



Article

Field Demonstration of a Low-Cost NDVI-Guided Stepwise Variable-Rate Nitrogen Toppdressing Applicator for Rice

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Abstract

Low-cost variable-rate applicators are needed to translate crop-sensing nitrogen (N) recommendations into field-scale fertilizer delivery. This study presents a field demonstration of a normalized difference vegetation index (NDVI)-guided stepwise variable-rate granular urea topdressing applicator for rice in a single-site, single-season comparison with a uniform split-management treatment. The tractor-mounted system used an active optical canopy sensor, a deterministic NDVI-to-rate rule, pulse-width-modulation actuator control, and fluted-roller metering. Fertilizer rates are reported as urea product, with elemental N equivalents calculated from 46% N content. The uniform split-management treatment prescribed three 75.00 kg urea ha⁻¹ splits, totaling 225.00 kg urea ha⁻¹ seasonally. The NDVI-guided split-management treatment prescribed two fixed manual splits of 56.25 kg urea ha⁻¹ each and used a sensor-guided third split at 45 days after transplanting. Because the first two splits differed between treatments, the comparison represents two complete split-management strategies rather than the isolated effect of the sensor-guided third application. The aggregate field-collection estimate for the sensor-guided third split was 100.92 kg urea ha⁻¹, which was 25.92 kg urea ha⁻¹ greater than the uniform third split; the estimated seasonal total was 213.42 kg urea ha⁻¹, or 5.1% less than the prescribed uniform seasonal total because of the two lower early manual splits. Harvest measurements adjusted to 14% grain moisture showed mean grain yields of 7.35 and 8.02 t ha⁻¹ for the uniform and NDVI-guided split-management treatments, respectively. Treatment-level partial factor productivity, calculated from treatment-mean yield and estimated seasonal N input, was 71.0 and 81.7 kg grain kg⁻¹ N, respectively. These results show the effectiveness of the applicator within the tested split-management comparison; however, the retained records do not verify rate-class frequency, spatial as-applied delivery, or complete strip coverage, and the yield and partial-factor-productivity differences should not be attributed solely to NDVI sensing or variable-rate actuation.



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1. Introduction

Nitrogen (N) fertilizer management is a central challenge in rice production because N strongly affects crop growth, grain yield, production cost, and environmental loss pathways. Conventional uniform fertilizer application remains common because it is simple to implement, but it assumes that crop N demand is spatially and temporally uniform within a given area. In practice, rice fields often show variability in soil N supply, crop vigor, water status, and growth response, so a fixed blanket rate can over-supply some areas while under-supplying others [1–4]. These inefficiencies reduce fertilizer-use efficiency and can increase the risk of N losses through volatilization, leaching, runoff, and other pathways [5,6].

Sensor-based N management offers a way to adjust in-season fertilizer application according to crop status rather than relying only on fixed regional recommendations. Active optical canopy sensors are particularly useful for field operation because they provide their own illumination and can measure crop reflectance under variable ambient light conditions. The normalized difference vegetation index (NDVI), derived from red and near-infrared reflectance, has been widely used as an indicator of crop vigor, biomass development, and N status in cereal crops [7–9]. In rice, active canopy sensing has been used to support in-season N diagnosis and topdressing decisions, with several studies showing potential to maintain yield while improving N-use efficiency when fertilizer input is adjusted according to crop demand [10–13].

However, the agronomic ability to diagnose crop N status is only one part of a working variable-rate fertilizer system. From an agricultural engineering perspective, a sensor-based recommendation is useful only if it can be translated into reliable field delivery. This requires a stable sensor–controller–actuator chain, calibrated fertilizer metering, acceptable rate-transition behavior, and transparent control logic that can be evaluated and adapted by other users [14–19]. Many studies emphasize canopy-sensing algorithms or crop response, while fewer report enough detail on machinery implementation, calibration basis, rate-control behavior, and field-level operation of low-cost fertilizer applicators.

Low-cost and locally adaptable systems are especially important where commercial variable-rate platforms are limited by equipment cost, operational complexity, or lack of local support [20]. A practical rice topdressing system should therefore be operationally simple, readily calibrated, and stable under field conditions. Deterministic NDVI-to-rate rules remain relevant in this context because they can be implemented with modest computing hardware and can be audited more easily than complex black-box models. Although recent work has advanced sensor-fusion and machine-learning approaches for rice N diagnosis and recommendation [13], there remains a practical need to evaluate simpler deployable applicator platforms that can support accessible precision N management.

Previous studies reported the development and performance characterization of this low-cost sensing–control–metering architecture. One study described applicator design, development, and wheat-field evaluation [21]. A subsequent rice assessment under pre-defined N-status plots reported system response, rate accuracy, sensor-height effects, and crop-stage effects, but did not report grain-yield outcomes [22]. The present six-strip trial and the fertilizer-accounting, canopy-sampling, and grain-yield data analyzed here were not included in the dataset reported in that publication. The current study uses the previously developed platform within an NDVI-guided split-management treatment and compares it with a uniform split-management treatment using split-wise and estimated seasonal fertilizer input, moisture-adjusted grain yield, and partial factor productivity (Table 1). Here, “field demonstration” refers to field use of the platform within this treatment comparison, not to a new trial-specific validation of rate-switching accuracy or spatial as-applied coverage.

Table 1. Distinction between previous publications from this research program and the present study.

Publication	Primary Focus	Distinction of the Present Study
Mirzakhaninafchi et al. [21]	Applicator design, development, and wheat-field evaluation	The current study uses the previously developed architecture in a rice field demonstration rather than repeating the wheat-platform development study.
Mirzakhaninafchi et al. [22]	Rice performance assessment under predefined N-status plots, including response time, application error, sensor height, and crop-stage effects	Using a separate six-strip dataset, the current study adds split-wise and estimated seasonal fertilizer-input accounting, grain-yield measurement, and partial factor productivity for a comparison of two complete split-management treatments.
Current study	Single-site, single-season rice field demonstration using fertilizer-input, NDVI, and harvest measurements	Provides treatment-level fertilizer-input and harvest outcomes for the tested split-management comparison, without claiming new platform validation or broad agronomic superiority.

Therefore, the objective of this study was to evaluate the field operation of a low-cost NDVI-guided stepwise variable-rate N topdressing applicator for rice under practical field conditions. The specific aims were to (i) provide the sensing, control logic, target setpoints, and metering strategy used for the sensor-guided third fertilizer split; (ii) quantify split-wise and estimated seasonal urea input and elemental-N equivalent under the NDVI-guided and uniform split-management treatments; and (iii) compare canopy NDVI variability, moisture-adjusted grain yield, and partial factor productivity between the two complete split-management treatments in a single-site, single-season replicated strip layout.

2. Materials and Methods

2.1. Applicator Platform

The field experiment used the previously developed tractor-mounted stepwise variable-rate granular-urea applicator [21]. The retrofit combined an 11-row seed-cum-fertilizer drill with a single active optical canopy sensor, microcontroller-based control, PWM actuation, hydraulic motor drive, and fluted-roller metering. The applicator had 11 fertilizer-discharge outlets spaced at 0.20 m and an effective operating width of 2.2 m. The previously reported construction cost was approximately USD 700. This historical value is retained only to explain the low-cost designation used for the original retrofit platform; it is not a current itemized cost, ownership-cost, replacement-cost, tractor-cost, or labor-cost analysis. Comparable variable-rate fertilizer systems have emphasized rate-control accuracy, transition response, and field verification [14–16,23]. Earlier characterization of this platform reported response times of 3.53–4.93 s and overall application errors of 0.83–4.92% under the tested conditions [22]. The present trial used the predefined controller target setpoints in described in Section 2.3 and the field-collection procedure described in Section 2.5. The tractor-mounted applicator configuration is shown in Figure 1, and its functional command pathway from canopy NDVI sensing through setpoint selection to PWM-controlled fertilizer metering is summarized in Figure 2.



Figure 1. Archival photograph of the tractor-mounted low-cost NDVI-guided stepwise variable-rate applicator configuration, showing the active optical canopy sensor, controller, and fertilizer-metering unit. Adapted from Mirzakhani et al. [22], licensed under CC BY 4.0.

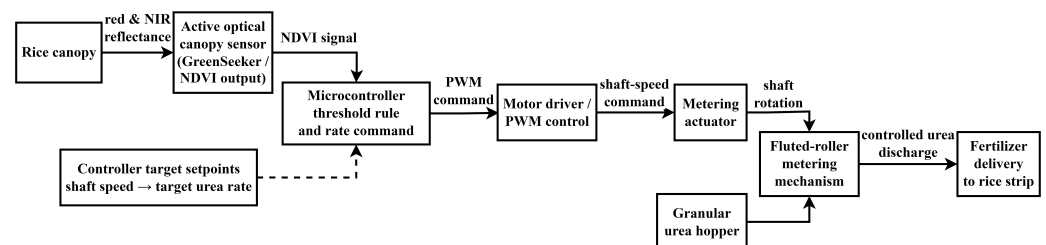


Figure 2. Functional architecture of the NDVI-guided stepwise variable-rate urea topdressing applicator. Canopy NDVI was clipped to the predefined control range, converted to a target rate, assigned to the nearest metering-shaft setpoint, and implemented through PWM control of the hydraulic drive and fluted-roller metering mechanism. The same setpoint command controlled all 11 fertilizer outlets. The diagram represents the command pathway; it does not indicate real-time travel-speed compensation, closed-loop discharge measurement, or trial-specific telemetry logging. The dashed arrow denotes the stored controller setpoint reference supplied to the microcontroller rather than a real-time sensor or actuator feedback signal.

2.2. Field Site and Experimental Design

The field trial was conducted during the 2020 rice-growing season (June–October 2020) at the research farm of Punjab Agricultural University (PAU), Ludhiana, India. The PAU research farm is located near 30.91° N, 75.81° E, at an elevation of approximately 244 m, in a subtropical semi-arid rice-production region previously described for related applicator field evaluation [22]. Before transplanting, soil samples were collected from the 0–15 cm layer to characterize the experimental field. Pre-transplant soil analysis indicated loamy soil with pH 7.3, organic C of 3.2 g kg^{−1}, 0.5 M NaHCO₃-extractable P of 6.4 mg kg^{−1}, and NH₄OAc-extractable K of 58 mg kg^{−1}, determined using standard procedures [24–26]. Initial mineral-N and total-N measurements were not available for the present analysis; therefore, baseline plant-available N supply could not be compared among treatment strips. The study compared two complete fertilizer-management schedules: (i) the NDVI-guided split-management treatment and (ii) the uniform split-management treatment. The field was arranged in alternating strips with three replications (Figure 3). The fixed strip sequence shown in Figure 3 was not randomized. Strip-level pre-treatment NDVI, surveyed field orientation and slope, irrigation/drainage direction, buffer dimensions, pass direction, and georeferenced harvest-subarea locations were not retained for the present analysis. Each replication consisted of one adjacent strip pair, with one strip assigned

to the NDVI-guided split-management treatment and one strip assigned to the uniform split-management treatment; replication-level yield differences were therefore calculated as paired strip contrasts rather than as independent small-plot observations. The layout should be interpreted as a replicated alternating-strip field study rather than a fully randomized small-plot agronomic trial. Based on the experimental layout used in the trial, each strip was approximately 72 m long and 7.1 m wide. Because the applicator's effective operating width was 2.2 m, each 7.1-m treatment strip required multiple parallel applicator passes to cover the strip width. The exact number of passes, center-to-center spacing, overlap or skip width, boundary margins, and whether any pass crossed a treatment boundary, were not retained in the records available for this analysis; therefore, pass-level coverage could not be reconstructed. The replicated strip was treated as the experimental unit. Non-nitrogen agronomic practices were managed uniformly across treatments according to PAU kharif rice recommendations so that the noted comparison focused on fertilizer-management strategy. Rice cultivar PR-122 was grown during the June–October 2020 kharif season. The crop was established as transplanted rice, and fertilizer operations were scheduled at 7, 21, and 45 days after transplanting (DAT). For transplanted rice, fields were maintained with approximately 5–8 cm standing water during the first 15 DAT and then irrigated at 4–7 day intervals, with the final irrigation applied 10 days before harvest. Harvest measurements for the NDVI-guided and uniform split-management treatments were recorded on 13 October 2020. Other crop-management operations, including land preparation, weed control, pest and disease management, and non-N nutrient management, were applied uniformly across treatments according to PAU kharif rice recommendations [27].

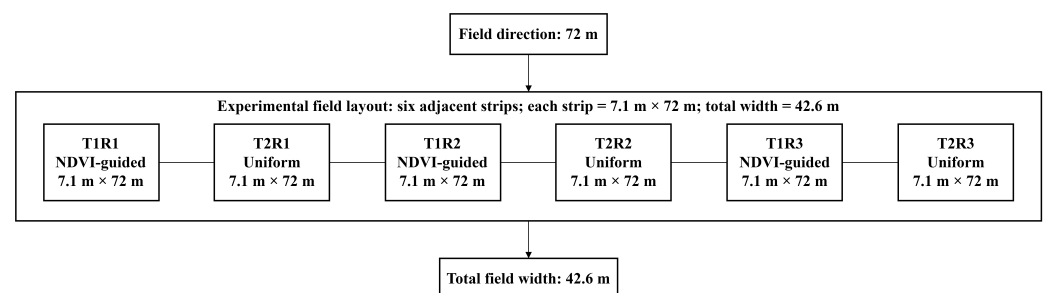


Figure 3. Schematic experimental field layout showing the fixed alternating-strip sequence: T1R1 (NDVI-guided), T2R1 (uniform), T1R2 (NDVI-guided), T2R2 (uniform), T1R3 (NDVI-guided), and T2R3 (uniform). Each strip was 7.1 m wide and 72 m long, giving a total experimental width of 42.6 m. The diagram is not a surveyed map; north orientation, slope/drainage direction, buffer dimensions, pass tracks, and harvest-subarea coordinates were not retained for the present analysis.

2.3. Nitrogen Treatments and NDVI-to-Rate Rule

The total recommended fertilizer-product rate for the crop was 225 kg urea ha^{−1}, equivalent to 103.50 kg N ha^{−1} based on the 46% N content of urea. Unless explicitly stated as elemental-N equivalent, fertilizer rates in this paper refer to urea-product input. In the uniform split-management treatment, urea was prescribed manually in three equal splits of 75.00 kg urea ha^{−1} at 7, 21, and 45 DAT. In the NDVI-guided split-management treatment, the first two splits were prescribed manually at 56.25 kg urea ha^{−1} at 7 and 21 DAT, and only the third split at 45 DAT was sensor-guided. The lower first and second splits were prespecified components of the complete NDVI-guided split-management treatment, not sensor-generated rates. Early splits were applied manually because the crop canopy was not sufficiently developed for reliable sensor discrimination from soil background. The third split was applied using the NDVI-guided stepwise variable-rate applicator with a maximum preset rate of 112.50 kg urea ha^{−1} (Table 2). Commercial granular urea was used for establishing the controller target setpoints and for field application. The urea

was specified as 46% total N, maximum moisture of 1%, maximum biuret of 1.5%, and granules with approximately 90% passing a 2.8 mm sieve and 80% retained on a 1 mm sieve. Therefore, the treatment contrast evaluated two complete split-management schedules and was not designed to isolate the causal effect of the 45 DAT sensor-guided pass from the lower first and second splits. Fertilizer for each manual split was weighed separately for each strip and applied by the same trained field personnel. Spatial broadcasting uniformity was not independently measured.

Table 2. Fertilizer application schedule and crop-measurement timeline under the NDVI-guided and uniform split-management treatments. Difference—NDVI-guided input minus uniform urea input; positive values indicate greater input under the NDVI-guided split-management treatment. The 45 DAT value is the aggregate field-collection estimate. DAT—days after transplanting.

DAT	NDVI-Guided Split Management	Uniform Split Management	Difference (kg urea ha ^{−1})
7	Manual urea split: 56.25 kg urea ha ^{−1}	Manual urea split: 75.00 kg urea ha ^{−1}	−18.75
21	Manual urea split: 56.25 kg urea ha ^{−1} ; NDVI sampling stage 1	Manual urea split: 75.00 kg urea ha ^{−1} ; NDVI sampling stage 1	−18.75
35	NDVI sampling stage 2	NDVI sampling stage 2	—
45	Sensor-guided third split: target range 0–112.50 kg urea ha ^{−1} ; aggregate field-collection estimate 100.92 kg urea ha ^{−1}	Manual urea split: 75.00 kg urea ha ^{−1}	+25.92
59	NDVI sampling stage 3	NDVI sampling stage 3	—
Maturity	Grain-yield measurement	Grain-yield measurement	—

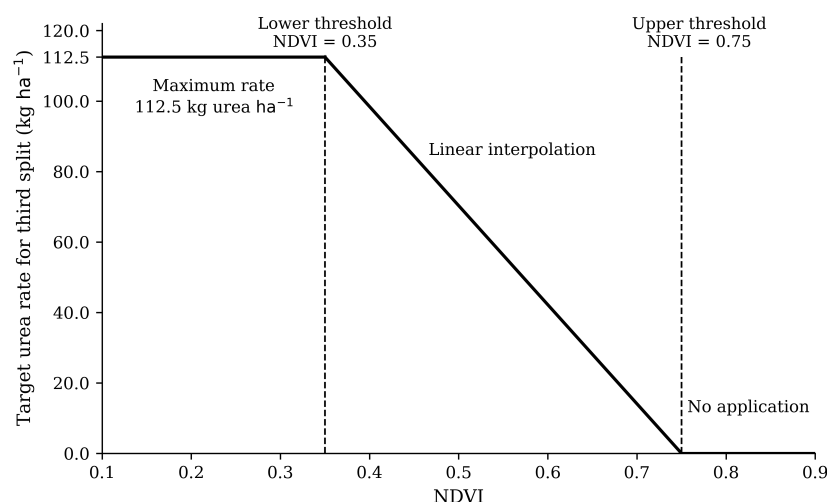
During the 45 DAT application event, the controller implemented the inverse NDVI-to-metering-shaft-speed relation of the previously developed applicator platform within the predefined NDVI control range of 0.35–0.75, using the controller target setpoints shown in Table 3 [21,22]. In this field implementation, NDVI values below 0.35 were clipped to the lower bound and assigned the maximum preset rate, whereas NDVI values above 0.75 were clipped to the upper bound and assigned a zero rate. For intermediate NDVI values, the target urea application rate was calculated as

$$R_{u,\text{target}} = \begin{cases} 112.50, & NDVI \leq 0.35, \\ 112.50 \times \frac{0.75 - NDVI}{0.75 - 0.35}, & 0.35 < NDVI < 0.75, \\ 0, & NDVI \geq 0.75, \end{cases}$$

where $R_{u,\text{target}}$ is the target urea product rate in kg urea ha^{−1}. The target rate was implemented by selecting the numerically nearest available metering-shaft setpoint from Table 3. The corresponding elemental N rate is $R_N = 0.46R_{u,\text{target}}$. The thresholds were used as fixed engineering parameters for field deployment and should not be interpreted as a calibrated rice N recommendation rule for other cultivars, fields, or seasons. The number of controller updates assigned to each setpoint was not retained and could not be reconstructed (Figure 4). Table 3 identifies the target setpoints used by the controller; the table does not by itself constitute a trial-specific validation of discharge accuracy or outlet-to-outlet uniformity.

Table 3. Controller target setpoints relating metering-shaft speed to urea product rate during the 45 DAT topdressing event.

Metering Shaft Speed (rpm)	Target Urea Rate (kg urea ha ⁻¹)	Equivalent N Rate (kg N ha ⁻¹)
0	0.00	0.00
10	28.13	12.94
20	56.25	25.88
30	84.38	38.81
40	112.50	51.75

**Figure 4.** Theoretical rule-based mapping between canopy NDVI and target urea product rate for the sensor-guided third fertilizer split. NDVI values below 0.35 were assigned the maximum preset rate, values between 0.35 and 0.75 were linearly interpolated, and values above 0.75 were assigned a zero rate. During field operation, the target rate was implemented through the nearest available metering-shaft setpoint. The figure presents the control rule and not the observed 45 DAT NDVI distribution or rate-class frequency.

Control Update and Rate-Transition Behavior

The controller recalculated the commanded application-rate setpoint at fixed intervals of 1 s. At the nominal operating speed used in this study, approximately 3 km h⁻¹ or 0.83 m s⁻¹, each command interval corresponded to about 0.8 m of travel. Rate transitions were implemented as step changes between discrete metering-shaft setpoints rather than continuous modulation. Previous characterization of the same platform reported sensor-to-metering-shaft response times of approximately 3.53–4.93 s [22]; at 3 km h⁻¹, this corresponds to approximately 2.9–4.1 m of travel. The earlier platform study described look-ahead intervals based on response time, forward speed, and sensor-to-outlet distance; however, the available records for the present trial do not indicate the implemented sensor-to-outlet offset, look-ahead interval, or headland-transition handling. Consequently, trial-specific alignment of sensed canopy position with fertilizer discharge, abrupt-transition behavior, and headland behavior could not be quantified. Forward speed was maintained near 3 km h⁻¹ but was not used as a real-time feedback input to the controller. Because area-based application rate varies inversely with forward speed, a 10% decrease or increase from the nominal speed would produce approximate rate deviations of +11.1% or −9.1%, respectively.

2.4. Calibration and NDVI Measurements

Crop canopy reflectance was measured using an active optical GreenSeeker sensor mounted at approximately 750 mm above the crop canopy. The sensor was front-mounted;

however, the available trial records do not state its lateral alignment relative to individual rice rows. The GreenSeeker sensor has been described as sensing an approximately 0.25–0.50 m wide field zone within the recommended mounting-height range [22]. Therefore, in the present setup, the single sensor represented a subsample of the 2.2 m applicator swath rather than the full swath width. The resulting rate command was applied across all 11 fertilizer outlets, and no lateral NDVI transects were collected to test the representativeness of the single sensor across the full swath. The single-sensor configuration was part of the low-cost platform architecture, but the present study does not establish full-swath representativeness. NDVI was computed as

$$NDVI = \frac{NIR - Red}{NIR + Red},$$

where *NIR* and *Red* are canopy reflectance in the near-infrared and red bands, respectively. Because the sensor provides active illumination, measurements could be acquired under variable ambient light conditions.

Two NDVI data streams were used. Continuous 45 DAT records of NDVI, selected rate setpoint, PWM command, shaft speed, travel speed, pass identity, and GPS position were not retained for the present analysis. During the 45 DAT applicator pass, the GreenSeeker provided on-the-go canopy readings to the controller for real-time rate-command updates rather than for continuous georeferenced as-applied mapping. Separately, for canopy-variability assessment, NDVI point observations were collected at 21, 35, and 59 DAT, corresponding to tillering, stem elongation, and panicle initiation, respectively. When NDVI point sampling and fertilizer application occurred on the same date, point NDVI measurements were completed before fertilizer application. At each stage, five NDVI readings were recorded at each of six locations within each replication of each treatment, giving 90 NDVI readings per treatment per sampling stage. These point-level readings were used to describe canopy variability within treatments; they were not treated as independent replicated experimental units for yield inference.

Before field application, urea output was collected and weighed at the shaft-speed settings used to establish the target-rate relationship in Table 3. The target setpoints are reported because they define the controller commands used in the trial. Trial-specific replicated outlet-level discharge records needed to calculate mean measured discharge, SD, CV, RMSE, rate error, regression fit, and outlet-to-outlet uniformity were not retained for the present analysis. Therefore, Table 3 reports controller target setpoints only and should not be interpreted as a new calibration-accuracy validation; detailed platform performance characterization has been reported previously [22].

2.5. Outcome Variables and Data Summary

The main outcomes of the study were total seasonal urea fertilizer applied, equivalent elemental N input, NDVI variability across growth stages, grain yield at maturity, and partial factor productivity of applied N. The effective operating width of the applicator was 2.2 m and the forward speed during fertilizer application was approximately 3 km h^{−1}. During the actual 45 DAT treatment passes, fertilizer discharged from all 11 outlets was temporarily collected in poly bags during multiple monitored passes through the NDVI-guided strips, weighed after each monitored pass, and then reapplied to the corresponding treatment area. The monitored collection locations did not overlap the four harvest sub-areas. The retained records do not identify the reapplication locations at harvest-subarea resolution, and a separate third-split estimate was not available for each strip replication. The aggregate mass-flow rate was converted to an area-based urea application rate as

$$R_u = \frac{M/t}{wv} \times 10000,$$

where R_u is urea product rate (kg urea ha⁻¹), M is total collected urea mass across all monitored outlet collections (kg), t is total collection time across monitored passes (s), w is effective operating width (m), and v is forward speed (m s⁻¹). This procedure yielded an aggregate field-collection estimate for the third split of 100.92 kg urea ha⁻¹, equivalent to 46.42 kg N ha⁻¹. Accordingly, this value is a pooled treatment-level estimate for seasonal-input accounting; it is not a strip-specific or harvest-subarea-specific application rate. Estimated seasonal input under the NDVI-guided split-management treatment was calculated as the sum of the two fixed manual splits and the aggregate third-split field-collection estimate, i.e., 56.25 + 56.25 + 100.92 = 213.42 kg urea ha⁻¹, equivalent to 98.17 kg N ha⁻¹. For each treatment, PFP_N was calculated once as treatment-mean grain yield divided by the treatment-level estimated seasonal N input (kg grain kg⁻¹ N); it is therefore a descriptive treatment-level ratio rather than a replicated strip-level response. NDVI response was summarized using the coefficient of variation (CV) at each sampling stage. The estimated seasonal total therefore combines the prescribed manual rates for the first two splits with the aggregate field-collection estimate for the third split.

2.6. Grain Yield Measurement

Grain yield was measured at maturity from central harvest areas within the treatment strips. Within each replicated strip, four central subareas of 8.0 m² each (4.0 m × 2.0 m) were harvested away from strip edges and headlands, threshed, cleaned, weighed, and adjusted to a standard grain moisture content of 14%. The total sampled area was 32.0 m² per strip, representing approximately 6.3% of the 511.2 m² strip area. The recorded 14%-moisture-adjusted grain-yield values were expressed as kg grain m⁻² for the four within-replication subareas in each of three replications under each fertilizer-management treatment. The four subarea values within each replication were averaged to obtain one strip-level yield value per treatment and replication. Grain yield was converted from kg grain m⁻² to t ha⁻¹ by multiplying by 10. Yield results are reported as descriptive outcomes from a single-site, single-season strip trial. Exact georeferenced harvest-subarea coordinates, distances from strip boundaries and headlands, and the within-strip subarea-selection record were not retained for the present analysis. The subarea-level grain-yield values used to calculate the strip-level means are provided in Supplementary Table S1.

2.7. Statistical Analysis

The replicated strip was treated as the experimental unit for the fertilizer-management comparison. Descriptive statistics were used to summarize seasonal urea input, equivalent elemental N input, NDVI variability across growth stages, 14%-moisture-adjusted grain yield, and partial factor productivity of applied N. For grain yield, the four subarea harvest values were first averaged within each strip replication, and treatment summaries were then calculated from the three strip-level means. Because the layout consisted of three adjacent treatment strip pairs, the NDVI-guided minus uniform yield difference was calculated within each pair and summarized using the arithmetic mean and standard deviation. No confidence interval or hypothesis test was used because only three fixed adjacent strip pairs were available and treatment order was not randomized. Individual NDVI readings and harvest subareas were not treated as independent treatment-level experimental replicates.

3. Results

3.1. Fertilizer Input Under the Two Split-Management Treatments

The previously developed NDVI-guided applicator was used during the third fertilizer split at 45 DAT. Detailed response-time and application-error characterization of the same applicator platform has been reported previously [22]; the present study focuses on descriptive outcomes for the NDVI-guided and uniform split-management treatments.

Under field conditions, the aggregate field-collection estimate for the sensor-guided third split was 100.92 kg urea ha⁻¹, equivalent to 46.42 kg N ha⁻¹. Because trial-specific telemetry and pass geometry were not retained, this pooled estimate does not verify the occurrence, frequency, or spatial distribution of individual rate classes or complete strip coverage. This was 11.58 kg urea ha⁻¹ below the preset maximum cap of 112.50 kg urea ha⁻¹, but 25.92 kg urea ha⁻¹ above the 75.00 kg urea ha⁻¹ third split prescribed in the uniform split-management treatment (Table 4). Therefore, the seasonal saving should be interpreted as the outcome of the complete split-management strategy, not as a reduction caused by the third split alone. The sensor-guided third split increased late-season urea input relative to the uniform third split; the seasonal saving resulted from the complete split schedule.

When fertilizer inputs were summed across all split applications, the estimated seasonal input was 213.42 kg urea ha⁻¹, equivalent to 98.17 kg N ha⁻¹, for the NDVI-guided split-management treatment, compared with the prescribed seasonal total of 225.00 kg urea ha⁻¹, equivalent to 103.50 kg N ha⁻¹, for the uniform split-management treatment. This corresponds to an 11.58 kg urea ha⁻¹ or 5.33 kg N ha⁻¹ reduction, equivalent to 5.1% of the uniform seasonal input.

Table 4. Split-wise and estimated seasonal urea inputs under the uniform and NDVI-guided split-management treatments. Manual rates are prescribed values; the 45 DAT NDVI-guided value is the aggregate field-collection estimate. Difference—NDVI-guided minus uniform. Uniform and NDVI-guided denote the uniform and NDVI-guided split-management treatments, respectively.

Treatment	7 DAT (kg urea ha ⁻¹)	21 DAT (kg urea ha ⁻¹)	45 DAT (kg urea ha ⁻¹)	Seasonal Urea (kg urea ha ⁻¹)	Seasonal N (kg N ha ⁻¹)
Uniform	75.00	75.00	75.00	225.00	103.50
NDVI-guided	56.25	56.25	100.92	213.42	98.17
Difference	−18.75	−18.75	+25.92	−11.58	−5.33

3.2. NDVI Variability Across Growth Stages

Canopy NDVI CV declined over time in both treatments. At 21 DAT, NDVI CV was 16% under the NDVI-guided split-management treatment and 14% under the uniform split-management treatment. At 35 DAT, the corresponding values were 7% and 6%, and at 59 DAT they were 4% and 3%, respectively (Figure 5). The NDVI-guided split-management treatment did not show lower NDVI CV than the uniform split-management treatment; its CV was slightly higher at all three sampling stages. These CV values describe relative within-treatment variability only. Because the complete original point-level NDVI dataset and replication-resolved mean and SD or SE summaries were not available for reliable retrospective analysis, the CV values should not be interpreted as evidence of similar mean crop N status or canopy convergence between treatments.

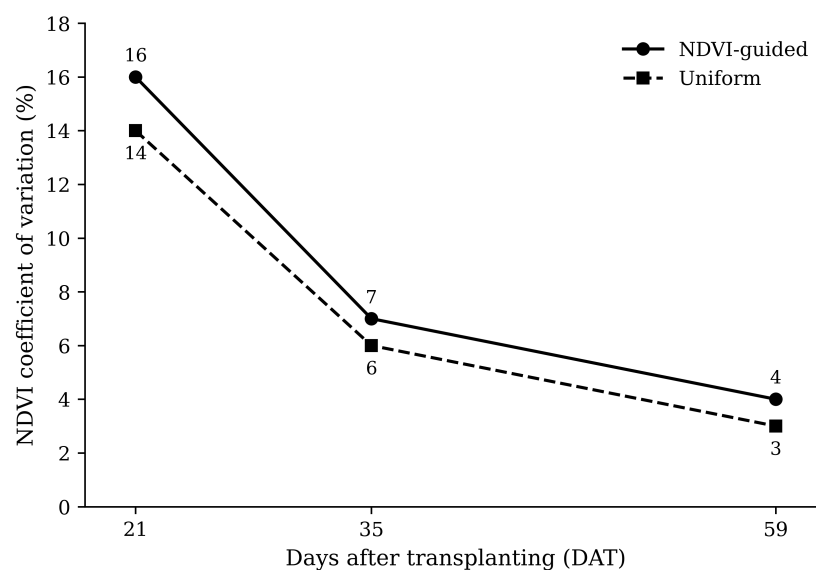


Figure 5. NDVI coefficient of variation under the NDVI-guided and uniform split-management treatments at 21, 35, and 59 days after transplanting. Values describe relative within-treatment variability; the complete original point-level dataset required to report replication-resolved mean NDVI and SD or SE was not available for reliable retrospective analysis.

3.3. Grain Yield and Nitrogen Productivity

Recorded 14%-moisture-adjusted harvest data were expressed as kg grain m⁻² for the NDVI-guided and uniform split-management treatments. After conversion to t ha⁻¹ and averaging the four subarea values within each strip, mean grain yield was 7.35 t ha⁻¹ under the uniform split-management treatment and 8.02 t ha⁻¹ under the NDVI-guided split-management treatment (Table 5). At the subarea level, values ranged from 7.00 to 7.63 t ha⁻¹ under the uniform split-management treatment and from 7.68 to 8.42 t ha⁻¹ under the NDVI-guided split-management treatment. The NDVI-guided minus uniform differences for the three adjacent strip pairs were 0.71, 0.56, and 0.72 t ha⁻¹ for R1, R2, and R3, respectively, giving an arithmetic mean difference of 0.67 t ha⁻¹ (SD = 0.09 t ha⁻¹). Using the treatment-level estimated seasonal N inputs, the treatment-level PFP_N ratios were 71.0 kg grain kg⁻¹ N under the uniform split-management treatment and 81.7 kg grain kg⁻¹ N under the NDVI-guided split-management treatment. These ratios are descriptive rather than replicated strip-level responses and do not isolate the effect of NDVI sensing or stepwise variable-rate control.

Table 5. Descriptive grain-yield and nitrogen-productivity summary calculated from 14%-moisture-adjusted harvest measurements. Four subarea values were averaged to one strip-level value for each treatment within each adjacent strip pair. R1–R3 are adjacent strip pairs and not independently randomized blocks. PFP_N—partial factor productivity based on estimated equivalent elemental N input. The PFP_N values are treatment-level ratios, not observations replicated across R1–R3.

Treatment	R1 (t ha ⁻¹)	R2 (t ha ⁻¹)	R3 (t ha ⁻¹)	Mean ± SD (t ha ⁻¹)	CV (%)	PFP _N (kg grain kg ⁻¹ N)
Uniform	7.23	7.41	7.42	7.35 ± 0.11	1.5	71.0
NDVI-guided	7.94	7.97	8.15	8.02 ± 0.11	1.4	81.7

4. Discussion

4.1. Field-Demonstration Contribution of the NDVI-Guided Stepwise Variable-Rate Applicator

This study uses the previously developed and characterized applicator [21,22] within a separate six-strip rice split-management trial. Its additional contribution is treatment-level seasonal fertilizer-input accounting, grain-yield measurement, and descriptive PFP_N for the two complete management schedules, rather than a new validation of platform response, application accuracy, or spatial variable-rate delivery.

The aggregate field-collection estimate for the 45 DAT sensor-guided event was $100.92 \text{ kg urea ha}^{-1}$, equivalent to $46.42 \text{ kg N ha}^{-1}$. This value supports seasonal-input accounting but does not resolve the spatial frequency or location of individual rate commands. The sensor-guided third split increased late-season urea input relative to the uniform third split; the seasonal saving resulted from the complete split schedule. The study therefore provides use of the previously developed applicator within the treatment comparison rather than trial-specific verification of spatial variable-rate delivery.

4.2. Canopy NDVI Variability Across Growth Stages

NDVI variability declined across growth stages in both treatments. Higher early-stage variability at 21 DAT is consistent with incomplete canopy closure and greater soil-background influence in optical canopy sensing, whereas lower variability at 35 and 59 DAT is consistent with increasing canopy cover and reduced marginal sensitivity of NDVI in denser canopies [8,9,12]. Active-sensor studies in rice likewise show that an NDVI-based diagnosis must be interpreted relative to crop stage and canopy development rather than treated as a universal direct proxy for final yield [10–12].

The NDVI-guided split-management treatment did not show lower NDVI CV than the uniform split-management treatment; its CV values were slightly higher at all three measured stages. CV declined over time in both treatments, but CV without the corresponding mean NDVI cannot establish convergence in mean crop N status or canopy uniformity. The results therefore support only the narrower observation that relative within-treatment NDVI variability declined during crop development.

4.3. Yield Response and Nitrogen Productivity

The NDVI-guided split-management treatment produced a higher measured strip mean than the uniform split-management treatment in this single trial. Calculated PFP_N was also higher under the NDVI-guided split-management treatment. However, the treatments differed in the first two fertilizer splits, the estimated third-split rate, total seasonal N input, N timing, and application method. Consequently, the observed yield and calculated PFP_N differences cannot be attributed specifically to NDVI sensing, stepwise variable-rate control, or the applicator. The positive difference in each of the three adjacent strip pairs is therefore reported as descriptive consistency within the tested layout rather than as statistical evidence of agronomic superiority.

4.4. Implications for Low-Cost Precision Fertilizer Management

The engineering implication of this study is that a deterministic NDVI-to-rate rule can be implemented through a low-cost granular fertilizer applicator using limited sensing and control hardware. Locally adaptable variable-rate systems may broaden access to precision fertilizer management where high-capital platforms are impractical [19,20]. This study does not present a new algorithm; it evaluates field implementation of an auditable control rule on a deployable hardware platform.

The NDVI thresholds and rate-mapping parameters used here should not be treated as general rice N recommendation thresholds. They were retained to evaluate field de-

ployment of a fixed deterministic rule [21,22]; application to other cultivars, establishment methods, soil backgrounds, seasonal conditions, and yield environments will require recalibration and multi-season validation. Low NDVI can also result from poor stand establishment, disease, water stress, or soil-background effects; therefore, the rule should not be interpreted as a specific diagnosis of N deficiency. Here, “low-cost” refers to the historical retrofit designation and not to a current itemized economic comparison.

4.5. Limitations

This study has several limitations. The trial was conducted at a single site in one growing season and used a fixed alternating-strip layout, so residual spatial confounding cannot be excluded. Only the third fertilizer split was sensor-guided, while the first two splits differed between treatments. The design also lacked equal-early-split, equal-total-N, fixed-rate-machine, and manual-versus-machine controls; therefore, the effects of sensing, N timing, total N, and application method cannot be separated. The third-split amount was estimated from aggregate field-collection measurements rather than from a spatially resolved as-applied map. Exact pass geometry and boundary crossing, the implemented sensor-to-outlet offset and look-ahead interval, headland-transition logs, lateral sensor-row alignment, continuous controller and GPS logs, the complete original point-level NDVI dataset and replication-resolved NDVI summary statistics, exact harvest-subarea coordinates and selection records, and the original strip-by-strip manual-application weighing records were not retained for the present analysis. Initial mineral N, lateral NDVI validation, manual-broadcast uniformity, leaf N concentration, chlorophyll, biomass, plant N uptake, yield components, grain-quality traits, post-harvest soil N, and environmental N losses were not measured or were not available. Consequently, yield and calculated PPF_N should be interpreted as descriptive outcomes of the complete split-management comparison, and environmental interpretation should be limited to the difference in estimated fertilizer input.

5. Conclusions

This study used a low-cost NDVI-guided stepwise variable-rate urea topdressing applicator during the third fertilizer split in a single-site, single-season rice strip comparison. The complete NDVI-guided split-management treatment had a lower estimated seasonal urea input, although its sensor-guided third split had a higher aggregate field-collection estimate than the prescribed uniform third split. The NDVI-guided split-management treatment also produced higher measured yield and calculated PPF_N in this single strip trial. However, the pooled third-split estimate was not replicated by strip or linked to the harvest subareas, and the retained telemetry and pass records do not verify rate-class switching or complete strip coverage.

The observed yield and treatment-level PPF_N differences cannot be attributed solely to NDVI sensing or stepwise variable-rate control because the early split rates, third-split rate, total seasonal N input, N timing, and application method differed between treatments, and the trial used three fixed adjacent strip pairs at one site in one season. The principal contribution is therefore the separate split-management and harvest dataset and its treatment-level fertilizer-input and yield accounting, not a new validation of platform performance or a mechanistic agronomic test. Future studies should use randomized multi-site and multi-season designs with matched early-split and total-N schedules, fixed-rate-machine and manual-versus-machine controls, independent application-rate verification, continuous controller and position logging, and additional soil, plant, grain, and environmental N-loss measurements.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/agriengineering8080325/s1>, Table S1. Subarea-level grain-yield values used to calculate the strip-level treatment summaries.

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