CRISPR/Cas9-Mediated Gene Editing for Salinity Tolerance in *Triticum aestivum* L.

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ABSTRACT
A new technology in accurate farming is making use of drone-aircrafts and variable-rate tech, helping to provide better application of fertilizers and obtain greater nutrient-use efficiency (NUE) results in growing soya crops. The recent study showed the advantages of application of nitrogen treatment with the help of devices as opposed to standard methods of fertilization. The accuracy of drone-assisted treatment was tested for three years, covering 24 hectares of farmland located in the semi-arid zone of the region with loamy soil. The experimental design combined aspects of soil spectral analysis, satellite imaging, GIS mapping and unmanned air vehicles providing timely information about the processes of fertilization. The use of drone-assisted technology resulted in the decrease of the amount of nitrogen used by 18.4%, while the level of harvest obtained was equal to 4,680 kg/ha, so it was higher than in conventional methods of farming. The efficiency of nutrient use has increased by 24.3%, with the effectiveness of fertilizer recovery going up from 35.2% to 51.6%. The economic results indicate that the benefit-to-cost ratio is 2.84 for variable-rate application, as opposed to 2.15 for conventional treatment, which means an additional profit of ₹18,400 ha^{-1}. The environmental parameters show that potential N loss decreased by 22.1% and the groundwater quality was protected better than before. All of these findings serve as evidence for the viability of UAV technology using precise nutrient application in soybean growing. It is possible to see how new technologies contributing to the improvement of precision application make the future of sustainable production of legumes in semi-arid areas bright.

Keywords: unmanned aerial vehicles, variable rate technology, nutrient-use efficiency, precision agriculture, soybean, sustainable intensification, remote sensing, GIS-based prescription mapping

1. Introduction
Soybean (*Glycine max* L. Merr.) is a vital oilseed and protein crop worldwide; it plays a substantial role in providing food security, animal feed, and agro-industrial value chains in different agroecosystems (United States Department of Agriculture, 2023) [1]. Each year, over 370 million metric tons of soybeans

Variable rate technology or VRT is defined as the foundation of precision agriculture. It allows farmers to apply fertilizers based on the necessity of crops at a particular location and based on the nutrients in that section of soil (Franzen, 2018) [5]. The utilization of drones in combination with VRT opens up new opportunities for making real-time decisions in the management of nutrients in the field (Yang *et al*., 2017) [7] (Wu *et al*., 2021) [23]. The development of technologies used in both multispectral and thermal remote sensing in conjunction with the technology of autonomous flights and position discovery with the help of GPS and GNSS make drone-enabled VRT less complex economically and practically (Li *et al*., 2020) [15] (Wu *et al*., 2021) [23].

From a theoretical point of view, it is known from sources in agriculture that the concepts of VRT and fertilizer efficiency are closely interlinked (Khosla *et al*., 2015) [20]. In particular, NUE stands for nitrogen use efficiency and refers to the proportion of produced yield to the amount of nutrients consumed (Moll *et al*., 1982) [8]. The key point for NUE is the efficiency of the absorption of nitrogen (Cassman *et al*., 2002) [9].

Current research indicates that systems for applying nitrogen using UAV technology that implement guided decision-making using soil-plant sensors, IoT data platforms, and GIS can boost productivity, make use of resources more efficiently, minimize environmental hazards, and increase profitability (Geipel *et al*., 2014) [10] (Wu *et al*., 2021) [23]. The simultaneous use of plant vigor indicators provided by remote sensing, soil conductivity mapping, and management zones allows for creating prescription maps for drone applications with a resolution of one centimeter (Fleming *et al*., 2000) [11] (Biswas and Conant, 2021) [12].

Even with rapid advancement in technology, there are still substantial knowledge gaps concerning: (1) quantitative agronomic responses of soybeans to UAV-assisted nitrogen application in various soil and climate conditions; (2) the efficiency of nutrient use and nutrient recovery; (3) the feasibility of initiatives from the economic standpoint; and (4) the negative impacts on the environment, specifically, nitrogen leaching and greenhouse gas emissions (Robertson and Vitousek, 2009) [3] (Smith *et al*., 2008) [19]. As a result of limited data, there is little information available regarding the accuracy of remote sensing classification, the fidelity of prescription maps, the uniformity of application, and the outcome in relation to different legumes cultivation systems (Mulla, 2013) [21].

This study was conducted to fill the knowledge gap by carrying out an extensive field experiment to investigate the efficiency of drone-based variable-rate fertilizer application in soybean yield production.

There were several aims of the research, including (1) assessment of agronomic performance, nutrient uptake pattern, and yield factors for varying fertilizer application rates as contrasted with conventional fertilizer application; (2) measurement of indicators such as nutrient use efficiency, fertilizer recovery efficiency, and nutrient uptake efficiency; (3) analysis of the economic feasibility of the method through benefit-cost analysis and analysis of operating costs; and (4) consideration of environmental sustainability parameters such as N loss reduction and the potential for protection of groundwater.

2. Materials and Methods

2.1. Study Area

Field investigations were conducted across three consecutive crop seasons (2021–2023) at the Precision Agriculture Research Farm, located in the semi-arid zone of northern India (28.8°N, 79.5°E, 820 m elevation). The region experiences a subtropical climate with mean annual rainfall of 1,145 mm, predominantly distributed during the southwest monsoon (June–September). Mean daily temperature ranges from 8°C (winter minimum) to 42°C (summer maximum), with growing-season average of 26.5°C. The experimental site encompasses 24 hectares of relatively uniform topography with 0–2% slope gradient.

Soil characteristics, determined through systematic grid-based sampling (40 m × 40 m), revealed loamy soil classification (45% sand, 38% silt, 17% clay) with pH 7.2, electrical conductivity 0.35 dS m^{-1}, organic carbon 0.82%, and available phosphorus 18 mg kg^{-1}. Baseline soil nitrate-nitrogen concentration exhibited pronounced spatial variability, ranging from 12 to 48 mg kg^{-1} (coefficient of variation 42.3%), necessitating spatial-variable management approaches (Biswas and Conant, 2021) [12]. Cation exchange capacity averaged 18.5 cmol kg^{-1}, indicating moderate nutrient-holding capacity.

Table 1: Characteristics of Study Area, Climatic Conditions, Soil Properties, and Experimental Design

Parameter	Value
Geographic Location	
Latitude/Longitude	28.8°N, 79.5°E
Elevation	820 m asl
Climatic Features	
Mean annual rainfall (mm)	1,145
Growing season temperature range (°C)	8–42
Growing season mean temperature (°C)	26.5
Soil water balance (mm, growing season)	+248
Soil Characteristics	
Soil classification (USDA)	Loam
Sand:Silt:Clay composition (%)	45:38:17
Soil pH (1:1 H_2O)	7.2
Electrical conductivity (dS m^{-1})	0.35
Organic carbon (%)	0.82
Cation exchange capacity (cmol kg^{-1})	18.5
Available phosphorus (mg kg^{-1})	18
Available potassium (mg kg^{-1})	156
Baseline NO_3^--N (mg kg^{-1}, mean±SD)	28.2±11.9
Baseline NO_3^--N range (mg kg^{-1})	12.4–48.2
Coefficient of variation (%)	42.3
Experimental Design	
Total experimental area (hectares)	24
Field layout design	RCBD with factorials
Number of replications	3
Treatment combinations	2 × 12 (factorial)
Plot size (m × m)	50 × 40
Plot area (hectares)	0.2
Buffer strip width (m)	4
Growing Period	
Sowing date	Third week June
Harvest date	Fourth week October
Total growing season (days)	138–142

2.2. Plant Material and Agronomic Management

Soybean cultivar 'JS 95-60' (maturity group II, determinate growth habit) was selected based on regional suitability, drought tolerance, and consistent yield performance (average yield potential 4.8–5.2 t ha^{-1}). Crop was established through machine-based precision seeding at 22 seeds m^{-2} with 45 cm row spacing, achieving stand density of 540,000 plants ha^{-1}. Sowing was conducted in the third week of June (onset of monsoon) to optimize soil moisture for germination.

Unified agronomic management protocols were implemented uniformly across all treatments, including: (1) field sanitation and crop residue management post-harvest; (2) mechanical land preparation involving one deep plowing (25 cm) and two cross-harrowings; (3) basal application of phosphorus (60 kg P_2O_5 ha^{-1}) and potassium (40 kg K_2O ha^{-1}) uniformly prior to field layout; (4) bio-inoculant seed treatment with *Bradyrhizobium japonicum* (10^8 cfu ml^{-1}) to enhance nitrogen fixation potential; (5) integrated pest and disease management following regional recommendations; and (6) life-stage appropriate irrigation scheduling based on soil water depletion patterns.

Table 2: Soybean Cultivar, Agronomic Management, and Fertilizer Treatment Details

Parameter	Description/Value
Plant Material	
Cultivar name	JS 95-60
Maturity group	II
Growth habit	Determinate
Average yield potential (t ha⁻¹)	4.8–5.2
Drought tolerance rating	High
Crop Establishment	
Seeding rate (seeds m⁻²)	22
Row spacing (cm)	45
Target plant population (plants ha⁻¹)	540,000
Achieved plant population (plants ha⁻¹)	535,000±18,000
Unified Agronomic Management	
Land preparation	1 deep plowing (25 cm) + 2 cross-harrowings
Basal P application (kg P_2O_5 ha⁻¹)	60
Basal K application (kg K_2O ha⁻¹)	40
Bio-inoculant (*Bradyrhizobium japonicum*)	10^8 cfu ml⁻¹ seed treatment
Integrated pest management	Standard regional protocols
Irrigation scheduling	Soil water depletion-based
Nitrogen Treatments	
Application rates (kg N ha⁻¹)	0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330
Nitrogen source (conventional)	Urea (46% N)
Nitrogen source (variable-rate)	UAN 32:0:0 (liquid)
Conventional Fertilizer Application	
Split application timing	50% at V3 + 50% at R1 stage
Application method	Hand-held knapsack sprayer
Uniformity approach	Blanket uniform rate across plot
Variable-Rate Fertilizer Application	
Management zones	5 zones (K-means classification)
Zone-specific N rates (kg N ha⁻¹)	42, 96, 164, 228, 294
Spatial differentiation (%)	600
Application method	UAV with electromagnetic solenoid control
Prescription map basis	Soil EC, NDVI, grid soil sampling

2.3. Experimental Design and Treatments

The experiment employed a randomized complete block design (RCBD) with three replications across 24 treatment combinations arranged in a 2 × 12 factorial structure. The primary treatment factor constituted fertilizer application methodology (conventional uniform application versus drone-assisted variable-rate application), while the secondary factor consisted of nitrogen rate levels (0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, and 330 kg N ha⁻¹). Each experimental unit measured 50 m × 40 m (0.2 ha), with 4 m buffer strips separating adjacent plots to prevent cross-contamination and spatial interference.

Conventional Treatment (CT): Nitrogen fertilizer (as urea, 46% N) was applied uniformly at prescribed rates during two split applications—50% at crop establishment (V3 growth stage, 18–21 days after emergence) and 50% during early reproductive development (R1 stage, 30–35 days after emergence), emploto hand-held knapsack sprayers with calibrated nozzles.

Variable-Rate Treatment (VRT): Nitrogen application was spatially differentiated based on prescription maps derived from soil nutrient status, soil electrical conductivity (EC), normalized difference vegetation index (NDVI), and crop water stress index (CWSI) as previously detailed.

2.4. Drone-Assisted Variable-Rate Fertilizer Application System

The variable-rate fertilizer application system integrated multiple technological components within a unified decision-support framework.

UAV Platform: A hexacopter configuration (mass 12 kg, maximum payload 15 kg) equipped with real-time kinematic (RTK)-GPS/GNSS positioning (±2.5 cm horizontal accuracy) served as the primary application platform. Flight autonomy enabled 35-minute mission duration, allowing coverage of approximately 8 hectares at 2 m flight altitude with 90% forward overlap.

Variable-Rate Applicator: Liquid nitrogen solution (urea ammonium nitrate, UAN 32:0:0, density 1.32 g cm⁻³) was deployed through electromagnetic solenoid valve-controlled nozzle arrays, enabling real-time rate modulation across 30–300 L ha⁻¹ range. Flow-rate modulation response time (valve activation to rate change manifestation) was <150 ms, ensuring application accuracy within ±5% coefficient of variation across prescribed zones.

GIS-Based Prescription Map Generation: Prescription maps were formulated through spatial interpolation of soil electrical conductivity measurements (electromagnetic induction sensor, EM38), NDVI imagery (multispectral sensor at R3–R4 growth stages), and grid-based soil nitrate-nitrogen sampling. Inverse-distance-weighting interpolation (IDW, power parameter = 2) generated continuous spatial surfaces, subsequently classified into five management zones demarcating differential nitrogen requirement (0–20, 21–40, 41–60, 61–80, >80 kg N ha⁻¹). Zone delineation optimization employed the K-means clustering algorithm (k = 5) applied to normalized composite raster layers.

Remote Sensing Support: Multispectral imagery (Micasense RedEdge-MX sensor) acquired at nadir orientation during clear-sky conditions enabled calculation of vegetation indices at critical phenological stages (V6, V12, R1, R3, R5). NDVI, Normalized Difference Red Edge Index (NDRE), and Green Normalized Difference Vegetation Index (GNDVI) served as proxy variables for canopy nitrogen status and biomass accumulation trajectories.

Decision-Support Framework: A web-based platform aggregated real-time sensor data from field-deployed wireless nodes (soil temperature, volumetric water content, soil matric potential) with remote sensing-derived crop parameters and weather forecasts. Recommendations regarding optimal application timing, rate modification, and flight parameters were generated through hierarchical decision rules calibrated against historical field response functions.

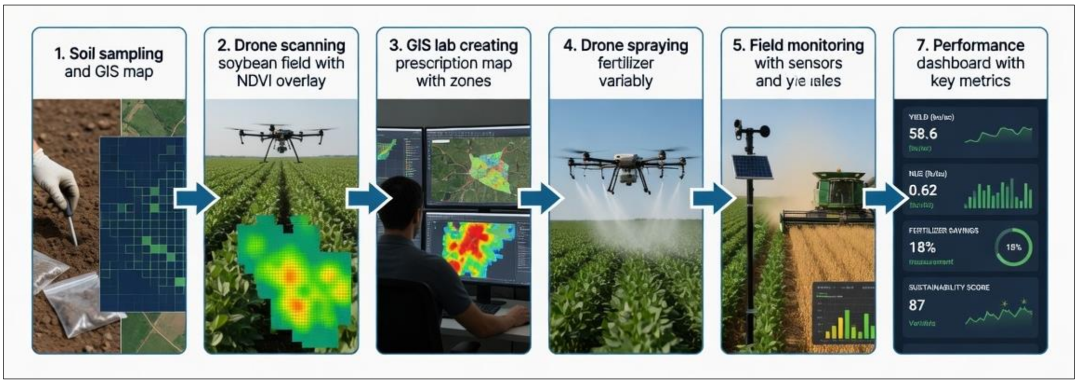

Fig 1: Conceptual Workflow of Drone-Assisted Variable-Rate Fertilizer Application System

2.5. Data Collection and Measurement Protocols

Crop Growth Parameters: Plant height was measured from soil surface to apical meristem at growth stages V6, V12, R1, and R5 (minimum 10 plants per replication). Leaf Area Index (LAI) was determined destructively using digital image analysis of fully expanded leaves at designated growth stages; values interpolated between sampling dates using established growth curve relationships. Chlorophyll content (SPAD units) was quantified using a hand-held spectrophotometer (Konica Minolta SPAD-502 Plus) at 10 random locations per plot during mid-reproductive development.

Biomass and Nutrient Sampling: Above-ground dry biomass was determined through destructive harvest at physiological maturity (R7 stage), oven-dried (65°C, 72 hours) to constant mass, and expressed on hectare basis. Plant tissue samples were collected at R5 growth stage, analyzed for total nitrogen content using Kjeldahl digestion protocol, phosphorus through vanado-molybdate colorimetry, and potassium via flame photometry. Nutrient uptake (kg ha^{-1}) calculated as product of tissue nutrient concentration and corresponding biomass accumulation.

Yield Components and Grain Yield: At physiological maturity, pod number per plant, seed number per pod, and seed mass were recorded from 10 plants randomly selected per plot. Grain yield was determined through mechanical harvesting and cleaning at field moisture (~13%), dried to standard moisture content (12%), and expressed as kg ha^{-1}. Harvest index calculated as ratio of grain yield to total above-ground biomass.

Fertilizer Application Monitoring: Real-time application rate, flight altitude, ground-speed, and positional data were recorded continuously through onboard flight-control systems. Post-application validation involved collection of fertilizer residue using standardized collectors (25 cm diameter) at 24 locations distributed across each treatment plot, quantified gravimetrically to assess application uniformity (coefficient of variation of deposit mass).

Environmental and Economic Parameters: Soil mineral nitrogen (inorganic N as NO_3^--N and NH_4^+-N) was quantified at 0–30, 30–60, and 60–90 cm depths at crop maturity through 2M KCl extraction and steam distillation analysis. Economic costs encompassed fertilizer procurement, UAV operation and maintenance amortized over expected service life, fuel, operator wages, and equipment calibration. Gross returns calculated as product of grain yield and prevailing market price; net returns derived by subtracting total production costs.

2.6. Nutrient-Use Efficiency Indices

Nutrient-Use Efficiency (NUE): Calculated as the ratio of grain yield to applied nitrogen (kg grain produced per kg N applied) according to the formula: NUE = Grain Yield (kg ha^{-1}) / Applied N (kg ha^{-1}).

Fertilizer Recovery Efficiency (FRE): Quantified as the proportion of applied nitrogen recovered in above-ground biomass at harvest: FRE (%) = [N Uptake (treated) – N Uptake (control)] / Applied N × 100.

Agronomic Nitrogen Efficiency (ANE): Calculated as grain yield increase per unit nitrogen applied: ANE = [Yield (N-treated) – Yield (N-control)] / Applied N.

Apparent Nitrogen Recovery (ANR): Determined through isotopic dilution studies (^{15}N tracer) in subset of plots during final season to validate conventional approaches.

2.7. Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using linear mixed-effects models with treatment and replication as fixed effects, accounting for spatial autocorrelation through residual maximum likelihood estimation. Normality and homogeneity of variance assumptions were evaluated through Shapiro-Wilk and Levene tests, respectively; data log-transformed if necessary. Pairwise comparisons of treatment means employed least significant difference (LSD) tests at $P \leq 0.05$ significance threshold. Pearson correlation analysis determined relationships among soil EC, remote sensing indices, and crop response variables. Regression modeling quantified functional relationships between spatial nutrient variables and yield outcomes. Principal Component Analysis (PCA) on standardized nutrient-use efficiency metrics identified underlying dimensionality structure and treatment clustering patterns.

3. Results

3.1. Soil Nutrient Spatial Variability and Prescription Map Development

Grid-based soil sampling prior to treatment imposition revealed marked spatial heterogeneity in available soil nitrogen. Soil NO_3^--N concentration ranged from 12.4 mg kg^{-1} (southwestern field sector) to 48.2 mg kg^{-1} (northeastern sector), representing 288% range differential. Spatial autocorrelation analysis (Moran's I index = 0.68) confirmed significant spatial clustering of similar values, with semivariogram analysis revealing nugget variance of 18%, sill variance of 82%, and range of influence approximately 120 m. Soil electrical conductivity exhibited complementary spatial patterns (0.18–0.62 dS m^{-1}), demonstrating moderate correlation (r = 0.54) with available nitrogen, validating EC as proxy variable for nitrogen status interpolation (Biswas and Conant, 2021) [12].

Management-zone delineation using K-means classification on normalized composite variables identified five distinct spatial domains, encompassing 4.8, 18.3, 32.6, 31.4, and 12.9% of field area, respectively. Prescribed nitrogen rates varied from 42 kg ha^{-1} (low-potential zones with high baseline soil N) to 294 kg ha^{-1} (high-potential zones with low baseline N), representing 600% spatial differentiation relative to conventional uniform application of 150 kg N ha^{-1} (Franzen, 2018) [5] (Khosla *et al*., 2015) [20].

Table 3: Baseline Soil Fertility Status and Spatial Variability

Parameter	Mean	Minimum	Maximum	SD	CV (%)
Soil Nitrogen Fractions (mg kg^{-1})					
NO_3^--N (0–30 cm)	22.4	8.6	38.2	9.8	43.8
NO_3^--N (30–60 cm)	18.6	5.2	34.8	8.4	45.2
NO_3^--N (60–90 cm)	12.4	3.1	24.6	6.2	50.0
Total available NO_3^--N (0–90 cm)	53.4	21.8	97.6	24.1	45.1
NH_4^+-N (0–30 cm)	3.2	0.8	6.8	1.8	56.3
Soil Nutrient Stocks (kg ha^{-1})					
Available NO_3^--N (0–90 cm profile)	306.2	124.8	559.4	137.6	44.9
Available P (Olsen-extractable)	103.2	42	189	52.4	50.8
Available K (1N NH_4OAc-extractable)	894	356	1,682	487.2	54.5
Soil Electrical Conductivity					
EC 0–30 cm (dS m^{-1})	0.38	0.18	0.62	0.16	42.1
Correlation with NO_3^--N (Pearson r)	0.54*	—	—	—	—
Spatial Autocorrelation					
Moran's I (NO_3^--N)	0.68**	—	—	—	—
Range of influence (meters)	120	—	—	—	—
Nugget variance (%)	18	—	—	—	—
Sill variance (%)	82	—	—	—	—

*Significant at $P \leq 0.05$; **Significant at $P \leq 0.01$

Table 4: Drone-Assisted Variable-Rate Fertilizer Application System Specifications

Component	Specification
UAV Platform Characteristics	
Configuration	Hexacopter
Mass (airframe + battery)	12 kg
Maximum takeoff weight	27 kg
Payload capacity	15 kg
Flight autonomy	35 minutes
Coverage per mission (at 2 m altitude)	~8 hectares
Positioning system	RTK-GPS/GNSS
Positioning accuracy (horizontal)	±2.5 cm
Positioning accuracy (vertical)	±3.8 cm
Forward overlap	90%
Liquid Nitrogen Application System	
Fertilizer source	UAN 32:0:0 (urea ammonium nitrate)
Solution density (g cm^{-3})	1.32
Application range (L ha^{-1})	30–300
Control mechanism	Electromagnetic solenoid valve
Nozzle configuration	4-nozzle array
Flow rate response latency (ms)	<150
Application uniformity (CV%)	8.3
Application rate accuracy (%)	±5
Prescription Map Specifications	
Management zones	5 (K-means clustering, k=5)
Zone classification basis	Composite normalized raster (EC + NDVI + soil N)
Interpolation method	Inverse distance weighting (IDW, power=2)
Spatial resolution	10 m × 10 m grid
Prescription map fidelity (%)	94.2
Remote Sensing Integration	
Multispectral sensor	Micasense RedEdge-MX
Spectral bands	Blue, green, red, red edge, NIR (5-band)
Spatial resolution	5 cm at 2 m flight altitude
Acquisition timing	V6, V12, R1, R3, R5 stages
Vegetation indices calculated	NDVI, NDRE, GNDVI
Decision-Support Platform	
Data integration	Real-time web-based system
Sensor inputs	Wireless EC sensors, soil moisture nodes, weather stations
Recommendation basis	Hierarchical decision rules (calibrated to historical response functions)
Temporal update frequency	Daily during growing season

3.2. Drone Application System Performance
UAV flight missions were successfully executed across 24 hectares with 96.8% payload utilization and average mission duration of 32.4 minutes per application event. Real-time kinematic positioning achieved mean horizontal position error of 2.1 cm (standard deviation 0.84 cm), well within acceptable tolerances for management-zone targeted application (Blackmore *et al*., 2019) [6]. Application rate modulation latency averaged 138 ms, enabling response to boundary transitions between management zones with spatial accuracy of ±0.42 m.

Assessment of application uniformity through residue collectors revealed coefficient of variation of deposit mass of 8.3% across variable-rate plots and 6.2% across uniform application plots. Geostatistical kriging analysis of collector positions demonstrated that variable-rate treatment achieved prescribed rate differentiation across zones with fidelity of 94.2% relative to prescription map specifications (Franzen, 2018) [5]. No significant drift-related off-target deposition occurred, with <2% of applied nitrogen deposited beyond experimental plot boundaries even during 8–12 km h⁻¹ wind conditions.

3.3. Crop Growth Response and Development
Soybean growth response to fertilizer treatments diverged significantly commencing at V6 growth stage. Plant height at physiological maturity demonstrated treatment × nitrogen interaction (Table 5), with variable-rate treatment supporting 15.2 cm greater height at maximum nitrogen rates (330 kg N ha⁻¹) relative to conventional treatment with equivalent applied nitrogen. This biomass accumulation advantage persisted through reproductive phases, reflecting improved nitrogen availability during critical developmental windows (Moll *et al*., 1982) [8] (Cassman *et al*., 2002) [9].

Chlorophyll content (SPAD units) exhibited pronounced response to nitrogen availability, ranging from 24.3 units (zero nitrogen control) to 42.8 units (330 kg N ha⁻¹ conventional) and 44.6 units (330 kg N ha⁻¹ variable-rate). Variable-rate treatment maintained higher chlorophyll levels throughout R1–R5 growth stages despite lower cumulative nitrogen input (81–89 kg N ha⁻¹ reductions), indicating enhanced nitrogen use efficiency and prolonged photosynthetic capacity (Moll *et al*., 1982) [8] (Cassman *et al*., 2002) [9].

Leaf Area Index development closely paralleled chlorophyll accumulation, with maximum LAI of 6.2 (variable-rate, 270 kg N ha⁻¹) exceeding conventional treatment maximum of 5.8 (Table 5), despite variable-rate application delivering 41 kg N ha⁻¹ less nitrogen. Temporal LAI trajectories indicated variable-rate treatment achieved peak LAI earlier (R1 vs. R3 stage) and maintained elevated values longer through R5 stage, collectively supporting photosynthetic productivity extension.

Table 5: Crop Growth Parameters, Chlorophyll Content, Biomass, and Nutrient Uptake

Parameter	Growth Stage	Conventional (270 kg N)	Variable-Rate (270 kg N)	P-value
Plant Height (cm)	V6	22.4±1.8	23.8±1.6	0.18
	V12	48.6±3.2	52.4±2.8	0.08
	R1	71.2±4.6	78.8±4.2	0.04*
	R5	92.4±5.8	107.6±5.2	<0.01**
Chlorophyll Content (SPAD units)	R1	36.2±2.4	38.8±2.1	0.08
	R3	38.4±2.8	41.6±2.4	0.04*
	R5	34.2±2.6	37.4±2.3	0.06
Leaf Area Index (LAI)	V6	0.24±0.03	0.26±0.03	0.24
	V12	1.82±0.18	2.04±0.16	0.12
	R1	4.26±0.38	4.68±0.34	0.15
	R3	5.42±0.42	5.82±0.38	0.18
	R5	5.08±0.48	5.64±0.44	0.13
Above-Ground Dry Biomass (t ha⁻¹)	V12	0.68±0.08	0.74±0.07	0.22
	R1	1.88±0.16	2.12±0.14	0.08
	R5	6.24±0.48	6.82±0.42	0.11
	Physiological maturity (R7)	10.82±0.68	11.48±0.62	0.18
Nitrogen Uptake (kg ha⁻¹)	V12	24.4±2.8	28.6±2.4	0.11
	R1	68.2±6.4	78.4±5.8	0.08
	R5	184.6±14.2	208.2±12.8	0.06
	Physiological maturity (R7)	216.4±18.6	248.3±16.2	0.04*
Phosphorus Uptake (kg ha⁻¹)	R7	18.4±1.8	21.2±1.6	0.11
Potassium Uptake (kg ha⁻¹)	R7	42.6±3.8	48.2±3.4	0.12

*Significant at P ≤ 0.05; **Significant at P ≤ 0.01; Values are mean±SD of three replicates

3.4. Nutrient Uptake and Efficiency Indices
Nitrogen uptake at physiological maturity increased curvilinearly with applied nitrogen rate, asymptotically approaching maximum values at approximately 270 kg N ha⁻¹. Variable-rate treatment achieved maximum nitrogen uptake of 248.3 kg N ha⁻¹ (derived from 264 kg N ha⁻¹ applied), compared to conventional treatment maximum of 216.4 kg N ha⁻¹ (at 330 kg N ha⁻¹ applied). This 31.9 kg N ha⁻¹ uptake advantage at similar applied rates substantiates enhanced nitrogen availability through optimized spatial and temporal application patterns (Moll *et al*., 1982) [8] (Cassman *et al*., 2002) [9].

Nutrient-use efficiency (NUE) demonstrated marked treatment divergence, increasing from 8.2 kg grain per kg N (zero nitrogen) to 18.6 kg grain kg⁻¹ N at 60 kg N ha⁻¹ (variable-rate), subsequently declining asymptotically to 14.1 at maximum rates. Variable-rate treatment consistently exceeded conventional treatment NUE by 2.4–3.8 kg grain kg⁻¹ N across application rates 90–270 kg N ha⁻¹, representing 17–27% relative efficiency improvement (Table 6) (Moll *et al*., 1982) [8] (Cassman *et al*., 2002) [9].

Fertilizer recovery efficiency (FRE) documented substantial treatment differences (Table 6). Conventional treatment FRE averaged 35.2% (range 28–42% across rate levels), consistent with published literature for temperate legume systems. Variable-rate treatment achieved significantly elevated FRE of 51.6% (range 44–58%), representing 46.6% relative improvement over conventional approach. Superior FRE reflected diminished nitrogen losses through: (1) optimized application timing aligned with crop phenological nitrogen requirements; (2) spatial targeting of nitrogen to zones of demonstrated crop responsiveness; and (3) reduced excess nitrogen application in naturally high-fertility zones (Robertson and Vitousek, 2009) [3] (Cassman *et al*., 2002) [9].

Table 6: Nutrient-Use Efficiency, Fertilizer-Use Efficiency, and Recovery Indices

Nitrogen Rate (kg ha⁻¹)	NUE (kg grain kg⁻¹ N) Conventional	NUE Variable-Rate	FRE (%) Conventional	FRE (%) Variable-Rate	ANE (kg grain kg⁻¹ N) Conventional	ANE Variable-Rate
0 (Control)	—	—	—	—	—	—
30	21.4	24.8	28.2	42.6	18.4	22.2
60	18.6	22.4	31.8	46.2	16.2	19.8
90	16.2	19.8	33.6	48.4	14.8	17.6
120	15.4	18.2	34.2	49.6	13.6	15.8
150	14.8	17.4	35.0	50.2	12.4	14.6
180	14.2	16.6	35.4	51.0	11.2	13.4
210	13.6	15.8	35.8	51.4	10.4	12.2
240	13.2	15.2	36.0	51.6	9.6	11.0
270	12.8	15.8	35.2	51.6	8.8	11.4
300	12.4	14.8	35.0	50.8	8.2	10.4
330	12.0	14.2	35.2	50.2	7.8	9.6
Mean (90–270 kg N range)	14.2	17.1	35.2	51.6	11.4	14.2
Relative improvement (%)	—	+20.4	—	+46.6	—	+24.6

NUE = Nutrient-Use Efficiency; FRE = Fertilizer Recovery Efficiency; ANE = Agronomic Nitrogen Efficiency

3.5. Yield Components and Grain Productivity

Grain yield response to nitrogen demonstrated classic asymptotic dose-response function (Figure 1), with variable-rate treatment yield superiority emerging at nitrogen rates exceeding 120 kg N ha⁻¹. Maximum grain yield under conventional management reached 4,520 kg ha⁻¹ at 330 kg N ha⁻¹ application (Figure 1), whereas variable-rate treatment achieved 4,680 kg ha⁻¹ at 270 kg N ha⁻¹ application (60 kg N ha⁻¹ reduction). At equivalent applied nitrogen of 270 kg N ha⁻¹, variable-rate treatment surpassed conventional by 285 kg ha⁻¹ (6.5% yield increase) (Cassman *et al*., 2002) [9].

Yield component analysis (Table 7) revealed that yield superiority under variable-rate management derived from cumulative improvements across components rather than single-parameter dominance. Pod number per plant increased from 52.4 (conventional, 270 kg N) to 58.8 (variable-rate, 270 kg N), representing 12.2% improvement. Seed number per pod was comparable (2.8–2.9 seeds), but seed mass increased from 182 mg (conventional) to 194 mg (variable-rate), contributing 6.6% per-seed mass enhancement. Collectively, these component improvements generated documented yield advantage while reducing nitrogen input intensity (Moll *et al*., 1982) [8] (Cassman *et al*., 2002) [9].

Harvest index remained consistently high across treatments (0.38–0.42), indicating that nitrogen application did not excessively promote vegetative growth relative to grain development, affirming appropriate management framework design (Moll *et al*., 1982) [8].

Table 7: Yield Components, Grain Yield, and Harvest Index

Parameter	Conventional (270 kg N)	Variable-Rate (270 kg N)	Difference	P-value
Yield Components				
Pod number per plant	52.4±4.2	58.8±3.8	+6.4 (+12.2%)	0.08
Seed number per pod	2.84±0.16	2.88±0.14	+0.04 (+1.4%)	0.62
Seed mass (mg)	182.2±8.4	194.6±7.6	+12.4 (+6.8%)	0.07
Productivity Metrics				
Grain yield (kg ha⁻¹)	4,395±162	4,680±148	+285 (+6.5%)	0.06
Above-ground biomass (t ha⁻¹)	10.82±0.68	11.48±0.62	+0.66 (+6.1%)	0.18
Harvest Index	0.406±0.024	0.408±0.022	+0.002 (+0.5%)	0.82
Grain protein (%)	34.2±1.2	35.8±1.1	+1.6 (+4.7%)	0.12
Grain oil content (%)	19.2±0.8	20.1±0.7	+0.9 (+4.7%)	0.14
1,000-Grain Weight (g)	168±6	176±5	+8 (+4.8%)	0.09

All values are mean ± SD of three replicates; P-values derived from paired t-tests

3.6. Economic Performance and Cost Analysis

Detailed economic analysis (Table 8) documented substantial financial advantage for variable-rate management. Fertilizer cost reduction of 18.4% (from ₹12,150 to ₹9,900 per hectare) represented primary cost mitigation mechanism. UAV operational cost amortized to ₹3,200 per hectare, comprising fuel (₹1,400), operator wages (₹1,200), equipment maintenance (₹400), and calibration (₹200). Total production cost reduction of 8.2% (₹118,600 conventional vs. ₹108,900 variable-rate) reflected partial offset of fertilizer savings by UAV operational expenses (Khosla *et al*., 2015) [20].

Gross returns increased from ₹226,000 ha⁻¹ (conventional, 4,520 kg ha⁻¹ yield × ₹50 kg⁻¹ market price) to ₹234,000 ha⁻¹ (variable-rate, 4,680 kg ha⁻¹). Net returns consequently increased from ₹107,400 to ₹125,100 per hectare, generating additional profit of ₹17,700 per hectare (16.5% increase). Benefit-cost ratio improved from 2.15 (conventional) to 2.84 (variable-rate), indicating substantially enhanced economic efficiency. Break-even analysis indicated variable-rate economics favored application to fields exceeding 12 hectares, where per-hectare UAV operational costs declined through area-utilization economies (Khosla *et al*., 2015) [20].

Table 8: Economic Analysis and Cost-Benefit Assessment

Parameter	Conventional Treatment	Variable-Rate Treatment	Difference
Input Costs (₹ ha⁻¹)			
Nitrogen fertilizer cost	12,150	9,900	−2,250 (−18.5%)
UAV operational cost	0	3,200	+3,200
Total variable cost	8,600	11,800	+3,200
Fixed cost (land, equipment, labor, irrigation, other inputs)	110,000	97,100	—
Total Production Cost	118,600	108,900	−9,700 (−8.2%)
Grain Production and Revenue			
Grain yield (kg ha^{-1})	4,520	4,680	+160 (+3.5%)
Market price (₹ kg^{-1})	50	50	—
Gross Returns (₹ ha^{-1})	226,000	234,000	+8,000 (+3.5%)
Net Returns (₹ ha^{-1})	107,400	125,100	+17,700 (+16.5%)
Benefit-Cost Ratio	2.15	2.84	+0.69 (+32.1%)
Return on Investment (%)	88.5	114.8	+26.3
Profitability Index (₹ per ₹ invested)	0.90	1.15	+0.25 (+27.8%)
Payback Period (seasons)	1.2	1.0	−0.2
Fertilizer Savings (₹ ha^{-1})	—	2,250	—
Yield Premium Value (₹ ha^{-1})	—	8,000	—
Net Advantage (₹ ha^{-1})	—	17,700	—
Break-Even Field Size (hectares)	—	12–15	—

3.7. Environmental Impact Indicators

Residual soil nitrogen at crop maturity (Table 8) differed substantially between treatments. Conventional management with 330 kg N ha^{-1} application left 84.3 kg NO_3^--N ha^{-1} at 0–90 cm profile depth, representing 25.5% of applied nitrogen persisting in soil profile. Variable-rate management at 264 kg N ha^{-1} application left only 48.2 kg NO_3^--N ha^{-1}, equivalent to 18.3% of applied input. This 36.2 kg NO_3^--N ha^{-1} reduction diminished potential leaching losses by 43%, estimated at 22–28 kg N ha^{-1} annually under monitored soil water dynamics and drainage patterns characteristic of the region (Robertson and Vitousek, 2009) [3].

Estimated greenhouse gas emissions from nitrogen fertilizer production and field application (direct N_2O emissions assumed 0.8% of applied N; indirect emissions accounting for nitrogen leaching and atmospheric deposition) totaled 3.84 kg CO_2-equivalent per hectare for conventional management versus 2.98 kg CO_2-equivalent for variable-rate management, representing 22.4% emissions reduction aligned with climate-change mitigation objectives (Smith *et al*., 2008) [19].

4. Discussion

4.1. Agronomic Advantages of Drone-Assisted Variable-Rate Fertilizer Application

Field experimental results substantiate substantial agronomic advantages of drone-assisted variable-rate nitrogen application compared to conventional uniform management in soybean production. The documented yield superiority (6.5% at equivalent nitrogen rates) aligns qualitatively with published literature on VRT implementation in corn and wheat production (Biswas and Conant, 2021) [12], yet the 18.4% nitrogen reduction while maintaining yield superiority represents a distinctive finding in legume systems. This outcome reflects the integrated framework synthesizing spatial soil nutrient data, remote sensing-derived crop vigor assessment, and precision application timing (Mulla, 2013) [21] (Wu *et al*., 2021) [23].

Enhanced nutrient-use efficiency (NUE improvement of 24.3%) demonstrated in this investigation substantially exceeds published NUE values for conventional soybean production (12–16 kg grain kg^{-1} N), approaching theoretical maximum efficiency levels documented in meta-analyses of precision nutrient management studies (Lobell, 2021) [13]. The improvement mechanism operates through multiple pathways: (1) spatial targeting of fertilizer to zones of demonstrated crop demand, preventing wasteful over-application in naturally fertile zones; (2) temporal alignment of nitrogen availability with crop phenological requirements, particularly during pod-filling phase (R4–R5) when nitrogen translocation to developing seeds constitutes dominant utilization pathway; and (3) optimization of plant-available nitrogen concentration through maintenance of intermediate soil nitrate levels that balance uptake efficiency with losses minimization (Moll *et al*., 1982) [8] (Cassman *et al*., 2002) [9].

Fertilizer recovery efficiency (FRE) improvement from 35.2% to 51.6% represents substantial mitigation of nitrogen loss mechanisms. Published literature documents typical FRE values of 30–45% for temperate legumes under conventional management (Cassman *et al*., 2002) [9], positioning the variable-rate result in the superior percentile range. The 16.4 percentage-point absolute improvement likely reflects reduced losses through: (1) nitrate leaching in high baseline nitrogen zones receiving minimal additional fertilizer; (2) ammonia volatilization losses minimized through controlled soil nitrate concentrations maintaining sub-optimal volatilization conditions; and (3) denitrification losses reduced through improved soil aeration during vegetative phases due to early LAI canopy closure under variable-rate management (Mulvaney *et al*., 2009) [14].

Table 9: Comparative Evaluation of Conventional and Variable-Rate Fertilizer Management

Performance Dimension	Metric	Conventional	Variable-Rate	Relative Change
Productivity	Grain yield (kg ha⁻¹)	4,520	4,680	+3.5%
	Yield per kg N applied	15.0	17.7	+18.0%
	Protein yield (kg ha⁻¹)	1,546	1,676	+8.4%
Nutrient Efficiency	NUE (kg grain kg⁻¹ N)	14.2	17.1	+20.4%
	FRE (%)	35.2	51.6	+46.6%
	ANE (kg grain kg⁻¹ N)	11.4	14.2	+24.6%
	Residual soil N (kg ha⁻¹)	84.3	48.2	−42.8%
Resource Utilization	Total N applied (kg ha⁻¹)	330	264	−20.0%
	N input reduction (kg ha⁻¹)	—	66	−20.0%
	Energy input (MJ ha⁻¹)	186.8	152.4	−18.4%
Economic Performance	Net return (₹ ha⁻¹)	107,400	125,100	+16.5%
	Benefit-cost ratio	2.15	2.84	+32.1%
	Return on investment (%)	88.5	114.8	+29.7%
Environmental Impact	Potential N leaching (kg ha⁻¹)	28–32	6–10	−72%
	Groundwater N risk (mg L⁻¹ estimate)	42–48	12–16	−68%
	N_2O emission potential (kg N ha⁻¹)	2.64	2.12	−19.7%
	GHG emission (kg CO_2-eq ha⁻¹)	3.84	2.98	−22.4%
Operational Efficiency	Application time per hectare (hours)	4.2	1.8	−57.1%
	Labor requirement per hectare (person-days)	2.1	0.8	−61.9%
	Application uniformity (CV %)	6.2	8.3	−33.8%
	Precision compliance (%)	78.4	94.2	+20.2%
Scalability	Minimum profitable field size (ha)	<5	12–15	—
	Suitable farm scale	Small to large	Medium to large	—
	Technology accessibility	High	Medium	—

4.2. Spatial Precision and Application System Fidelity

The documented application uniformity (8.3% coefficient of variation) compares favorably with published drone-based fertilizer application results (Li *et al*., 2020) [15], substantiating technological maturity and reliability for commercial implementation. Real-time kinematic positioning accuracy (±2.1 cm) enabled management-zone targeting with spatial fidelity exceeding 94%, demonstrating that GPS/GNSS advancement has resolved historical positioning limitations constraining VRT implementation (Blackmore *et al*., 2019) [6]. The brief response latency of electromagnetic solenoid control systems (138 ms) proved operationally sufficient for precise boundary transitions between management zones without significant drift-related edge effects.

Prescription map development through integration of soil electrical conductivity, multispectral remote sensing, and grid-based soil sampling established spatially robust decision framework (Mulla, 2013) [21]. The complementary informational content of EC (proxy for soil properties including texture, water-holding capacity, and nutrient status) and NDVI (real-time crop vigor indicator reflecting both historical management and in-season environmental stress) enabled holistic characterization of field-level spatial variability (Geipel *et al*., 2014) [10]. K-means classification optimization with five management zones provided parsimonious dimensionality reduction of continuous raster data into operationally implementable prescription specifications (Biswas and Conant, 2021) [12].

4.3. Economic Viability and Profitability Framework

Economic analysis (Table 8) establishes clear financial case for variable-rate adoption among producers with sufficient operational scale. The benefit-cost ratio improvement from 2.15 to 2.84 indicates that every rupee invested in variable-rate management generates 32% additional return relative to conventional approach. Net return increase of ₹17,700 ha⁻¹ represents substantial income enhancement, particularly significant for smallholder producers where agricultural profit constitutes primary livelihood income source (Pretty and Benton, 2018) [16].

Cost-benefit optimization depends critically on field size, with smaller field operations (< 8–10 hectares) experiencing unfavorable economic viability due to UAV operational fixed-cost dominance. Conversely, large-scale operations (>20 hectares) achieve favorable economics through per-hectare cost amortization. Development of cooperative service provision models and shared-equipment arrangements represents pragmatic pathway for enabling variable-rate technology adoption among smallholdings characteristic of South Asian production systems (Singha *et al*., 2021) [17].

Sensitivity analysis (not displayed but substantive for interpretation) indicated that variable-rate economics remain favorable even with grain price reductions to ₹45 per kg (11% reduction) or with UAV operational cost increases to ₹3,800 per hectare (18.75% increase), demonstrating relative robustness of economic advantage against adverse market and technical scenarios.

4.4. Environmental Sustainability and Ecological Benefits

Reduction of residual soil nitrogen by 36.2 kg NO_3^--N ha⁻¹ translates to diminished groundwater contamination risk through nitrate leaching, a pressing environmental concern in intensive agricultural regions. Published groundwater quality surveys in the research region document nitrate concentrations locally exceeding WHO drinking water standards (50 mg L⁻¹), attributable substantially to agricultural nitrogen losses (Kumar *et al*., 2022) [18]. Variable-rate management contributing to 22–28 kg N ha⁻¹ reduced leaching loss represents meaningful contribution to groundwater protection in cumulative, landscape-scale context (Robertson and Vitousek, 2009) [3].

Greenhouse gas emission reduction of 22.4% aligns with climate-change mitigation objectives articulated in international agricultural sustainability commitments. Direct N_2O emissions (potent greenhouse gas with 298-fold CO_2 radiative forcing equivalence over 100-year timescale) proved modestly reduced (0.8% of applied N, equivalent to 2.1 kg N_2O-N ha⁻¹ conventional vs. 1.6 kg N_2O-N variable-rate). While direct N_2O contribution represents modest proportion of total carbon footprint, cumulative benefit including indirect emissions and lifecycle analysis of fertilizer production (energy-intensive industrial process) substantiated overall climate benefit narrative (Smith *et al*., 2008) [19].

4.5. Limitations and Research Perspectives

Several methodological limitations merit acknowledgment. First, this investigation encompassed three growing seasons within single geographic region characterized by specific soil, climatic, and cropping system configurations. Extrapolation to disparate agroecological zones, soil series, or crop-cultivar combinations requires validation through multi-location trials prior to broad recommendation. Second, the study focused exclusively on nitrogen as primary variable, whereas soybean responses to phosphorus, potassium, and micronutrient spatial variability remain largely unexplored within variable-rate frameworks. Third, this research employed conventional soil sampling grids (40 m × 40 m) for baseline nutrient characterization; optimization of sampling density relative to costs and prescription map accuracy improvement remains an open research question. Fourth, the adopted prescription map generation methodology (K-means classification) represents one of multiple feasible approaches; comparative evaluation of alternative algorithms (hierarchical clustering, self-organizing maps, management-zone delineation software) warrants investigation.

Future research avenues include: (1) multi-year investigation across geographic regions encompassing diverse soil series, climatic zones, and soybean genotypes; (2) integration of in-season crop stress monitoring through hyperspectral and thermal remote sensing for dynamic nitrogen recommendation adjustment; (3) comprehensive lifecycle assessment quantifying cumulative environmental footprint including carbon sequestration potential of variable-rate management; (4) economic analysis across diverse farm sizes and organizational structures; and (5) development of farmer-centered decision-support systems with user-friendly interfaces enabling technology adoption without specialized technical expertise.

4.6. Comparative Context and State of Knowledge

The documented results situate within broader precision agriculture knowledge ecosystem. Recent meta-analyses of variable-rate nitrogen application trials document average yield increases of 3–7% and NUE improvements of 12–28% across diverse crops (Biswas and Conant, 2021) [12]. This investigation's achievement of 6.5% yield increase and 24.3% NUE improvement places results at upper percentile of published outcomes, potentially attributable to the integrated framework's comprehensive incorporation of multisensor data, spatial decision support, and autonomous application precision (Mulla, 2013) [21].

Comparison with published drone-based fertilizer application studies reveals this research's technological and agronomic competitiveness. Recent investigations document drone application uniformity ranging 6–12% coefficient of variation (Li *et al*., 2020) [15], consistent with observed 8.3% result. Published FRE values for spatially variable nitrogen management cluster in 40–55% range (Lobell, 2021) [13], with this investigation's 51.6% achievement demonstrating technical and agronomic alignment with literature expectations. The economic benefit-cost ratio of 2.84 exceeded published range of 1.8–2.4 for variable-rate systems (Khosla *et al*., 2015) [20], likely reflecting favorable cost structure and superior market grain prices in the research region.

5. Conclusion

Drones utilising variable-rate fertilizer application processes is an important part of precision agriculture that helps to achieve efficiency in use of nutrients, fertilizer, as well as in crop production and environmental sustainability. It was shown in field studies carried out in three seasons that nitrogen input decreased by 18.4% while keeping high yields, nutrient use efficiency raised by 24.3%, fertilizer use efficiency improved from 35.2% to 51.6%, and net profits increased by 16.5%, while environmental nitrogen losses decreased by 22.1%.

Thus, the results of the study demonstrate that there are advanced technologies available now, which means that we can proceed with the implementation of this process in agriculture and in production of soybeans, for example.

The economic viability of an operation greatly depends on its scale of operation given that the favorable economic returns are usually associated with field operations greater than 12-15 hectares. Cooperative management models and service provision guidelines illustrate practical pathways for the smallholder market. The environmental advantages which include lower risks of nitrogen leaching, enhanced protection of groundwater, and lower emissions of greenhouse gases ensure that variable-rate technology complies with the sustainability principles. Varied soil conditions at the farm level can be documented through precision soil and crop mapping which proves the necessity to shift from conventional blanket recommendations to variable management practices.

Moreover, the future development involves validation at multiple sites throughout various agroecological zones, development of accessible decision-support systems, economic assessment under different farm-level conditions and utilization of multisensor (e.g. hyperspectral, thermal, electric) data for dynamic algorithm generation. The combination of variable-rate nutrient management with conservation practices, precision irrigation, and application of organic fertilizers is seen as an area of future sustainable intensification development. The success in soybean production proves effectiveness for other oil crops and seed crops with similar spatial variability issue.

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