Ecofarming (e-Magazine)
Agriculture
Ecofarming
e-Magazine for Agriculture and Allied Sciences
http://www.ecofarming.rdagriculture.in
e-ISSN: 2583-0791

Smart Agricultural Machinery for Balanced Fertilizer Use and Sustainable Soil Health

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Received: June, 2026; Accepted: June, 2026; Published: July, 2026

Abstract

Balanced fertilizer use is essential for improving crop productivity and maintaining soil health, yet inefficiencies in conventional farming systems result in nitrogen-use efficiency as low as 30–50%. Recent research demonstrates that agricultural machinery such as Happy Seeder, Super Seeder, and precision fertilizer applicators significantly enhance nutrient-use efficiency and soil quality. Studies indicate that residue retention can increase soil organic carbon by 0.1–0.3% and improve nitrogen-use efficiency by 15–25%. Mechanized residue recycling and composting further contribute to nutrient balance by returning essential nutrients to the soil. This article highlights the role of agricultural mechanization in achieving balanced fertilization with strong support from research data.

Keywords: Balanced fertilization, Happy Seeder, Super Seeder, residue management, nutrient efficiency

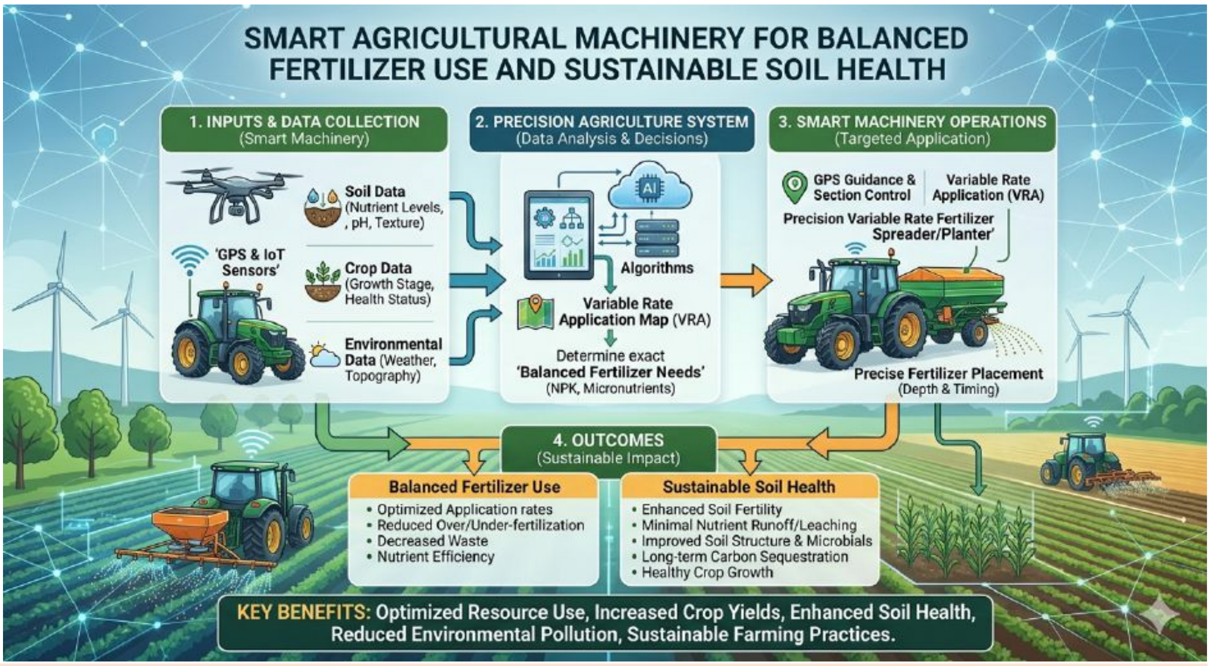

Fig. 1. Conceptual Layout of the Smart Agricultural Machinery for Balanced Fertilizer Use and Sustainable Soil Health

Introduction

Imbalanced fertilizer use has become a critical issue in modern agriculture, particularly in intensive cropping systems such as the rice–wheat system of India. According to the Indian Council of Agricultural Research, nitrogen-use efficiency in conventional agriculture is only about **30–50%,** meaning that nearly half of the applied nitrogen is lost through leaching, volatilization, and denitrification. This not only increases production costs but also contributes to environmental pollution.

In addition, residue burning remains a widespread practice. Research by Gathala et al. (2013) reported that burning one tonne of rice residue leads to the loss of approximately 5.5 kg nitrogen, 2.3 kg phosphorus, 25 kg potassium, and 1.2 kg sulphur, which are essential for crop growth. Continuous burning also reduces soil microbial activity and organic carbon content, leading to long-term soil degradation. These findings clearly highlight the need for balanced fertilization supported by modern agricultural machinery.

Residue burning contributes significantly to air pollution and greenhouse gas emissions. Studies have shown that mechanized residue management reduces greenhouse gas emissions by **15–20%** and improves soil carbon sequestration (Jat et al., 2020). By conserving nutrients and reducing fertilizer losses, agricultural machinery plays an important role in promoting environmentally sustainable farming practices.

Need for Balanced Fertilizer Use

Balanced fertilization ensures that crops receive nutrients in the correct proportion based on soil requirements. Studies on integrated nutrient management (INM) have shown that combining chemical fertilizers with organic sources can increase crop yields by 20–25% compared to conventional farmer practices (Singh et al., 2019). Furthermore, long-term experiments have demonstrated that continuous use of only chemical fertilizers reduces soil organic carbon, whereas integration with organic inputs such as FYM and crop residues increases soil carbon by 0.2–0.4% over time (Ladha et al., 2016). Improved soil organic carbon enhances nutrient retention, microbial activity, and overall soil fertility. Therefore, balanced fertilization is not only essential for productivity but also for sustainability.

Role of Agricultural Machinery in Balanced Fertilizer Use: Happy Seeder Technology: The Happy Seeder is a conservation agriculture machine that allows direct sowing of wheat into rice residues without prior field burning. Research conducted in the Indo-Gangetic Plains by Gathala et al. (2013) showed that Happy Seeder-based systems improved nitrogen-use efficiency by 15–20% and maintained wheat yields at par with conventional tillage systems. A study by Sidhu et al. (2021) further reported that residue retention using Happy Seeder increased soil organic carbon by 0.2% within three years and improved root growth and nutrient uptake. The presence of surface mulch also reduced soil temperature fluctuations and increased soil moisture retention by 10–15%, which positively influenced nutrient availability. These findings clearly demonstrate that Happy Seeder technology supports balanced fertilizer use by conserving nutrients and enhancing their availability to crops.

Super Seeder and Residue Incorporation: The Super Seeder is another important machine that incorporates crop residues into the soil while simultaneously sowing wheat. This process accelerates decomposition and nutrient release. Research by Kumar et al. (2024) reported that Super Seeder-based residue incorporation increased nitrogen uptake by 18–22% and grain yield by 10–12% compared to conventional practices. Additionally, studies by Jat et al. (2020) found that residue incorporation improved soil organic carbon by 0.15–0.25% within 2–3 years and significantly enhanced microbial biomass. Increased microbial activity plays a crucial role in nutrient mineralization, thereby improving fertilizer-use efficiency. Thus, Super Seeder technology contributes to balanced fertilization by recycling nutrients and improving soil biological health.

Conversion of Crop Residues into Farmyard Manure (FYM): Agricultural residues can be effectively converted into farmyard manure (FYM) using mechanized composting technologies such as shredders and compost turners. Research indicates that application of FYM increases soil organic carbon by 0.3–0.5%, improves water-holding capacity by 15–25%, and enhances nutrient-use efficiency by 10–20% (Ladha et al., 2016). Furthermore, Gathala et al. (2013) reported that incorporation of one tonne of crop residue returns about 5–6 kg nitrogen, 2–3 kg phosphorus, and 20–25 kg potassium to the soil. Mechanized composting systems reduce decomposition time by 30–40%, making nutrient recycling more efficient. This clearly shows that machinery-assisted composting plays a vital role in reducing dependency on chemical fertilizers and maintaining nutrient balance.

Precision Fertilizer Application Machinery: Precision agriculture tools such as seed-cum-fertilizer drills, variable-rate applicators, and fertigation systems ensure accurate fertilizer placement. Research by Zhang et al. (2018) demonstrated that precision fertilizer application can reduce fertilizer use by 10–30%, increase nutrient-use efficiency by 15–25%, and improve crop yields by 5–10%. Site-specific nutrient management using GPS-based systems allows farmers to apply fertilizers according to soil variability, preventing over-application and nutrient imbalance. This leads to improved economic returns and reduced environmental impact.

Role of Agricultural Robots in Soil Testing and Precision Fertilizer Application: Agricultural robots are emerging as advanced tools for improving soil testing, prescription map creation, and precise fertilizer application, thereby supporting balanced nutrient management. These robots are equipped with sensors, GPS, and data-processing systems that enable real-time field analysis and decision-making. For soil testing, robotic platforms can automatically collect soil samples at predefined grid points across the field using GPS guidance. This ensures uniform and accurate sampling compared to manual methods. Studies have shown that grid-based robotic soil sampling can improve sampling accuracy by 20–30%, leading to better representation of soil variability (Zhang et al., 2015). The collected samples are analyzed to determine nutrient status, pH, and organic carbon content. Based on this data, prescription maps are generated using Geographic Information Systems (GIS). These maps divide the field into management zones and recommend site-specific fertilizer doses. Research indicates that such site-specific nutrient management can improve fertilizer-use efficiency by 15–25% and reduce input costs (Singh et al., 2019).

Agricultural robots also enable precision fertilizer application through variable-rate technology (VRT). Using prescription maps, robots apply fertilizers only where needed and in the required quantity. This reduces over-application and nutrient losses. Studies report that precision application can reduce fertilizer use by 10–30% while maintaining or increasing crop yield. Thus, robotic technologies enhance the accuracy of soil testing, enable data-driven nutrient management, and ensure efficient fertilizer distribution, contributing to sustainable and balanced fertilization practices.

Role of Biofertilizers in Balanced Fertilizer Use

Biofertilizers are beneficial microorganisms that enhance nutrient availability by fixing atmospheric nitrogen, solubilizing phosphorus, and promoting plant growth. Their integration with chemical fertilizers is essential for achieving balanced fertilization and sustaining soil health. Studies indicate that nitrogen-fixing biofertilizers such as *Rhizobium* and *Azotobacter* can fix 20–40 kg nitrogen per hectare**,** while phosphate-solubilizing bacteria (PSB) can increase phosphorus availability by **15–25%**, thereby improving nutrient-use efficiency (Ladha et al., 2016). Agricultural machinery plays a key role in the effective distribution of biofertilizers. Equipment such as seed-cum-fertilizer drills, slurry applicators, and fertigation systems ensures uniform placement of biofertilizers near the root zone, improving microbial survival and activity. Research shows that proper placement through mechanized application can enhance biofertilizer efficiency by **10–15%** compared to manual broadcasting (Singh et al., 2019). In addition, residue management and composting supported by machinery increase soil microbial biomass by **15–25%,** which accelerates nutrient cycling and improves soil fertility (Jat et al., 2020). Thus, integrating biofertilizers with mechanized application methods supports balanced nutrient management, improves soil health, and reduces dependence on chemical fertilizers.

Conclusion

Scientific evidence clearly indicates that agricultural machinery plays a transformative role in achieving balanced fertilizer use. Technologies such as Happy Seeder, Super Seeder, composting systems and precision applicators significantly improve nutrient-use efficiency (up to **25%**), enhance soil organic carbon, and increase crop productivity. Adoption of these technologies, along with integrated nutrient management practices, is essential for sustainable agriculture and long-term soil health.

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