhancement in rice.

Rice Crop Manager-based nutrient management has been shown to improve rice productivity under transplanted conditions, as reported by Keerthi et al. (2024), with higher grain yield (about 5.1 t ha⁻¹) and increased nitrogen uptake (about 124 kg ha⁻¹). The study highlights RCM as an effective decision-support tool for improving nutrient use efficiency and profitability. Large-scale on-farm validation by Chaudhary et al. (2024) further demonstrated that RCM-based fertilization increased grain yield by about 17–19% over farmers' practice, with mean yields around 5.0 t ha⁻¹ and reduced phosphorus use. These results confirm the scalability and sustainability of RCM-based SSNM across diverse rice ecosystems.

V. PRECISION WATER MANAGEMENT IN RICE

Precision water management aims to enhance water use efficiency in rice by optimizing the timing, amount and method of irrigation based on crop water demand and field conditions. Techniques such as alternate wetting and drying (AWD), micro-irrigation, sensor-based irrigation and digital decision-support systems reduce water losses while maintaining yield stability. These approaches are increasingly important for sustainable rice production under water-scarce and climate-variable environments.

Improved water productivity under SRI was demonstrated by Singh and Chakraborti (2019), where AWD saved about 30% irrigation water while maintaining higher grain yield (about 5.9 t ha⁻¹) compared with continuous flooding. The practice significantly improved water use efficiency (about 18.5 kg ha⁻¹ mm⁻¹), highlighting AWD as an effective water-saving strategy.

Advanced digital irrigation was evaluated by Zhang et al. (2024) using an intelligent precision irrigation control system integrating satellite, UAV and IoT sensors. The system reduced irrigation water use by about 25% while maintaining grain yield around 7.0 t ha⁻¹ and improving water use efficiency by about 32%. The study highlights the role of data-driven irrigation in large-scale sustainable rice farming.

Integration of micro-irrigation with SRI was shown to enhance water productivity by Kumar et al. (2015). The study reported 27–39% irrigation water saving along with more than 150% improvement in water productivity compared with conventional check basin irrigation, demonstrating the effectiveness of micro-irrigation in rice-based systems.

Precision drip irrigation was evaluated by Goud et al. (2022), where irrigation scheduled at about 1.75–2.0 Epan recorded higher grain yield (about 4.1 t ha⁻¹) and improved economic returns. The study demonstrated that drip irrigation combined with optimum nitrogen enhances water use efficiency and profitability in aerobic rice.

Automated AWD irrigation was studied by Kumar et al. (2023) using IoT-based soil moisture and water-level sensors. AWD at about 5 cm depletion maintained grain yield (about 6.1 t ha⁻¹) while saving around 16% irrigation water and improving water productivity. The approach also reduced methane emissions, indicating both water and climate benefits.

VI. PRECISION WEED MANAGEMENT IN RICE

Precision weed management focuses on site-specific detection and control of weeds to minimise herbicide use while maintaining effective weed suppression. Technologies such as UAV-based spraying, variable-rate application and integrated nutrient-weed management reduce chemical inputs, environmental load and production costs. These approaches are particularly relevant under direct-seeded and reduced-flooding rice systems.

Precision herbicide spraying using drones was demonstrated by Jeevan et al. (2024), where drone-applied herbicides significantly reduced weed density (about 2–3 weeds m⁻²) and weed biomass. The approach minimized nutrient removal by weeds and improved nutrient availability to rice, highlighting the efficiency of drone-based weed control.

The benefits of combining precision nutrient and weed management were reported by Padhan et al. (2021) in direct-seeded upland rice. Nutrient Expert-guided fertilization reduced weed density (about 7 m⁻²) and improved grain yield (about 3.6 t ha⁻¹), while integrated herbicide and hand-weeding achieved superior weed control and productivity.

Site-specific weed control using UAV-based variable-rate spraying was evaluated by Guo et al. (2024). The variable-rate approach reduced herbicide use by about 15% without compromising weed control effectiveness, demonstrating reduced chemical input and environmental load compared with blanket spraying.

VII. ROBOTS' ROLE IN PRECISION MANAGEMENT IN RICE

Robotics and automation are emerging as key components of precision agriculture, addressing labour scarcity and improving operational accuracy in rice production systems. Autonomous machines integrated with GPS, sensors and artificial intelligence enable precise field operations such as harvesting, navigation and weed control. These technologies enhance efficiency, reduce human drudgery and support sustainable and smart rice farming.

Autonomous harvesting using robotic navigation systems has shown promising results in rice fields. Lee et al. (2023) reported that a dual GPS antenna-based autonomous combine harvester achieved high path-tracking accuracy (about 0.04–0.05 m on straight paths) with an operational efficiency of about 77% compared to manual harvesting. The study demonstrated that robotic harvesting can ensure precise field coverage while significantly reducing labour dependence.

Artificial intelligence-driven robotic weed control was effectively demonstrated by Ju et al. (2024) using a deep learning-based adaptive cruise weeding robot. The system achieved high crop detection accuracy (about 90%) and effective weed control (about 82%) with minimal crop injury (about 3%). These results highlight the potential of AI-powered robots for precise, labour-efficient and sustainable weed management in paddy fields.

VIII. CONSTRAINTS AND FUTURE PROSPECTS

The adoption of precision farming technologies in Indian rice systems is constrained by several structural and institutional factors. Predominantly small and fragmented landholdings limit the economic feasibility of high-cost technologies such as UAVs, sensor-based systems and autonomous machinery. High initial capital investment, limited access to credit, inadequate digital infrastructure and poor connectivity in rural areas further impede large-scale implementation. In addition, insufficient technical expertise, limited farmer awareness, lack of localized calibration of decision-support tools and weak extension linkages restrict effective field-level adoption. Variability in agro-climatic conditions and socio-economic disparities also challenge uniform technology dissemination.

Nevertheless, the future prospects remain substantial. Government initiatives promoting digital agriculture, drone subsidies, micro-irrigation expansion and climate-smart agriculture provide an enabling policy environment. Development of cost-effective sensors, mobile-based advisory platforms and region-specific decision-support systems can enhance accessibility for smallholders. Strengthening capacity building, public-private partnerships and adaptive research will be critical to scaling precision rice farming. With appropriate institutional support and technological refinement, precision agriculture has strong potential to improve productivity, resource-use efficiency and sustainability in Indian rice ecosystems.

IX. CONCLUSION

Precision farming offers a sustainable pathway to enhance rice productivity while addressing challenges of water scarcity, low nutrient-use efficiency, labour shortages and environmental degradation. Technologies such as LCC, SPAD, Green Seeker, SSNM tools, AWD irrigation, laser land levelling, UAV-based spraying and robotics enable site-specific, data-driven management of water, nutrients and crop health. These approaches improve yield, resource-use efficiency, profitability and environmental sustainability compared with conventional blanket practices. Although constraints such as high initial costs and technical limitations exist, supportive policies, capacity building and digital infrastructure can accelerate adoption. Overall, precision agriculture represents a transformative strategy for resilient and climate-smart rice production systems.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this research paper.

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