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PRECISION AGRONOMY FOR RICE PRODUCTION: INTEGRATING SOIL FERTILITY MAPPING, REMOTE SENSING, OPTIMIZED NITROGEN MANAGEMENT, AND WATER-SAVING IRRIGATION IN PAKISTAN

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Abstract

Rice (Oryza sativa L.) is the second most critical staple food and export commodity in Pakistan, cultivated on 2.50–2.74 million hectares with annual production of 6.00–6.80 million metric tons. However, the sector faces severe challenges from flood-irrigated systems consuming 2,500–5,000 liters of water per kilogram of paddy, widespread soil degradation characterized by low organic matter (<1.0%), alkaline pH (7.28–8.23), and extensive nutrient deficiencies. Conventional uniform fertilizer applications result in nitrogen losses of 40–50% and poor nutrient use efficiency (10–20 kg grain kg^{-1} N). This review synthesizes precision agronomy strategies integrating geostatistical soil fertility mapping, remote sensing, site-specific nitrogen management (SSNM), and water-saving irrigation for Pakistani rice systems. Geostatistical interpolation using Ordinary Kriging delineates management zones based on spatial variability, with zinc deficiency affecting over 47% of agricultural land. Remote sensing via Sentinel-2 red-edge bands and UAV hyperspectral imagery coupled with machine learning enables accurate nitrogen stress detection (R^2 > 0.85). SSNM using Leaf Color Chart and SPAD meters saves 27.5–75 kg N ha^{-1} while maintaining yields. Alternate Wetting and Drying reduces irrigation water use by 20–44%, increases water productivity by 38.7–50%,

and decreases methane emissions by 30–70%. Direct Seeded Rice saves 20–35% water and reduces labor by 60%. Synergistic integration of these technologies offers a pathway to enhance productivity, optimize resource use, and bolster climate resilience in Pakistani paddy production, though land fragmentation, limited extension capacity, and unequal water access remain adoption barriers requiring coordinated policy interventions.

INTRODUCTION

Rice (*Oryza sativa* L.) serves as a cornerstone of global food security and represents the second most critical staple food and export commodity in Pakistan. Occupying an estimated cultivated area between 2.50 and 2.74 million hectares, national paddy production consistently averages between 6.00 and 6.80 million metric tons annually (Ramzan et al., 2026). The sector generates substantial foreign exchange, with annual exports reaching up to 6.55 million metric tons, while contributing approximately 3.1% to the value added in agriculture and 0.6% to 1.6% to Pakistan's Gross Domestic Product (GDP) (Islam et al., 2026).

The rice-growing landscape of Pakistan is geographically and ecologically bifurcated into distinct production zones. The traditional "Kallar Tract" encompassing the agro-climatic districts of Sheikhupura, Gujranwala, Hafizabad, Sialkot, Narowal, Nankana Sahib, Jhang, and Okara in northern and central Punjab is globally celebrated for fine, highly aromatic Basmati rice production (Shahid et al., 2022). Fine Basmati varieties constitute roughly 40% of the total national output. Conversely, lower Punjab and the fertile alluvial plains of Sindh specialize in coarse and high-yielding hybrid rice varieties (e.g., IRRI and modern commercial hybrids), which account for the remaining 60% of total output (Lakhiar et al., 2024).

Despite its economic significance, the Pakistani rice sector faces severe threats from environmental and management constraints. Paddy production relies on flood-irrigated systems, which consume excessive volumes of fresh water requiring between 2,500 and 5,000 liters of water to produce a single kilogram of paddy rice. Concurrently, widespread soil degradation, characterized by low soil organic matter (SOM < 1.0%), high surface alkalinity (pH 7.28–8.23), and extensive macronutrient and micronutrient deficiencies, limits crop yields (Bwambale et al., 2022).

These edaphic constraints are compounded by conventional farm management practices that apply fertilizers uniformly across spatially heterogeneous fields, resulting in low Nutrient Use Efficiency (NUE), elevated input costs, and environmental pollution (Akbar et al., 2025). Transitioning from uniform blanket management to precision agronomy integrating geostatistical soil mapping, remote sensing monitoring, real-time site-specific nitrogen management (SSNM), and water-saving irrigation regimes presents a pathway to enhance crop productivity, optimize resource use, and bolster climate resilience in Pakistani paddy production (Ali et al., 2025).

2. Soil Fertility Mapping and Spatial Heterogeneity in Pakistani Paddy Fields

Understanding field-scale spatial variability in soil physicochemical properties is fundamental to operationalizing site-specific crop management. Paddy soils across the primary rice belts of Punjab and Sindh exhibit distinct morphological, physical, and chemical heterogeneity driven by parent alluvial materials, changing river hydrology, and long-term land management practices (Nabi et al., 2018).

Laboratory characterizations across major rice-producing districts such as Shaheed Benazirabad in Sindh and grid-sampled tracts in Punjab reveal that paddy soils range from sandy loam to clay loam textures, with loam and silt loam dominating the central alluvial basins. The inherent soil reaction across these agro-ecosystems is predominantly slightly to strongly alkaline, with pH values ranging between 7.28 and 8.23 (mean pH ~7.75) (Yousra et al., 2025). This sustained alkalinity is reinforced by indigenous calcareous parent material, low rainfall, and high evapotranspiration rates. Electrical conductivity (EC) readings generally remain under 4.0 dS m^{-1} in non-saline rice fields, though localized hyper-saline pockets ($EC > 4.0$ dS m^{-1}) frequently emerge in lower Sindh talukas such as Kazi Ahmed and Daur (Masood et al., 2012).

Soil Organic Matter (SOM) content across Pakistani paddy fields is low, rarely exceeding 1.0% (typical range: 0.17% to 1.51%, mean ~0.73%). The high ambient temperatures accelerate the mineralization of

organic carbon, limiting natural SOM accumulation. Consequently, over 90% of Pakistani agricultural soils display acute deficiencies in plant-available mineral Nitrogen ($NO_3^- - N$ and $NH_4^+ - N$) and extractable Phosphorus (P) (Ahmad et al., 2017). Available P is rapidly fixed into insoluble calcium phosphate complexes due to high soil pH and calcareousness. Conversely, plant-available Potassium (K) levels are generally adequate to rich across Punjab's rice belt due to the dominance of potassium-bearing mica minerals in the sand, silt, and clay fractions, although eroded, light-textured sandy soils remain susceptible to K depletion (Kousar et al., 2025).

Micronutrient dynamics in Pakistani paddy fields are governed by pH-dependent availability and organo-metal complexation. Zinc (Zn) deficiency is the most widespread micro-nutritional disorder, with bioavailable DTPA-extractable Zn falling below critical thresholds (< 0.5 to 1.0 mg kg^{-1}) in more than 47% of the national agricultural land area (Fayyaz et al., 2025). Zinc availability is restricted by alkaline pH, low organic matter, high soil bicarbonate concentrations under submerged conditions, and persistent heavy application of P fertilizers. Boron (B) and Copper (Cu) display moderate to high spatial variability, with localized deficiencies emerging in lighter-textured soils, whereas Iron (Fe) and Manganese (Mn) levels generally remain adequate due to reductive dissolution under continuous flooding regimes (Khan et al., 2014).

To move away from traditional uniform fertilizer recommendations, geographic information systems (GIS) and global positioning systems (GPS) are employed to map soil nutrient variability. Geostatistical techniques rely on spatial interpolation methods, primarily Ordinary Kriging (OK) and Inverse Distance Weighted (IDW) interpolation, executed on georeferenced grid-sampling schemes (e.g., 50 m $\times$ 50 m or 1-acre composite sampling grids at 0–20 cm soil depth) (Ameer et al., 2022).

The spatial dependency of soil variables is quantified through semi-variogram analysis using the nugget-to-sill ratio:

$$\text{Nugget Ratio (\%)} = \left(\frac{C_0}{C_0 + C}\right) \times 100$$

Where C_0 represents the nugget variance (measurement error and micro-scale variation) and $C_0 + C$ represents the total sill (total spatial variance). A ratio below 25% indicates strong spatial dependence, 25% to 75% signifies moderate spatial dependence, and above 75% indicates weak spatial dependence (Zia et al., 2021).

Soil properties such as pH, EC, SOM, available N, and available P typically demonstrate moderate spatial dependence (30%–50% nugget ratio), reflecting the combined influence of intrinsic parent material and extrinsic management factors (e.g., tillage, continuous cropping, uneven irrigation). Available K and bioavailable Zn frequently display strong spatial dependence ($< 25\%$ nugget ratio) in surface soils (Khan et al., 2021). Micronutrients exhibit high coefficients of variation (CV $> 35\%$), following the variability hierarchy Zn $>$ Fe $>$ Mn $>$ Cu. Digital fertility mapping using Ordinary Kriging converts discrete soil test data into continuous spatial surfaces, delineating Management Zones (MZs) that serve as the foundational input for variable-rate fertilizer applicators to match nutrient supply with spatial soil demand (Li et al., 2021).

Table 1: Soil Fertility Status and Spatial Heterogeneity Characteristics in Pakistani Rice Belts

Soil Parameter	Measurement Unit / Method	Baseline Range (Pakistani Paddy Soils)	Coefficient of Variation (CV %)	Spatial Dependence Level	Primary Agronomic Drivers / Constraints
Soil Texture	Hydrometer Method	Sandy Loam to Silt Clay Loam	Moderate (18 - 28%)	Moderate	Influences percolation, water holding capacity, and cation exchange.
Soil pH	1:2 Soil-Water Suspension	7.28 - 8.23 (Mean: 7.75)	Low (< 15%)	Moderate	High alkalinity reduces P and Zn solubility; driven

					by calcareous parent material.
Electrical Conductivity (EC)	1:2 Suspension Meter	0.07 - 0.47 dS m^{-1} (Up to > 4.0 in pockets)	High (> 35%)	Moderate to Strong	Non-saline overall, but hyper-saline patches impair root uptake in lower Sindh.
Soil Organic Matter (SOM)	Walkley-Black Carbon %	0.17 - 1.51 % (Mean: 0.73 %)	Moderate (20 - 32%)	Moderate	Rapid thermal oxidation leads to persistent organic carbon depletion.
Available Nitrogen ($NO_3^- - N$)	Kjeldahl / AB-DTPA Extract	1.37 - 18.74 mg kg^{-1} (Mean: 7.89)	Moderate (25 - 35%)	Moderate	Acute deficiency (> 90% soils); susceptible to volatilization and leaching.
Available Phosphorus (P)	AB-DTPA / Olsen Extract	Low (< 5.0 - 8.0 mg kg^{-1})	Moderate (22 - 34%)	Moderate	High P-fixation into insoluble Ca-P complexes due to alkaline pH.
Available Potassium (K)	AB-DTPA / Ammonium Acetate	Moderate to High (> 120 mg kg^{-1})	Low to Moderate	Strong	Indigenous sufficiency supported by K-bearing mica in clay/silt fractions.
Bioavailable Zinc (DTPA-Zn)	AB-DTPA / Atomic Absorption	0.008 - 8.12 mg kg^{-1} (Mean: 0.83)	High (> 35 - 55%)	Strong	Widespread deficiency (47% of land area) due to alkaline pH and high P.

3. Remote Sensing and Sensor-Based Crop Health Monitoring

Integrating satellite remote sensing and Unmanned Aerial Vehicles (UAVs) provides a mechanism for real-time monitoring of rice canopy growth, chlorophyll content, and nitrogen stress across spatial and temporal scales (Omia et al., 2023).

Spaceborne optical remote sensing platforms such as the European Space Agency's Sentinel-2 (Multispectral Instrument, MSI) and NASA/USGS Landsat-8/9 (Operational Land Imager, OLI) offer free, high-temporal-resolution data suitable for regional crop monitoring. Sentinel-2's inclusion of strategic "Red-Edge" spectral bands (Band 5 at 705 nm, Band 6 at 740 nm, and Band 7 at 783 nm) enables high sensitivity to canopy chlorophyll variations while mitigating signal saturation at dense leaf area index (LAI) stages (Khanal et al., 2020). To complement satellite observations, low-altitude UAVs equipped with multispectral or hyperspectral sensors provide millimeter-to-centimeter spatial resolution. UAV platforms eliminate cloud cover interference a frequent issue during the summer monsoon season in Punjab and Sindh and allow targeted imaging during key phenological stages, such as active tillering, panicle initiation, and flowering (Sajib & Sayem, 2025).

Remote sensing quantifies crop health by tracking leaf optical properties. Nitrogen is a structural component of plant chlorophyll molecules; leaf N status directly governs light absorption in the blue (450 nm) and red (670 nm) regions and light scattering in the near-infrared (NIR, 750–900 nm) spectrum (Li et al., 2020).

Key Spectral Vegetation Indices (SVIs) used to assess rice physiological status include:

- **Normalized Difference Vegetation Index (NDVI):**

$$\text{NDVI} = \frac{\rho_{\text{NIR}} - \rho_{\text{Red}}}{\rho_{\text{NIR}} + \rho_{\text{Red}}}$$

Tracks canopy coverage and biomass accumulation, though it saturates when LAI exceeds 3.0.

- **Normalized Difference Red Edge Index (NDRE):**

$$\text{NDRE} = \frac{\rho_{\text{NIR}} - \rho_{\text{RedEdge}}}{\rho_{\text{NIR}} + \rho_{\text{RedEdge}}}$$

Replaces the standard red band with the red-edge wavelength (705–740 nm), penetrating deeper into dense rice canopies to assess leaf nitrogen concentration.

- **Enhanced Vegetation Index (EVI):**

$$\text{EVI} = 2.5 \times \frac{\rho_{\text{NIR}} - \rho_{\text{Red}}}{\rho_{\text{NIR}} + 6 \cdot \rho_{\text{Red}} - 7.5 \cdot \rho_{\text{Blue}} + 1}$$

Adjusts for atmospheric interactions and soil background reflectance during early vegetative stages prior to full canopy closure (Shukla et al., 2023).

Integrating UAV hyperspectral imagery with machine learning regressors such as Random Forest (RF), Support Vector Machines (SVM), and Partial Least Squares Regression (PLSR) allows accurate mapping of leaf nitrogen concentration ($R^2 > 0.85$, RMSE $< 0.25\%$ N). Coupling satellite-derived NDRE time-series data with machine learning algorithms translates canopy reflectance maps directly into variable-rate nitrogen prescription maps, allowing growers to address N stress across broad spatial extents (Chaudhari et al., 2022).

4. Real-Time Site-Specific Nitrogen Management (SSNM)

Synthetic nitrogen (N) fertilizer applications represent a primary operational input in Pakistani rice production. However, conventional N fertilizer practices suffer from poor Agronomic Efficiency. Farmers typically apply fixed-rate, calendar-based N split applications (e.g., broadcasting urea in two or three bulk doses) without assessing the actual plant dynamic demand or native soil supply capacity (Sarma et al., 2024).

Under flooded or poorly drained rice environments, blanket broadcasting of urea results in significant nitrogen losses ranging from 40% to 50% of total applied N. The primary loss pathways include ammonia volatilization (NH_3), which is exacerbated by alkaline soil pH (> 7.5) and elevated water temperatures in flooded fields; denitrification (N_2O and N_2), driven by anaerobic soil conditions (Ray et al., 2026). Where facultative anaerobic microbes reduce nitrate (NO_3^-) into gaseous oxides; and leaching (NO_3^-), where high downward percolation in sandy loam textures carries mobile nitrate beyond the active root zone (> 20 cm). These losses depress Agronomic Nitrogen Use Efficiency (NUE_a), which frequently ranges between 10 and 20 kg grain per kg N under fixed scheduling, compared to optimal values of > 25–30 kg kg^{-1} (Fan et al., 2007).

Site-Specific Nitrogen Management (SSNM) uses diagnostic tools to align fertilizer timing and rates with seasonal plant demand. The Leaf Color Chart (LCC) is an inexpensive, non-destructive plastic strip containing standardized color panels ranging from yellowish-green (panel 1 or 2, indicating severe N deficiency) to dark green (panel 5 or 6, indicating excessive N saturation) (Ali, 2020). Local innovations, such as the customized mirror-backed LCC ("Nitrom") developed in Sindh, enable smallholder farmers to evaluate leaf chlorophyll content under field conditions. LCC readings are taken weekly starting at 14–21 days after transplanting (DAT) on the topmost fully expanded leaf. When the average LCC score drops below critical threshold values LCC 4 for fine Basmati varieties or LCC 5 for high-yielding coarse/hybrid varieties a split dose of 25–30 kg N ha^{-1} is applied (Patel et al., 2023).

Optical chlorophyll meters (e.g., SPAD-502) quantify relative leaf chlorophyll concentration by measuring light absorbance at two wavelengths (650 nm, red, absorbed by chlorophyll; and 940 nm, infrared, non-absorbed reference). SPAD readings correlate positively with total leaf nitrogen content ($r = 0.82$–0.94).

Maintaining a critical SPAD threshold value of 37 to 37.5 guides timely N top-dressing (Pratyusha et al., 2023). Field trial evaluation shows that SPAD-guided management saves between 27.5 and 47.5 kg N ha^{-1} compared to fixed-timing applications (150 kg N ha^{-1} in 3 splits) while matching or increasing total grain yield. In addition, active canopy sensors (e.g., GreenSeeker, Crop Circle) emit light pulses in the red and NIR spectrums to compute real-time NDVI or NDRE values, which are processed through algorithmic models to apply variable-rate nitrogen via synchronized tractor-mounted applicators (Akhil et al., 2025).

Adopting real-time SSNM using LCC or SPAD tools alters agronomic parameters, including Partial Factor Productivity of Nitrogen (PFP_N), Nitrogen Recovery Efficiency (RE_N), and overall grain yield. The mathematical metrics for evaluating NUE parameters include:

$$PFP_N = \frac{Y_N}{F_N}$$

$$NUE_a = \frac{Y_N - Y_0}{F_N}$$

$$RE_N = \left(\frac{U_N - U_0}{F_N}\right) \times 100$$

Where Y_N is the grain yield under N fertilization (kg ha^{-1}), Y_0 is the unfertilized control yield (kg ha^{-1}), F_N is the quantity of synthetic N fertilizer applied (kg ha^{-1}), U_N is total plant N uptake in fertilized plots (kg ha^{-1}), and U_0 is total plant N uptake in control plots (kg ha^{-1}) (Nandeppagari et al., 2025).

Table 2: Comparative Evaluation of Nitrogen Management Strategies in Rice Production

Management Strategy	Total Seasonal N Applied (kg ha−1)	Diagnostic Tool & Applied Threshold	Average Paddy Yield (t ha−1)	Total N Saved vs Fixed Schedule (kg ha−1)	PFPN (kg grain kg−1 N)	Environmental & Economic Output
Conventional Fixed-Timing Split	120 - 150	Calendar dates; 3 equal splits; no sensor input	4.17	0.0 (Reference)	27.8 - 34.75	High ammonia volatilization and leaching loss; low FUE.
LCC-Guided SSNM (Critical LCC 4)	95 - 110	Leaf Color Chart; top-dress when color score < 4.0 [cite: 22, 23]	4.65 - 4.82	20.0 - 42.5	42.2 - 50.7	Reduced production cost; enhanced agronomic efficiency.
LCC-Guided SSNM (Critical LCC 5)	100 - 120	Leaf Color Chart; top-dress when color score < 5.0 [cite: 22, 23]	4.78 - 4.90	15.0 - 30.0	39.8 - 49.0	Recommended regime for high-yielding hybrids in Sindh.
SPAD-Meter SSNM (Critical SPAD 35)	60 - 75	SPAD-502 Chlorophyll Meter; threshold	4.25 - 4.38	60.0 - 75.0	58.0 - 71.3	High N saving, but slightly under-fertilizes high-density crops.

		score < 35.0 [cite: 23]				
SPAD-Meter SSNM (Critical SPAD 37)	72.5 - 90	SPAD-502 Chlorophyll Meter; threshold score < 37.0 [cite: 23]	4.95	27.5 - 47.5	55.0 - 68.2	Yield enhancement; optimal balance between NUE and sink capacity.

5. Water-Saving Irrigation Practices and Climate-Smart Water Productivity

The agricultural sector in Pakistan faces growing water scarcity, driven by reduced river flows, groundwater depletion, and climate variability. Traditional rice farming relies on Continuous Flooding (CF), maintaining a continuous standing water depth of 5–10 cm throughout the growing season, which leads to large unproductive losses via deep percolation, surface runoff, and evaporation (Kumar et al., 2023).

Alternate Wetting and Drying (AWD) is a management practice designed to reduce irrigation water inputs without inducing crop water stress. Under AWD, the rice field is allowed to dry out for several days following irrigation before water is re-applied. The depth of the perched water table below the soil surface is monitored using a field water tube consisting of a 30-cm long perforated PVC pipe with a 10–15 cm diameter, buried 20 cm into the soil (Sikka et al., 2020). Water is re-applied to a depth of ~5 cm whenever the water level inside the field tube drops to 15 cm below the soil surface (15 cm threshold), corresponding to a soil matric potential of -10 to -20 kPa in the root zone (Frimpong et al., 2023). However, continuous flooding (2–5 cm) is maintained strictly during the flowering and heading windows (1 week before to 2 weeks after flowering) to prevent spikelet sterility and potential yield penalties. Field empirical data across Sindh and Punjab demonstrate that AWD intervention reduces seasonal irrigation water usage by 20% to 44% (and up to 49.78% under controlled conditions) compared to continuous flooding (Adimassu et al., 2025).

Contrary to concerns that soil drying degrades crop yields, moderate AWD induces favorable physiological acclimations. Periodic soil drying encourages deeper root penetration into lower soil strata (> 20 cm), increasing root oxidation activity, root dry weight, and total root length compared to anaerobic continuous flooding (Oiganji et al., 2025). Furthermore, AWD promotes early non-productive tiller death while boosting effective productive tillers per hill (increasing tiller density by up to 261% relative to CF during vegetative recovery). Paddy yield increases by 5% to 17.06% under AWD compared to CF due to higher photosynthetic rates during grain filling, elevated harvest index (HI), improved 1000-grain weight, and reduced lodging risk from stronger root anchorage. Milling quality is also improved, showing lower grain breakage percentages (down to 6.7%–9.7%) and higher head rice recovery rates (Sikka et al., 2018).

Direct Seeded Rice (DSR) represents another key water-saving technology, replacing labor-intensive manual transplanting of seedlings into puddled fields. Dry DSR involves drilling seeds directly into non-puddled, field-moist soil using zero-till seed drills or tractor-drawn seeders. DSR eliminates puddling operations, saving approximately 20% to 35% of total irrigation water, decreasing labor requirements by 60%, and cutting production costs (Bwire et al., 2024). Sowing DSR early allows timely harvest of the rice crop, facilitating early land preparation for the subsequent wheat crop within the Punjab rice-wheat rotation. However, profuse weed infestation remains a primary constraint in DSR systems, requiring integrated weed management strategies (Anand et al., 2025).

Crop Water Productivity or Water Use Efficiency (WUE) is defined as:

$$\mathrm{WUE} = \frac{Y}{\mathrm{WU}}$$

Where WUE is expressed in t ha^{-1} cm^{-1} or kg m^{-3}, Y represents grain yield (t ha^{-1} or kg ha^{-1}), and WU is total water consumption (cm or m^3 ha^{-1}), combining applied irrigation (IR) and effective rainfall

(ER). Under AWD regimes, WUE increases by 38.7% to 50% relative to continuously flooded systems (Zhuang et al., 2024).

From an environmental standpoint, water-saving irrigation alters paddy soil biogeochemistry. Continuous flooding creates prolonged anaerobic conditions that favor methanogenic archaea, making flooded rice fields a key source of atmospheric methane (CH_4). Periodic aeration under AWD introduces oxygen into the soil matrix, suppressing methanogenesis and reducing seasonal CH_4 emissions by 30% to 70% (Zhang et al., 2021). However, alternating oxidation-reduction cycles stimulate nitrifying and denitrifying bacterial pathways, which can increase nitrous oxide (N_2O) emissions. This trade-off requires combining AWD water management with optimized SSNM to limit residual soil nitrate accumulation and minimize overall Global Warming Potential (GWP) (Wu et al., 2015).

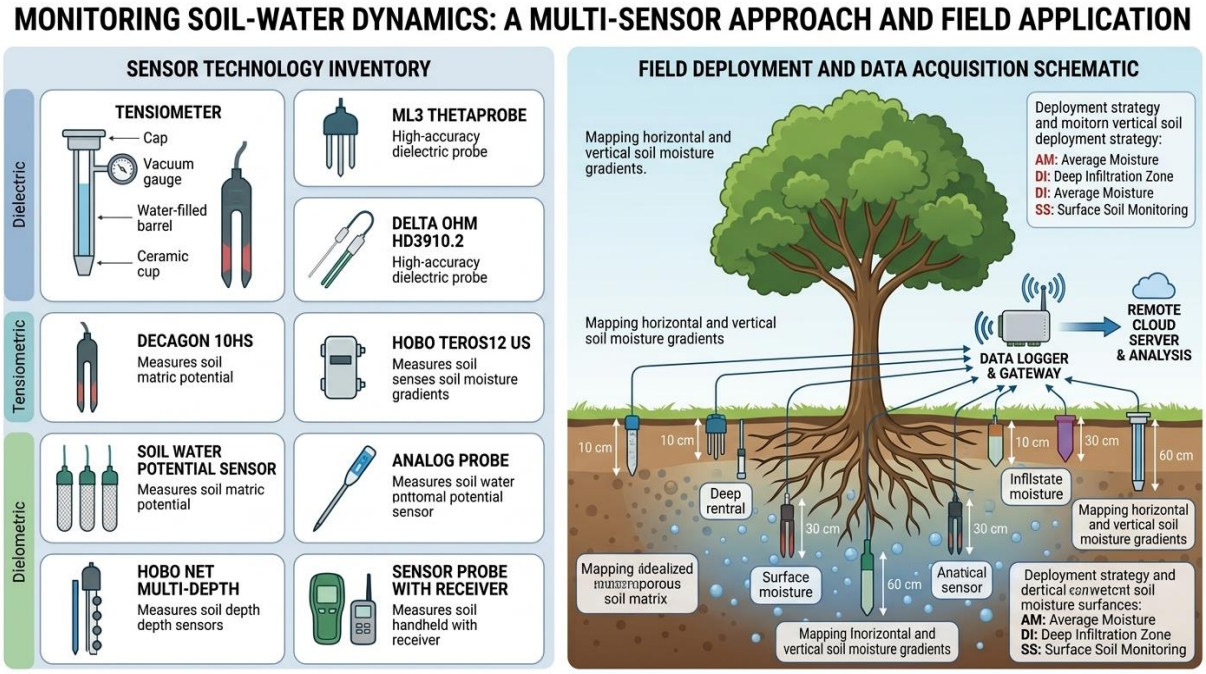


Figure 1: Multi-Sensor Inventory and Field Deployment Schematic for Monitoring In-Situ Soil Moisture Dynamics and Matric Potential Gradients in Rice Agro-Ecosystems

Table 3: Performance Comparison of Irrigation Techniques in Pakistani Rice Agro-Ecosystems

Agronomic & Hydrological Parameter	Continuous Flooding (CF)	Alternate Wetting and Drying (AWD)	Direct Seeded Rice (DSR)	Agronomic Mechanism & Primary Benefits
Seasonal Water Use (cm / m^3 ha^{-1})	High (1200 – 1800 mm)	Reduced (750 – 1100 mm)	Lowest (700 – 1000 mm)	AWD saves 20–44% water; DSR eliminates puddling water inputs.
Average Paddy Yield (t ha^{-1})	5.34 - 6.50	6.04 - 7.78 (+5% to +17%)	4.80 - 5.80	Enhanced photosynthetic rate, harvest index, and root oxidation capacity.
Water Productivity (WUE)	Baseline (0.35 – 0.50 kg m^{-3})	High (+38.7% to + 50%)	Elevated (+30% to + 45%)	Maximizes grain output per unit of freshwater consumed.
Root Growth & Lodging Resistance	Shallow, degraded roots; high lodging risk	Deep root extension; high oxidation	Moderate root depth; variable anchorage	Aeration cycles promote root

				elongation and soil structural stability.
Methane (CH_4) Emissions	Elevated (Primary agricultural source)	Substantially reduced (30 - 70% decrease)	Moderately low (Shorter flood duration)	Aerobic periods inhibit soil methanogenic archaea.
Nitrous Oxide (N_2O) Risk	Negligible to Low	Moderate to High (Requires SSNM)	Variable (Depends on dry/wet cycles)	Aeration triggers nitrification-denitrification sequence.
Primary Operational Challenges	Severe water wastage; high pumping energy	Field tube monitoring; weed management	Weed pressure; seed germination establishment	Needs farmer training for precise water level monitoring.

6. Synergistic Integration, Challenges, and Policy Perspectives

Combining site-specific diagnostic management tools into a unified platform yields compounded agronomic and environmental benefits. Combining GIS geostatistical fertility maps, remote sensing monitoring, LCC/SPAD-guided real-time N management, and AWD water management forms a precision agronomy model suited for Pakistan's agro-ecosystems (Velander, 2025).

Applying AWD irrigation enhances root zone oxygenation, which improves root structural health and accelerates nitrogen uptake. Supplying N based on LCC/SPAD dynamic thresholds prevents excess nitrate from accumulating in soil solution during drying cycles, mitigating potential N_2O emission spikes. Concurrently, digital soil mapping and remote sensing enable targeted variable-rate applications of micronutrients (such as Zn and B) and N top-dressings across broad regional scales (Parrilli & Lu, 2026).

Despite these performance benefits, large-scale adoption of precision agronomy across Pakistan faces institutional, economic, and technical challenges. Land fragmentation is a major impediment, as over 73.3% of rice farmers in traditional belts hold small farms (< 5 hectares), making the upfront costs of diagnostic tools (such as SPAD meters, active canopy sensors, and UAV services) prohibitive for individual purchase (Kosow ET AL., 2022). Furthermore, agricultural extension services often lack the training and capacity needed to assist farmers in interpreting geostatistical maps, operating remote sensing platforms, or using LCC thresholds. Unequal access to canal water particularly at the tail-ends of distributaries prompts farmers to over-irrigate during their turns rather than adhering to scheduled AWD drying cycles. Additionally, direct-seeded rice systems face high weed competition, and limited availability of selective post-emergence herbicides limits adoption among resource-poor farmers (Botah, 2023).

To transition Pakistani rice agriculture toward precision management, synchronized policy interventions are recommended. Government initiatives, such as the *Kisaan Card*, can be leveraged to subsidize water-saving infrastructure (e.g., laser land leveling, AWD field tubes) and site-specific nutrient tools (LCCs, zero-till DSR drills). Establishing public-private service-provider models allows local agricultural entrepreneurs to offer UAV imaging, field mapping, and custom variable-rate application services to smallholders on a per-acre basis (Larsen et al., 2012). Technology transfer should also align with regional breeding programs, protecting Basmati geographical indication (GI) status in the Kallar Tract while directing high-yielding hybrid varieties toward Sindh. Finally, incorporating AWD and precision SSNM into Pakistan's Nationally Determined Contributions (NDCs) under the Paris Agreement can secure international carbon market financing to incentivize farmers to adopt methane-reducing technologies (Nordbeck & Steurer, 2016).

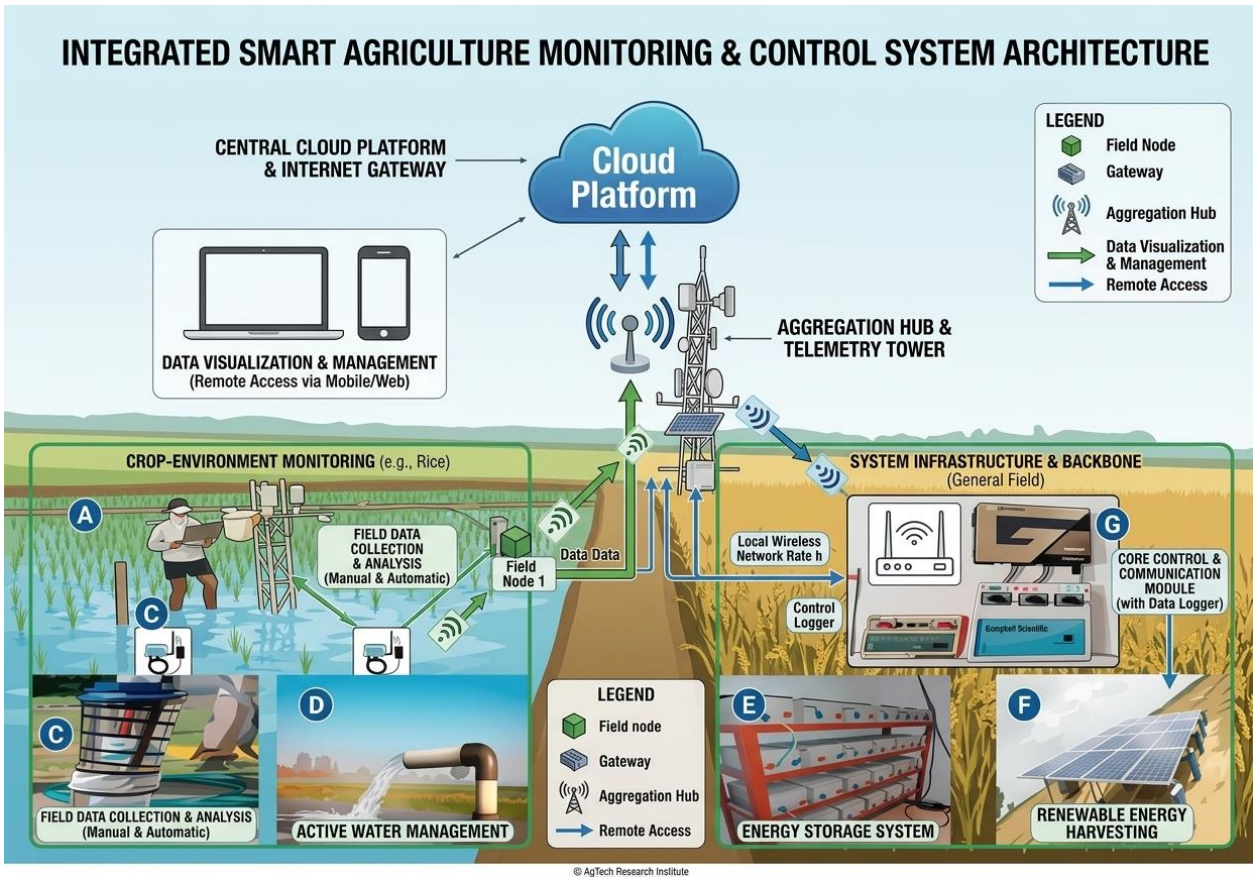


Figure 2: Architectural Framework of an Integrated Smart Agriculture System Combining Field-Level Environmental Monitoring, Telemetry Towers, Renewable Energy Harvesting, and Cloud-Based Remote Access

Conclusion

This review demonstrates that transitioning from conventional uniform management to integrated precision agronomy offers a transformative pathway for sustainable rice production in Pakistan. The synthesis of geostatistical soil fertility mapping, remote sensing-based crop monitoring, real-time site-specific nitrogen management, and water-saving irrigation technologies addresses the interconnected challenges of soil degradation, inefficient nutrient use, and escalating water scarcity facing Pakistani paddy systems. Geostatistical mapping using Ordinary Kriging effectively quantifies spatial heterogeneity in soil properties, with pH, electrical conductivity, organic matter, and available nutrients exhibiting moderate spatial dependence (30–50% nugget ratio), while potassium and zinc show strong spatial dependence (<25% nugget ratio). These digital fertility maps enable delineation of management zones for variable-rate fertilizer applications, particularly critical for addressing widespread zinc deficiency affecting 47% of agricultural land and phosphorus fixation in calcareous soils. Remote sensing technologies, including Sentinel-2 red-edge bands and UAV-based hyperspectral imaging coupled with machine learning algorithms, provide accurate, real-time assessment of rice canopy nitrogen status ($R^2 > 0.85$, RMSE < 0.25% N). Vegetation indices such as NDRE penetrate dense canopies to assess leaf nitrogen concentration, enabling translation of canopy reflectance data into variable-rate nitrogen prescription maps. Site-specific nitrogen management using Leaf Color Chart and SPAD meters significantly improves nitrogen use efficiency. LCC-guided SSNM saves 20–42.5 kg N ha^{-1} while increasing yields to 4.65–4.90 t ha^{-1}, with PFPN reaching 42.2–50.7 kg grain kg^{-1} N. SPAD-guided management at critical threshold 37 achieves optimal balance between nitrogen savings (27.5–47.5 kg N ha^{-1}) and yield enhancement (4.95 t ha^{-1}). Water-saving irrigation practices demonstrate substantial benefits. Alternate Wetting and Drying reduces seasonal water use by 20–44%, increases water productivity by 38.7–50%, and enhances yields by 5–17% through improved root development, higher harvest index, and reduced lodging. AWD also

reduces methane emissions by 30–70% by suppressing methanogenic archaea through periodic soil aeration. Direct Seeded Rice offers additional water savings of 20–35% and labor reduction of 60%, though weed management remains a constraint. The synergistic integration of these technologies creates compounded benefits: AWD enhances root zone oxygenation improving nitrogen uptake, while SSNM prevents excess nitrate accumulation during drying cycles, mitigating nitrous oxide emission spikes. Digital soil mapping enables targeted micronutrient applications across regional scales. However, large-scale adoption faces significant barriers including land fragmentation (73.3% of farmers hold <5 hectares), limited extension capacity for interpreting geostatistical maps and operating sensors, unequal canal water access prompting over-irrigation, and weed management challenges in DSR systems. Policy interventions recommended include leveraging Kisaan Card subsidies for water-saving infrastructure and precision tools, establishing public-private service-provider models for UAV imaging and variable-rate application services, aligning technology transfer with regional breeding programs to protect Basmati geographical indication status, and incorporating AWD and precision SSNM into Pakistan's Nationally Determined Contributions to secure international carbon market financing. Future research should focus on validating these technologies across diverse agro-ecological zones, developing affordable sensor technologies for smallholders, building local capacity for data interpretation and decision support, and creating integrated precision agronomy platforms that synthesize soil, crop, and water management components into actionable recommendations for Pakistani rice farmers.

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