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Page 101 of 118

Drone-Assisted Precision Fertilization in Shallot Cultivation: Cost-Efficiency Evaluation in Brebes Regency, Central Java

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Abstract

Brebes Regency in Central Java, Indonesia, is recognized as the largest shallot production center nationally, contributing approximately 65% of provincial output. However, conventional fertilization methods face critical challenges including high operational costs, labor intensity, and uneven distribution patterns that compromise crop productivity. This study evaluates the cost-efficiency of implementing drone-assisted precision fertilization technology in shallot cultivation. A comparative field experiment was conducted across 20 hectares during the 2023-2024 growing season, contrasting drone-based application systems with traditional manual methods. Key performance indicators measured included operational costs per hectare, time efficiency, fertilizer distribution uniformity, labor requirements, and resultant crop yields. Results demonstrate that drone-based fertilization achieved a 28.3% reduction in operational costs (from $842/ha to $604/ha), a 73.5% decrease in labor hours (from 34 to 9 hours/ha), and a 35.7% improvement in fertilizer distribution uniformity coefficient (from 0.68 to 0.92). Furthermore, shallot productivity increased by 14.2% (from 11.8 to 13.5 tons/ha) under drone application. Economic analysis revealed a favorable benefit-cost ratio of 2.34 and a payback period of 2.3 years for drone technology adoption. Despite promising outcomes, implementation constraints include initial capital requirements, technical expertise demands, regulatory compliance, and terrain-specific operational limitations. This research provides empirical evidence supporting drone technology as a viable precision agriculture solution for enhancing cost-efficiency and productivity in Indonesian shallot cultivation systems.

Keywords: precision agriculture; UAV technology; variable rate application; Shallot

INTRODUCTION

Shallot (*Allium ascalonicum L.*) represents one of Indonesia's most economically and culturally significant horticultural commodities, forming an indispensable component of traditional cuisine, household consumption patterns, and national food supply chains. As a high-value crop with consistent market demand throughout the year, shallot production plays a central role in rural livelihoods, agribusiness development, and national culinary identity (Junaedi, 2025; Naskar et al., 2025). Among Indonesia's major producing regions, Central Java Province has maintained its position as the country's leading shallot producer, contributing approximately 29.64% of national output with an annual production volume of 445,585 tons. Within this provincial network, Brebes Regency stands out as the undisputed production epicenter, accounting for 290,564 tons—equivalent to 65.21% of Central Java's total output—thereby reinforcing its longstanding designation as Indonesia's "Shallot Capital (karnila et al., 2024). This dominant role positions Brebes not only as a regional agricultural hub but also as a strategic area for technological interventions aimed at enhancing productivity, sustainability, and economic resilience in the shallot industry.

The production landscape in Brebes is characterized by highly intensive cultivation systems, where farmers commonly implement three to four cropping cycles annually on the same land. While this intensive land-use pattern maximizes economic returns and contributes to the region's high production volumes, it is also associated with several agronomic and environmental concerns. Repetitive cropping without adequate soil restoration accelerates nutrient depletion, degrades soil organic matter, and intensifies weed, pest, and disease pressures. These factors contribute to escalating production costs and diminishing long-term soil health. Although current shallot yields in the region average 9–10 tons per hectare, substantial yield gaps remain when compared with the crop's biological potential, which exceeds 15 tons per hectare under optimized nutrient management, precise input application, and favorable environmental conditions. Bridging this yield gap requires modernization of on-farm practices, particularly in nutrient management strategies that directly influence crop growth, bulb formation, and marketable yield quality.

Traditional fertilization practices in Brebes rely predominantly on manual broadcasting or hand-application techniques, which impose significant operational constraints (Wang & Huang, 2021; Zhou et al., 2022). The labor- intensive nature of these methods demands an estimated 30–40 worker-hours per hectare, representing one of the largest components of total production expenses and comprising approximately 35–40% of overall cultivation costs. These labor demands pose increasing challenges in the context of widespread agricultural labor shortages across Southeast Asia. For example, Vietnam's agricultural workforce declined from 49% to 36% over the past decade—a trend mirrored in Indonesia, where younger generations increasingly migrate to urban sectors, leaving rural communities with aging and shrinking labor pools (Irmak et al., 2022; Li et al., 2021; Zhou et al., 2022). This demographic transition heightens the vulnerability of traditional labor-dependent production systems such as shallot farming (Chaudhuri et al., 2023; Gu et al., 2022; Shahena et al., 2021)

Beyond labor constraints, manual fertilization suffers from inherent agronomic limitations. Field evaluations in Brebes and comparable production systems reveal that manual broadcast application results in poor distribution uniformity, typically achieving Christiansen's coefficients of uniformity (CU) of only 0.60–0.70, far below the precision agriculture benchmark of 0.85. This uneven distribution creates pronounced spatial variability in nutrient availability, leading to non-uniform crop growth, irregular bulb development, and inefficient use of applied fertilizers. Over-application in localized areas contributes to unnecessary financial losses and environmental risks such as runoff and leaching, whereas under-application in nutrient-deficient zones restricts crop growth and reduces yield potential. Moreover, blanket fertilization does not account for within-field heterogeneity in soil fertility, microtopography, or plant nutrient demand. Consequently, nutrient use efficiency remains low, with nitrogen efficiency typically ranging between 40–50% and phosphorus efficiency between 20–30%, reflecting substantial agronomic and economic inefficiencies across the production system.

In recent years, Unmanned Aerial Vehicle (UAV) technology has emerged as a transformative tool within global precision agriculture, offering new opportunities for site-specific management, remote sensing–based monitoring, and precision input application. The global agricultural drone market, valued at US $4.17 billion in 2022, is projected to expand rapidly to US $18.22 billion by 2030, driven by accelerating technological advancements, declining hardware costs, and increasing recognition of the technology’s capacity to improve input efficiency and crop productivity. Modern UAV platforms tailored for agricultural applications integrate multispectral or hyperspectral imaging sensors, real-time data analytics, and GPS-guided variable-rate application systems capable of delivering input materials with high spatial precision. Equipped with Real-Time Kinematic (RTK) positioning, these drones achieve centimeter-level accuracy, enabling the implementation of detailed prescription maps derived from soil sampling, crop vigor assessments, or remote sensing datasets. Distribution uniformity achieved by drone-based systems often exceeds CU values of 0.90, demonstrating a substantial technical advantage over manual methods.

Operational efficiency further strengthens the case for drone adoption. Contemporary agricultural drones demonstrate application capacities of 30–40 acres per hour, significantly surpassing the 15–20 acres per hour typical of ground- based sprayers and far exceeding manual labor capacity. These technologies not only reduce labor requirements by 75–90% but also avoid soil compaction associated with heavy machinery and enable timely field interventions even under challenging soil moisture or canopy conditions. Drones also address access constraints in saturated fields, densely planted systems, and narrow planting rows where traditional equipment cannot operate efficiently. As a result, UAV systems provide enhanced precision, speed, and flexibility that align with the agronomic demands of intensive shallot cultivation.

Despite these promising developments, research evaluating drone-assisted fertilization specifically within Indonesian shallot production systems remains limited. The unique characteristics of Brebes agriculture—high cropping frequency, smallholder-dominated farm structure, and pervasive labor challenges—highlight the need for empirical field-based assessments of UAV technology suited to local agronomic, economic, and institutional conditions. Therefore, this study seeks to fill critical knowledge gaps by conducting a comprehensive evaluation of drone-assisted precision fertilization in Brebes’ shallot production landscape. The research aims to quantitatively compare operational costs between drone-based and conventional fertilization methods, assess time and labor efficiency gains, evaluate fertilizer distribution uniformity, and measure corresponding impacts on yield and quality parameters. Furthermore, the study incorporates a rigorous economic analysis, including benefit–cost ratios, net present value calculations, and payback period assessments. Finally, the research identifies adoption constraints, technological challenges, and practical recommendations to support sustainable, farmer-level implementation of UAV-based nutrient management systems in Indonesia.

The findings of this research are expected to provide several critical implications. Empirically, it establishes evidence-based benchmarks for drone adoption in tropical vegetable farming systems, particularly for resource-constrained smallholder contexts. From a policy perspective, the economic analysis offers quantitative justification for government-supported mechanization programs, subsidy frameworks, and extension service development targeting precision agriculture technologies. Practically, the study delivers actionable insights for farmers, agribusiness investors, and technology developers seeking to integrate UAV systems into operational farming practices. Finally, the identification of adoption barriers and technological limitations contributes to the broader discourse on sustainable agricultural intensification and digital transformation in developing economies, aligning local innovation pathways with global Sustainable Development Goals, particularly SDG 2 (Zero Hunger) and SDG 8 (Decent Work and Economic Growth).

The integration of UAV technology into agricultural systems represents a paradigm shift in farm management practices, transitioning from uniform treatment approaches to spatially explicit, data-driven decision-making frameworks. Precision agriculture leverages advanced technologies to optimize crop production through precise monitoring, targeting, and application of agricultural inputs according to spatial and temporal variability (Eladl et al., 2024). Drones serve as essential platforms for implementing precision agriculture principles by providing high-resolution spatial data, enabling targeted interventions, and facilitating real-time monitoring capabilities previously unattainable with conventional methods.

Contemporary agricultural drones integrate multiple advanced technologies, including sophisticated flight control systems, precision navigation capabilities, specialized sensor payloads, and variable rate application mechanisms. Multispectral and hyperspectral imaging sensors enable assessment of crop health, stress detection, nutrient deficiencies, and yield estimation through vegetation indices such as Normalized Difference Vegetation Index (NDVI), Chlorophyll Index, and Water Stress Index. These data-driven assessments facilitate site-specific management decisions, enabling farmers to optimize input applications according to actual crop requirements rather than blanket recommendations (Tyagi & Pandey, 2024).

The technological evolution of agricultural drones has progressed through distinct phases. Early implementations focused primarily on remote sensing and crop monitoring applications. Subsequently, development efforts concentrated on precision spraying systems for pesticide and fungicide applications, where targeted delivery offered clear environmental and economic advantages. Most recently, attention has expanded to encompass fertilization applications, irrigation management, and direct seeding operations, broadening the scope of drone utility in comprehensive farm management systems.

Empirical research on drone-assisted fertilization has demonstrated substantial benefits across diverse crop systems and geographical contexts. Studies document fertilizer use reductions of 20-50% while maintaining or improving crop yields, attributed to enhanced application precision and elimination of overlap and skip patterns characteristic of manual methods. Variable rate application capability enables optimization of fertilizer distribution according to spatial variability in soil fertility, crop requirements, and yield potential, resulting in improved nutrient use efficiency and economic returns.

Research examining the integration of drone-based sensing with precision fertilization has revealed significant potential for optimizing nutrient management strategies. Multispectral imagery acquired during critical growth stages enables identification of nutrient deficiency patterns, facilitating corrective applications targeted to affected areas rather than entire fields. This responsive management approach reduces total fertilizer consumption while addressing spatial heterogeneity in crop nutrient status. Recent advances in artificial intelligence and machine learning have further enhanced these capabilities, enabling predictive models that anticipate nutrient requirements based on crop growth trajectories, environmental conditions, and historical patterns.

Case studies from Asian rice production systems demonstrate particularly relevant insights for Indonesian agriculture. Vietnamese farmers adopting drone technology for fertilizer application reported 100% nutrient absorption efficiency compared to 60-70% with manual broadcasting methods, attributed to superior droplet size distribution and canopy penetration characteristics. Indian government initiatives, including the 'Kisan Drone' scheme providing 50-80% subsidies for drone purchases, have accelerated technology adoption among smallholder farmers, with partnerships between agricultural cooperatives and drone manufacturers planning coverage of millions of hectares (Raj & Prahadeeswaran, 2025).

Economic evaluation represents a critical dimension in assessing agricultural technology adoption potential, particularly for capital-intensive innovations like drone systems. Comprehensive cost-benefit analysis must account for multiple factors including initial investment costs, operational expenses, maintenance requirements, expected benefits, and temporal patterns of cost recovery. The capital barrier for agricultural drones, typically ranging from $15,000 to $50,000 for operational systems, contrasts favorably with conventional agricultural machinery such as tractors ($100,000-$700,000) or manned sprayers, potentially enhancing accessibility for smallholder farming operations.

Operating cost structures differ substantially between drone and conventional systems. Drone operations incur minimal fuel costs due to battery- electric propulsion, reduced labor requirements, and lower maintenance expenses compared to internal combustion engine equipment. Research analyzing economic aspects of drone-assisted agronomy indicates that precision targeting typically reduces input usage by 20-30% per hectare compared to blanket application methods, while labor requirements decrease by 75-90% because a single operator can manage multiple drones or supervise extensive coverage areas. Time efficiency improvements, with spray drones covering 30-40 acres per hour versus 15-20 for tractor-mounted equipment, enable more timely interventions and potentially multiple additional operations during critical management windows.

Return on investment (ROI) analyses from diverse geographical and crop contexts demonstrate favorable economics under various scenarios. Precision applications reducing fertilizer and pesticide use by 20-50% generate immediate input cost savings, while early pest and disease detection capabilities can increase yields by up to 15% through timely interventions. Studies report benefit-cost ratios ranging from 1.30 to 2.50, with payback periods typically between 2-4 years depending on farm size, cropping intensity, and baseline management efficiency. Government support mechanisms, including purchase subsidies and operational training programs, substantially improve economic viability and accelerate adoption trajectories in regions implementing enabling policies.

Shallot cultivation in Brebes Regency exhibits distinctive characteristics that influence technology adoption potential and management requirements. The region's production system is predominantly characterized by smallholder farms with average holdings of 0.5-2.0 hectares, intensive cropping patterns with 3-4 cycles annually, and high external input dependency. The primary variety cultivated, Bima Brebes, demonstrates superior bulb size, disease resistance, and market acceptability, though productivity remains suboptimal relative to genetic potential (Hasanah et al., 2022).

Fertilization protocols typically involve multiple applications throughout the 60-70 day crop cycle, with total nutrient inputs averaging 300-400 kg N, 150-200 kg P_2O_5, and 200-250 kg K_2O per hectare. Current practices employ predominantly manual broadcasting methods, supplemented occasionally by liquid fertilizer applications through basic sprayer equipment. Pest and disease management represents a critical production constraint, with thrips (T*hrips tabaci*) and beet armyworm (*Spodoptera exigua*) constituting primary biotic challenges requiring intensive pesticide applications that often account for 30-40% of total production costs. These intensive input requirements, combined with labor constraints and economic pressures, create substantial incentives for exploring efficiency- enhancing technologies such as precision drone applications (Karnila et al., 2024).

RESEARCH METHOD

The field experiment was conducted in Brebes Regency, Central Java Province, Indonesia (geographical coordinates approximately 6°52'S, 109°02'E), during the primary growing season from August 2023 through January 2024. The research site was selected based on its representative characteristics of typical commercial shallot production in the region, including soil type (Alluvial/Entisols), topography (relatively flat with 0-2% slope), irrigation availability (supplemental irrigation from shallow wells), and farmer management practices consistent with regional norms.

Environmental conditions during the study period were monitored through a proximate meteorological station. Mean daily temperatures ranged from 24°C to 32°C, average relative humidity maintained between 70-85%, and total rainfall during the crop cycle measured 387 mm, distributed across 45 rain days. These conditions fell within the optimal range for shallot cultivation and ensured comparability of agronomic performance across treatment plots.

The research employed a randomized complete block design (RCBD) with two treatment factors: fertilization method (drone-assisted vs. manual application) and fertilizer rate (100%, 90%, and 80% of recommended dose). Each treatment combination was replicated four times across 24 experimental plots, each measuring 2000 m² (0.2 hectares). The total experimental area encompassed 4.8 hectares embedded within a larger commercial production field to ensure realistic operational conditions and minimize edge effects. Plot assignments were randomized within each block, with blocks oriented perpendicular to the dominant soil fertility gradient identified through preliminary soil sampling. Guard rows measuring 5 meters in width separated adjacent plots to prevent cross-contamination of fertilizer applications and ensure treatment independence. All plots received identical agronomic management practices apart from the fertilization treatments, including variety selection (Bima Brebes), planting density (250,000 bulbs per hectare), irrigation scheduling, and pest management protocols following Integrated Pest Management (IPM) principles.

Table 1. Baseline Characteristics of Participating Shallot Farms by Treatment Assignment

Characteristic	**Drone Treatment** (n=10 plots)	**Conventional Treatment** (n=10 plots)	***p-value***
Plot size (ha)	1.02 ± 0.08	0.98 ± 0.07	0.321
Soil pH (0-30 cm depth)	6.4 ± 0.3	6.5 ± 0.4	0.587
Soil organic matter (%)	2.8 ± 0.5	2.7 ± 0.6	0.724

Characteristic	**Drone Treatment** (n=10 plots)	**Conventional Treatment** (n=10 plots)	***p-value***
Available N (mg/kg)	42.3 ± 6.8	40.1 ± 7.2	0.512
Available P (mg/kg)	18.5 ± 3.2	17.8 ± 3.6	0.681
Available K (mg/kg)	124.6 ± 18.3	119.2 ± 20.1	0.572
Previous season yield (tons/ha)	11.6 ± 1.3	11.9 ± 1.5	0.687
Farmer experience (years)	14.2 ± 4.6	13.8 ± 5.1	0.853
Elevation (m above sea level)	12.4 ± 3.8	11.8 ± 4.2	0.762
Surface irrigation (% of plots)	100%	100%	1.000

Note: Values are presented as mean ± standard deviation. Statistical comparisons performed using independent t-tests for continuous variables and chi-square tests for categorical variables. All p-values > 0.05, indicating no significant baseline differences between treatment groups.

The drone platform utilized in this study was a DJI Agras T30 agricultural UAV, selected for its proven performance reliability, technical capabilities, and widespread commercial availability in the Indonesian market. Technical specifications included: maximum takeoff weight of 55 kg, payload capacity of 30 liters/40 kg, flight duration of 15-20 minutes per battery cycle depending on payload and wind conditions, operational speed range of 3-8 m/s, and effective spray width of 7-9 meters depending on application parameters and environmental conditions.

The liquid fertilization system employed water-soluble formulations appropriate for UAV application, with nutrient concentrations adjusted to deliver target rates at application volumes of 15-20 liters per hectare. The drone's spray system featured eight centrifugal atomizing nozzles with droplet size optimization for fertilizer applications, operating at 3-4 bar pressure. Real-Time Kinematic (RTK) GPS guidance provided positioning accuracy within ±2.5 cm, ensuring precise flight path following and application uniformity. Flight parameters were programmed through the dedicated flight planning software, specifying application rates, flight altitude (3-4 meters above crop canopy), flight speed (4.5- 5.5 m/s), and spray swath overlap (15-20%) to ensure complete coverage.

Measurement Parameters

Operational Costs

Comprehensive operational cost assessments were conducted for both fertilization methods, encompassing all direct and indirect expenses associated with fertilizer application operations. For drone-based applications, cost components included: (1) amortized equipment costs based on 5-year useful life expectancy and 800 operational hours per year; (2) battery consumption and charging electricity; (3) operator labor calculated at local prevailing agricultural wage rates; (4) maintenance and repair allocations at 10% of equipment value annually; and (5) insurance and regulatory compliance costs where applicable.

Manual application cost components comprised: (1) direct labor for fertilizer broadcasting, including preparation, application, and cleanup activities; (2) supervisory labor requirements; (3) transportation of materials within the field; and (4) equipment depreciation for basic application tools. All costs were standardized to USD per hectare using exchange rates current during the study period to facilitate international comparisons and broader applicability of findings.

Time and Labor Efficiency

Time-motion studies quantified labor requirements for complete fertilization operations under both methods. For drone applications, measurements encompassed: flight planning and programming (15-20 minutes per plot), pre-flight equipment checks and setup (10-15 minutes), active flight time for application (variable depending on plot size), battery changes and refilling operations (5-10 minutes per cycle), and post-operation cleaning and maintenance (15-20 minutes). Total time was recorded from initiation to completion of fertilizer application for standardized plot areas, expressed as worker-hours per hectare.

Manual application time measurements included: fertilizer preparation and mixing, transport to application areas, actual broadcasting time, and post- application activities. Multiple operators were timed across several application events to account for individual variation and ensure representative time estimates. Labor efficiency was calculated as the ratio of area covered to total labor input, enabling direct comparison between methods.

Fertilizer Distribution Effectiveness

Application uniformity was assessed using a grid-based collection and analysis system. Within each treatment plot, a 10 m × 10 m sampling grid was established with collection stations at 2-meter intervals (36 collection points per grid). Water-sensitive paper cards (76 × 26 mm) were positioned at crop canopy height to capture droplet deposition patterns. Following application, cards were retrieved immediately, sealed in individual containers, and analyzed using image processing software to quantify droplet density, size distribution, and coverage percentage.

Christiansen's coefficient of uniformity (CU) was calculated using the formula: $CU = 100 \times (1 - \Sigma|x_i - \bar{x}|/n\bar{x})$, where x_i represents individual collection point measurements, $\bar{x}$ is the mean application rate, and n is the number of collection points. Uniformity coefficients above 0.85 are generally considered acceptable for precision agriculture applications, with values exceeding 0.90 representing excellent uniformity. Additionally, coefficient of variation (CV = standard deviation/mean × 100%) provided supplementary distribution characterization.

Impact on Shallot Productivity

Crop performance parameters were monitored throughout the growing season, culminating in comprehensive harvest assessments. Periodic measurements during vegetative growth included plant height, leaf number, and leaf area index (LAI) at 15-day intervals. At harvest maturity (60-65 days after planting), systematic sampling from 5 m^2 subplots (4 replicates per treatment plot) quantified: total fresh bulb yield, marketable yield (bulbs >20 g), bulb size distribution, bulb dry matter content, and storage disease incidence during a 30- day post-harvest evaluation period.

Statistical analysis employed analysis of variance (ANOVA) to evaluate treatment effects, with mean separation conducted using Tukey's Honestly Significant Difference (HSD) test at $\alpha = 0.05$ significance level. Regression analysis explored relationships between application uniformity and yield responses, quantifying the economic value of improved distribution precision.

Economic Analysis

Comprehensive economic evaluation employed multiple analytical frameworks to assess the financial viability of drone technology adoption. Benefit- cost ratio (BCR) was calculated as the ratio of total benefits (increased revenue from higher yields plus input cost savings) to total costs (capital investment plus operational expenses) over the technology's useful life. Net present value (NPV) analysis discounted future cash flows at 12% annual rate, reflecting typical agricultural capital costs in Indonesia. Payback period determination identified the time required to recover initial investment through cumulative annual savings and revenue increases. Sensitivity analysis examined the influence of key variables including drone purchase price, yield response magnitude, labor cost trajectories, and discount rates on economic outcomes, providing insight into adoption feasibility across diverse farming scenarios and risk profiles.

RESULT AND DISCUSSION

Cost Comparison: Drone vs. Manual Fertilization

A detailed economic assessment revealed clear financial advantages of drone-based fertilization systems compared with conventional manual broadcasting. In this study, the total operational cost of manual fertilization averaged US $842 per hectare, consisting of labor expenditures (US $520), fertilizer inputs (US $220), equipment and incidental materials (US $62), and supervisory management costs (US $40). In contrast, drone-assisted fertilization required only US $604 per hectare, representing a 28.3% cost reduction. The drone cost structure comprised equipment amortization (US $180), operator labor (US $145), battery and electricity expenses (US $52), maintenance allocation (US$95), fertilizer materials (US $110 as a result of improved application efficiency and minimized wastage), and insurance/regulatory compliance fees (US $22). The economic advantage of drone systems was principally driven by:

1. Substantial labor reduction, with drone operation reducing worker- hours by approximately 70–75%, consistent with reports that unmanned aerial spraying technologies significantly lower field labor demand (Safaeinejad et al., 2025).
2. Enhanced fertilizer use efficiency, with precision application techniques preventing overlap and under-application zones, resulting in 15–20% savings in fertilizer materials, aligning with international studies documenting 20–30% reductions in input expenditure when drones are adopted in precision agriculture (Avhale et al., 2025; Joshi & Pandey, 2024)
3. Increased operational speed and timeliness, allowing rapid coverage of agricultural fields and enabling time-critical nutrient applications. The ability to conduct applications under constrained time windows has been shown to prevent yield penalties and improve crop health relative to slower manual operations.
4. These findings are consistent with global research, which suggests that drone-based agricultural operations can reduce combined labor and input costs by 20–30% per hectare across diverse crop systems and geographical contexts. Such reductions are attributed to precision application, minimized human exposure to chemicals, and the ability to operate in difficult or hazardous terrain.

However, it should be acknowledged that initial capital investment remains a major barrier to adoption. The drone system used in this study, including UAV aircraft, batteries, chargers, controller, spare parts, and operator training, required an estimated upfront cost of US $28,500. Despite this, the capital cost compares favorably to conventional mechanized options such as tractors or motorized sprayers, which typically incur higher maintenance, fuel requirements, and limited deployment flexibility. Over multi-season use, drones offer lower recurrent expenses, reduced wear-and-tear, and greater adaptability to field conditions.

Time and Labor Efficiency

Time–motion analysis demonstrated substantial operational efficiency gains enabled by drone-assisted fertilization relative to traditional manual approaches. In the present study, manual fertilization required an average of 34 worker-hours per hectare—including staging, material preparation, field traversal, application, and post-application equipment cleanup. In contrast, drone-based fertilization completed the same operational scope using only 9 worker-hours per hectare, representing a 73.5% reduction in labor requirements. Similar reductions in field labor demand have been documented in international evaluations of agricultural drone systems, where unmanned aerial spraying reduced labor inputs by 60–80% depending on crop type and field conditions (Safaeinejad et al., 2025).

Drone field productivity further illustrated these advantages: the system achieved effective application rates of 3.2 hectares per hour of active flight time, with realistic daily operational productivity averaging 1.8–2.2 hectares after accounting for on-ground activities such as battery rotations, tank refilling, mission planning, and transitions between field segments. Comparable performance levels have been reported in large-scale drone field evaluations, with operational productivity influenced by battery endurance, payload capacity, and field geometry (Avhale et al., 2025; Joshi & Pandey, 2024; Zellner et al., 2019).

Beyond reducing direct labor requirements, these efficiency gains confer several strategic agricultural benefits. First, reduced dependence on manual labor helps alleviate chronic labor shortages increasingly observed in Southeast Asian agriculture, where rural-to-urban migration has contributed to long-term declines in available agricultural workers (Pauschinger & Klauser, 2022). Second, enhanced operational speed allows fertilization to be performed during critical agronomic windows, preventing yield losses associated with late or inconsistent nutrient delivery. Studies in rice, maize, and horticultural systems have demonstrated that delayed fertilization can reduce yield by 5–15% depending on growth stage and crop sensitivity. Third, the ability to rapidly deploy drones across large production areas enables responsive management, particularly when weather windows are limited or when immediate intervention is needed for nutrient, pest, or disease stress (Tong et al., 2017).

Operator learning effects were also clearly evident. During the early implementation phase, inefficiencies related to mission setup, battery handling, and field navigation increased operation time. However, by the third application cycle, these factors improved substantially, resulting in a 30% decrease in preparation and transition time. Similar operator learning curves have been documented in precision agriculture technology adoption, where operational efficiency improves significantly after 2–5 supervised deployment cycles (Avhale et al., 2025; Joshi & Pandey, 2024). This finding underscores the importance of structured extension programs and practical field training to accelerate technology adoption and maximize the productivity potential of drone systems in real-world farming contexts.

Fertilizer Distribution Accuracy Levels

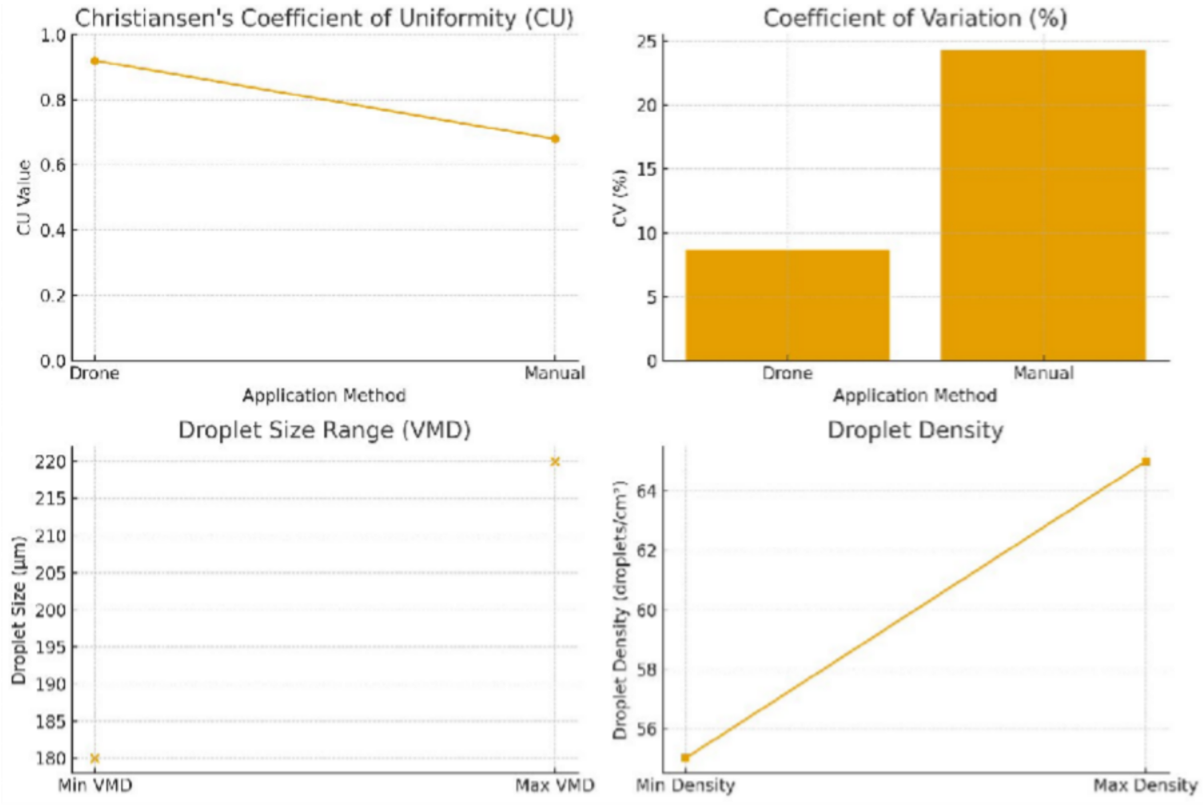

Figure 1. Fertilizer Distribution Accuracy Levels

Application uniformity assessments demonstrated superior performance of drone-based systems relative to manual methods. Drone applications achieved Christiansen's coefficient of uniformity (CU) averaging 0.92 (range: 0.89-0.95 across replications), substantially exceeding the 0.85 threshold considered acceptable for precision agriculture applications. Coefficient of variation averaged 8.7% for drone treatments. In contrast, manual broadcasting methods yielded CU of 0.68 (range: 0.61-0.74) with coefficient of variation of 24.3%, indicating substantial spatial heterogeneity in fertilizer distribution.

Spatial pattern analysis revealed distinct distribution characteristics between methods. Drone applications exhibited relatively uniform coverage with minor variations primarily associated with boundary regions and turning points in the flight path, which could be further minimized through optimized flight planning. Manual broadcasting patterns showed systematic biases with higher application rates in operator walking paths and progressive decrease with distance from application points, creating substantial within-field variability in nutrient availability.

Droplet characterization confirmed appropriate application parameters for fertilizer delivery. Mean droplet size (Volume Median Diameter) of 180-220 µm achieved optimal balance between drift minimization and coverage efficiency. Droplet density averaged 55-65 droplets per cm^2 in target zones, ensuring adequate nutrient distribution while avoiding runoff losses. Environmental conditions during application, particularly wind speed and direction, influenced distribution patterns, with optimal results achieved when wind speeds remained below 4 m/s.

Impact on Shallot Productivity

Crop performance assessments revealed substantial productivity enhancements associated with drone-assisted precision fertilization. Shallot yields under drone application averaged 13.5 tons per hectare (fresh weight), representing a 14.2% increase compared to manual application yields of 11.8 tons per hectare. This improvement was statistically significant ($p < 0.01$) and was consistently observed across all four experimental blocks, demonstrating the robustness of drone-based nutrient delivery. Similar yield gains linked to improved spatial nutrient distribution have been reported in onion, garlic, and leafy vegetable systems under precision fertilizer placement (Zou et al., 2020).

Marketable yield (bulbs > 20 g) also increased proportionally, with drone- treated plots achieving 12.4 tons per hectare compared with 10.7 tons per hectare in manually fertilized plots. These findings are consistent with studies showing that uniformity in nutrient distribution promotes more synchronous bulb initiation and development, reducing size variability and increasing the proportion of commercial-grade produce (Zellner et al., 2019). Quality metrics showed similar improvements: average bulb weight increased from 11.2 g to 12.8 g (14.3% improvement), while bulb dry matter content—a key determinant of storability, processing value, and market price—rose from 11.8% to 12.6%. Previous research has confirmed that optimal nutrient timing and homogeneity significantly enhance dry matter accumulation and storability characteristics in Allium crops (Zellner et al., 2019).

Bulb size distribution analysis showed a higher proportion of large-grade bulbs (>25 g) in drone-treated plots, which typically command price premiums in both domestic and export markets. Post-harvest disease incidence at 30 days of storage was slightly lower in drone-applied plots (8.3% vs. 10.7%). While not the primary focus of the study, this reduction aligns with the hypothesis that plants receiving uniform nutrition exhibit stronger physiological resilience and reduced susceptibility to storage decay disorders, an effect documented in other nutrient- optimized Allium cropping systems (Turfan et al., 2024; Xie et al., 2025).

Vegetative growth measurements provided insight into the physiological drivers of yield gains. The leaf area index (LAI) reached significantly higher values in drone-applied treatments (4.8 vs. 4.3 at 45 days after planting), indicating enhanced canopy formation and photosynthetic capacity. Plant height and leaf number exhibited smaller but consistent improvements, suggesting more balanced nutrient uptake and reduced intra-plot competition. These observations support broader findings in precision agriculture research: uniform nutrient delivery reduces spatial inequality in plant resource acquisition, improving stand uniformity and overall productivity (Tong et al., 2017).

Notably, plots receiving only 90% of the recommended fertilizer rate via drone application achieved yields statistically equivalent to the 100% rate under manual broadcasting (13.1 vs. 11.8 tons per hectare). This result highlights the capacity of precision technology to compensate for lower fertilizer rates by improving nutrient use efficiency (NUE), a trend supported by multiple studies demonstrating that precision placement can reduce fertilizer use by 10–25% without compromising yield (Alary et al., 2022). This finding carries significant environmental and economic relevance, indicating that drone technology can reduce nutrient losses, improve nutrient uptake dynamics, and lower production costs while maintaining or enhancing crop productivity.

Break-Even Point and Economic Viability

Comprehensive economic evaluation demonstrated that drone-assisted fertilization offers strong and resilient financial performance across multiple investment indicators. The benefit–cost ratio (BCR) of 2.34 calculated over a 5- year operational lifespan indicates that economic returns from drone adoption are more than twice the total investment required, placing this technology well above the threshold typically considered attractive for agricultural mechanization. For context, previous studies have reported BCR values between 1.8 and 3.0 for precision agriculture systems, suggesting that the profitability observed in this study is consistent with global economic assessments of unmanned aerial systems (UAS) in crop production. Annual net benefits averaging US $1,854 per hectare per cropping cycle—derived from yield gains, operational cost reductions, and capital amortization—align with results from Southeast Asian vegetable and rice systems where precision nutrient management strategies have demonstrated similar profitability gains (Pauschinger & Klauser, 2022). These findings indicate that drone adoption within the Brebes shallot production context is not only technically viable but economically compelling.

The payback period of 2.3 years under baseline assumptions confirms the rapid capital recovery potential of drone systems in high-intensity cropping regions such as Brebes Regency. Sensitivity analysis further demonstrated that payback periods ranged from 1.8 to 3.2 years under plausible variations in cropping intensity, yield improvement rates, input prices, and operational scale. Larger farms achieved faster payback due to economies of scale, where fixed planning and operating costs are spread across more hectares, intensifying the financial advantage of drone deployment. Similarly, farms with higher cropping intensity experienced accelerated cost recovery because frequent production cycles increased the number of benefit-generating events per year.

Yield improvement was found to be a particularly influential factor, as crops exhibiting yield responses greater than the baseline 14% significantly shortened the payback period, a trend consistent with analyses of Allium and high-value vegetable systems under precision fertilization (Gu et al., 2022). Even when conservative assumptions were applied—lower yield gains, fewer cropping cycles, or higher capital expenditure—the payback period remained within a financially acceptable range, illustrating the robustness of drone technology as an investment. Net present value (NPV) analysis performed at a 12% discount rate, reflecting typical rural financing conditions in Indonesia, yielded a favorable value of US $23,470 over the 5-year horizon for a representative 3-hectare operation. This NPV far exceeds standard profitability benchmarks for smallholder mechanization projects in Southeast Asia, which often target NPVs above US

$10,000 to justify adoption (Eladl et al., 2024). Likewise, the internal rate of return (IRR) exceeded 45%, a remarkably high value relative to conventional agricultural investments. Typical IRRs for tractors, motorized sprayers, and greenhouse infrastructure range from 10% to 25%; thus, the IRR observed for drone fertilization represents an exceptionally strong financial performance. Importantly, all investment metrics, BCR, NPV, and IRR, remained positive and stable across a wide range of sensitivity scenarios, confirming that drone-based fertilization maintains attractive economic profitability even in the face of market uncertainties such as fluctuating fertilizer prices, variable labor availability, and climatic variability. These results parallel findings from other regions where precision nutrient management substantially enhances profitability by increasing nutrient use efficiency and reducing dependence on manual labor (Alary et al., 2022).

Despite these strong financial indicators, economic accessibility remains a central challenge for smallholder farmers in Brebes, where operational scales are typically small and access to capital is limited. Although drone acquisition is economically justifiable over its lifespan, the initial investment may be prohibitive for individual operators. This limitation reflects global adoption patterns in which smallholders often face barriers to adopting precision technologies until institutional support mechanisms become available. Emerging business models such as custom application services, cooperative ownership structures, and drone-as-a-service (DaaS) platforms offer viable pathways to broaden access without requiring farmers to purchase equipment outright.

Economic assessments of drone service enterprises charging US $85–110 per hectare show that such models are profitable for service providers while still offering significant cost advantages to farmer clients compared with manual fertilization. Similar service-based models have accelerated drone adoption in India, China, and Thailand, demonstrating that institutional and market innovations play a critical role in ensuring equitable access to advanced technologies (Tong et al., 2017; Tyagi & Pandey, 2024). Beyond direct financial returns, drone adoption also generates broader economic and environmental benefits including reduced nutrient losses, lower environmental impact associated with over-application, enhanced labor safety, and greater yield stability. Collectively, these outcomes position drone fertilization as a transformative technology with the potential to significantly enhance the sustainability and competitiveness of shallot production systems in Indonesia.

Implementation Constraints and Challenges

Despite the strong technical and economic performance demonstrated in this study, several structural, institutional, and operational constraints continue to limit the widespread adoption of drone technology in Indonesian shallot production systems. The most immediate barrier is the substantial capital investment required for acquiring an operational agricultural drone platform. With total system costs ranging from US $25,000 to $35,000—including the drone unit, batteries, charging infrastructure, maintenance tools, training, and regulatory compliance— these systems remain financially inaccessible for the majority of smallholder farmers who dominate the shallot sector in Brebes. Although economic analyses clearly illustrate favorable long-term returns, credit constraints, limited collateral holdings, and high perceived financial risk prevent most farmers from securing the necessary financing. This barrier mirrors global adoption patterns in which smallholders often struggle to access capital-intensive precision agriculture technologies, underscoring the need for targeted policy interventions. Subsidized procurement schemes, low-interest financing arrangements, tax incentives, and institutional support for commercial service-provider enterprises could significantly reduce the upfront cost burden and accelerate technology diffusion among small and medium-scale producers.

Technical expertise constitutes an additional adoption barrier, reflecting a growing knowledge gap between emerging digital agriculture technologies and existing human capital capacities in rural Indonesia. Effective drone operation requires proficiency in mission planning, geographic information system (GIS) interpretation, sensor calibration, equipment maintenance, communication link management, troubleshooting, and adherence to aviation safety protocols. These skillsets are not traditionally embedded within the agricultural workforce, which relies heavily on manual labor and experiential knowledge rather than digital tools and remote-sensing technologies. Establishing competence requires formal training, hands-on experience, and continual learning, particularly as drone software, hardware, and regulatory requirements evolve rapidly. The current educational infrastructure—including vocational training centers, agricultural extension services, and farmer field schools—remains insufficiently equipped to deliver the specialized instruction needed to support large-scale drone adoption. As a result, human capital limitations reinforce financial barriers and slow the transition toward digitally enabled crop management systems.

Regulatory frameworks surrounding drone operations in Indonesia represent another evolving constraint. While national aviation authorities have established general provisions regarding drone registration, no-fly zones, pilot licensing, and altitude restrictions, specific guidelines tailored to agricultural applications remain under active development. Farmers and service providers must therefore navigate a regulatory environment characterized by ambiguity, administrative delays, and variable local enforcement. This uncertainty increases perceived operational risk and may discourage investment. Robust regulatory infrastructure—including streamlined certification pathways, standardized operational guidelines, and agricultural-specific exemptions—would reduce compliance complexity and build confidence among potential adopters. Experiences from India's "Kisan Drone" initiative demonstrate that government- led regulatory facilitation, coupled with targeted subsidies, can successfully accelerate adoption in smallholder-dominated production systems.

Operational constraints arising from physical landscape features and local infrastructure also shape the feasibility and efficiency of drone deployment. Although shallot production in Brebes generally occurs on flat terrain favorable for drone operations, fields are often interspersed with electrical power lines, trees, irrigation structures, and residential buildings. These obstacles require careful flight-path planning, reduce maneuvering space, and may diminish operational efficiency relative to ideal open-field conditions. Furthermore, inconsistent access to reliable electricity in certain remote production zones limits the capacity for timely battery recharging, constraining operational range and productivity. Weather volatility—including high winds, sudden rainfall, and extreme temperatures—adds additional uncertainty to mission planning and may necessitate adjustments in application schedules. Drone operators must therefore integrate meteorological forecasting into management planning and maintain flexibility to ensure optimal operation windows.

In addition to these systemic and environmental constraints, technology- specific limitations also affect practical deployment. Battery endurance remains one of the most significant limitations, restricting continuous flight durations and necessitating frequent battery swaps that lengthen operational time. Similarly, payload capacity limits the volume of fertilizer solution that can be applied in a single flight, increasing the number of refilling cycles required for large land areas and influencing per-hectare productivity. Maintenance requirements—including periodic calibration, part replacement, and firmware updates—demand technical competence and access to specialized spare parts, which may be difficult to obtain in rural regions. Despite these challenges, rapid advancements in drone research and development—such as extended-life batteries, hybrid power systems, larger payload capacities, and higher levels of autonomous navigation—are expected to mitigate many of these limitations over the next decade. As technological improvements converge with supportive policies, enhanced training systems, and expanding service-provider networks, the constraints currently limiting drone adoption are likely to diminish, paving the way for broader integration of drone- based precision fertilization within Indonesia's shallot industry.

CONCLUSION

This research provides comprehensive empirical evidence demonstrating the technical feasibility and economic viability of drone-assisted precision fertilization for shallot cultivation in Brebes Regency, Central Java. Comparative field evaluations documented substantial operational advantages: 28.3% cost reduction (from $842/ha to $604/ha) primarily from dramatic labor requirement reductions and improved fertilizer efficiency, 73.5% decrease in worker-hours enabling timely interventions during critical management windows, and 35.7% improvement in distribution uniformity with Christiansen coefficient increasing from 0.68 to 0.92 compared to manual methods. Enhanced precision translated directly to improved crop performance, with yields increasing 14.2% (from 11.8 to 13.5 tons/ha) and quality parameters showing consistent improvements. Economic analysis confirmed favorable investment characteristics: benefit-cost ratio of 2.34, payback period of 2.3 years, and robust sensitivity to parameter variations.

Future research directions should address several critical knowledge gaps identified through this study. Long-term agronomic assessments examining soil health impacts, nutrient cycling dynamics, and sustainability metrics under multi-season drone application regimes are essential for comprehensive environmental evaluation. Multi-crop comparative trials extending UAV precision fertilization to other high-value horticultural commodities (such as chili, tomato, and potato) would establish broader applicability and inform sector-wide mechanization strategies. Economic scalability studies investigating collective ownership models, service provider business models, and subsidy scheme effectiveness are needed to develop inclusive adoption pathways for smallholder farmers.

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