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Precession Agriculture: Farming Smarter, Not Harder

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The rapidly growing global population, coupled with declining per-capita agricultural land availability, is placing unprecedented pressure on agricultural systems to increase food production. However, growth in agricultural productivity is staggered at on place, while the intensive use of external inputs such as fertilizers, herbicides, pesticides, and irrigation water continues to increase and also escalating environmental degradation including soil health decline, water pollution, and greenhouse gas emissions. This imbalance highlights the need for more efficient and sustainable agricultural production systems that can produce more food from limited land and resources while minimizing environmental impacts. Precession agriculture can be the possible solution.

Precision agriculture is a management approach that leverages spatial and temporal variability within a field to optimize the use of agricultural inputs; ensuring that resources such as water, fertilizer, and seed are applied in the right amount, at the right place, and at the right time. The origins of precision agriculture can be traced back to 1929, when first grid-based soil sampling method to systematically address within-field variability. The technology took a major practical leap forward in 1988, with the introduction of the first commercial variable-rate fertilizer applicator, allowing farmers to vary input rates across a field for the first time. This was followed in 2002 by the commercialization of the Green Seeker™ sensor, which enabled real-time, on-the-go variable-rate nitrogen application based on live crop reflectance readings (Franzen & Mulla, 2015). A big turning point came in 1993-94, when GPS was made available for civilian and farm use. This allowed farmers and machines to know their exact location in a field, making it possible to apply inputs precisely where needed. Precision agriculture in India is still in its early stages. Most of the work so far has focused on using nutrients and water more efficiently, rather than being a fully integrated farming practice. Some low-cost tools have worked well, such as ICAR-NRRI's Customized Leaf Colour Chart, which helps farmers apply nitrogen better in rice, and the Tamil Nadu Precision Farming Project (2004–05), which helped spread drip irrigation among high-value crop farmers. The government has mainly supported water-related technologies, through schemes like the National Mission on Micro Irrigation (2010) and the BGREI program, which funds laser land levelling. In addition, 22 Precision Farming Development Centres across the country help test and share these technologies, especially for high-tech horticulture (Gupta *et al*., 2021). Given this evolving landscape, there is a need to consolidate current scientific understanding of precision agriculture; its core technologies, demonstrated benefits for nutrient and water management, and the specific challenges to its adoption in resource-constrained and smallholder-dominated systems such as India's. This review aims to synthesize existing literature on precision agriculture technologies, their application in nutrient and water management, and the opportunities and barriers to their wider adoption in the Indian context.

Core technologies of precession agriculture:

PA is not a single technology but a stack of interoperating tools that together enable site-specific management.

GNSS and geospatial mapping: GPS (GNSS) helps farmers and machines know exactly where they are in a field. But normal GPS is only accurate to about 10-15 meters, which is not precise enough when we need to treat small areas differently. To fix this, two better systems were developed Differential GPS (DGPS) and Real-Time Kinematic GPS (RTK-GPS). DGPS uses signals from fixed ground stations to correct GPS errors, bringing accuracy down to about 1-3 meters. RTK-GPS is even more accurate, using real-time correction to get down to just 1-2 centimeters. This high level of accuracy is what allows machines to steer themselves, apply inputs at the right spot, and return to the exact same location in the field season after season making precise, site-specific farming possible.

Remote sensing and proximal sensing: Remote sensing detects spatial variability in a field without physical contact, using sensors on ground, aerial, or satellite platforms; ground-based ones are called proximal sensors. These sensors are either multispectral (a few broad bands like red, green, blue, near-infrared) or hyperspectral (hundreds of narrow, continuous bands, offering finer detail at the cost of more data and processing). Sensor readings are converted into vegetation indices, formulas combining band values to highlight crop or soil traits. NDVI (from red and near-infrared) indicates crop greenness and nitrogen status; SAVI corrects for soil background in sparse canopies; and NDRE is better suited for denser canopies where NDVI saturates (Barnes *et al*., 2000). These indices turn raw sensor data into practical, field-level indicators of crop health and nutrient needs. A UAV remote sensing study on winter wheat (Zhai *et al*., 2025) tested irrigation (0-150 mm) and nitrogen (0-330 kg/ha) levels, finding yield plateaued beyond 120 mm and 225 kg N/ha. NDVI saturated at high input levels, while a texture index (Contrast) stayed sensitive, better capturing canopy variation. The optimal treatment achieved 1.28 kg/m³ irrigation-water-use efficiency and 13.33 kg/kg agronomic nitrogen efficiency. Hossain *et al*. (2025) compared a proximal soil sensor (FarmLab) with lab-based (KCl extraction) methods for measuring soil nitrogen, nitrate, and moisture across two fields. FarmLab significantly overestimated nitrate and mineral nitrogen versus lab values ($p < 0.05$), with notable disagreement in one field (limits of agreement: 17.40 to 29.66 mg kg^{-1}), while soil moisture readings matched closely. They then tested 11 data-fusion combinations of sensor, lab, satellite, and topographic data using k-means clustering to delineate nitrogen management zones. Molitor *et al*. (2025) found that task-agnostic satellite features (RCFs) predicted temporal yield anomalies in Zambian maize far better than NDVI (R^2 = 0.74 vs. 0.39), as NDVI showed strong bias, over-predicting low-yield years.

Variable rate technology (VRT): VRT lets a machine automatically vary the rate of seed, fertilizer, or crop-protection product applied as it moves across a field, guided by prescription maps built from yield history, soil sampling, or real-time sensor data. Hagn *et al*. (2025) tested sensor-based variable-rate nitrogen application against uniform application in winter wheat over four years (2020–2023) on 49 hectares of heterogeneous fields in Germany. Using a tractor-mounted sensor combined with a site-specific yield potential map, the variable-rate approach cut nitrogen fertilizer use by up to 38 kg N/ha/year without a corresponding yield loss. Site-specific seeding trials in maize found optimal seeding density ranged from 44,000 - 104,000 seeds/ha depending on soil quality, with variable-rate seeding modelled to increase farm income by up to USD 12/ha over uniform seeding (Kumar *et al*., 2022). However, other studies have found seeding-rate VRT is not always profitable, showing its value depends heavily on how much a field's soil conditions actually vary.

IoT, cloud computing, and AI/ML: A growing share of recent PA research integrates networked sensors with cloud-based analytics and machine learning to automate decision-making, including automation, computer vision, and robotics for crop monitoring, disease detection, and yield prediction.

Challenges

Despite its demonstrated benefits, several challenges continue to limit the widespread adoption of precision agriculture and variable rate technologies, particularly in developing and smallholder-dominated regions like India. The most significant barrier is the high initial investment required for GPS-guided equipment, sensors, drones, and rate controllers, which often puts these tools out of reach for small and marginal farmers. This problem is compounded in countries like India, where the majority of farms are fragmented and under two hectares in size, making it difficult to justify the fixed cost of expensive equipment when it cannot be spread across a large area.

Beyond cost, limited digital literacy and technical skill present a further obstacle, since operating GPS systems, interpreting sensor data, and managing farm software all require a level of technical familiarity that many rural farmers have not yet developed. This is made worse by poor rural infrastructure inconsistent internet connectivity, unreliable electricity, and limited access to repair and maintenance services all restrict the practical use of cloud-connected sensors and real-time data systems in many areas.

Even where technology is accessible, precision agriculture generates large volumes of spatial and temporal data; soil maps, yield maps, and sensor readings and translating this data into clear, actionable, field-ready decisions remains difficult even for well-resourced farms. Compounding this, the economic returns from precision technologies are not guaranteed: as seen with variable-rate seeding, profitability depends heavily on the degree of within-field variability, meaning the same technology can be highly profitable on one farm and uneconomical on another.

A further challenge is that many precision agriculture tools, algorithms, and sensor calibrations were originally developed for temperate, large-scale farming systems such as the U.S. Midwest or Europe, and may not directly translate to tropical, smallholder conditions without local validation. Finally, compared to countries with mature precision agriculture ecosystems, government support in the form of subsidies, custom-hiring centres, and farmer training programs remains limited in many developing regions, slowing the transfer of these technologies from research institutions to actual farms.

Future prospectus

Looking ahead, falling costs of sensors, drones, and computing are narrowing the gap between precision tools and smallholder farming, with shared-access models like custom-hiring centres and cooperatives helping extend access. AI and machine learning are expected to simplify complex sensor data into actionable recommendations, while data fusion (combining satellite, proximal sensor, and topographic data) improves reliability over single-source methods. Nano-enabled fertilizers like nano urea offer a complementary path to improving nutrient efficiency without requiring costly VRT machinery. Ultimately, translating research gains into field-level impact will depend as much on policy support, rural infrastructure, and local validation as on the technology itself.

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