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RESEARCH ARTICLE

Exploring the feasibility of using drones for seeding of rice (*Oryza sativa. L.*)

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Abstract

Rice planters worldwide face increasing challenges such as water scarcity, labor shortages and rising production costs. Traditional rice production techniques are time-consuming, labor-intensive, less economical and more susceptible to the excessive use of farm inputs. These conditions necessitate an advanced crop establishment technique that offers higher returns with lower input and labor than traditional methods. A field study was performed to assess the viability of employing drones for rice planting compared to alternative establishment methods concerning rice productivity. The treatments consisted of four different seed rates (30, 40, 50 and 60 kg ha^{-1}) for drone seeding, compared with drum seeding, manual broadcasting and transplanting. The performance of drone seeding was assessed using various growth and yield parameters. Transplanted rice exhibited significantly higher growth, yield parameters and grain yield than other methods; however, it was economically inferior to direct seeding methods, either by drum seeder or drones. Direct seeding using a drum seeder at 30 kg ha^{-1} and drone seeding at 40 kg ha^{-1} produced comparable growth and yield. Notably, drone seeding with a 40 kg ha^{-1} seed rate resulted in significantly higher growth, yield parameters and overall yield than manual broadcasting. This method saved 20 kg ha^{-1} of seeds and increased rice yield by 13% compared to manual broadcasting at 60 kg ha^{-1}. Considering the issues of labor scarcity, timeliness of operation and cost of establishment, drone seeding at a rate of 40 kg ha^{-1} is deemed a more sustainable and forward-looking technique for rice crop establishment.

Keywords

drones; direct seeding; rice; seed rate; yield

Introduction

Rice (*Oryza sativa L.*) is an important food crop grown worldwide, (1) constituting over 70% of the calorie intake in many Asian countries (2). In India, rice is cultivated over 48 million hectares, yielding 134 million tonnes, with an average productivity of 2.79 t ha^{-1}. In Tamil Nadu, located in southern India, rice is grown on 22 lakh hectares, producing 75 lakh metric tonnes and achieving a productivity of 3.5 t ha^{-1} (3).

However, rice growers are facing increasing challenges, particularly water and labor scarcity, which compel them to seek alternative methods of rice establishment that require less water and labor. One significant factor contributing to the demand for labor in the agricultural sector is the migration of rural human resources to urban areas (4). In response, farmers are increasingly adopting direct seeding of rice (DSR) using a drum seeder or seed drill (5). Direct seeding of rice facilitates timely establishment and allows for earlier maturation, typically 8-10 days sooner than transplanted rice (6). In wetland conditions, rice can be sown by manual broadcasting or drum seeding, requiring skilled labor for optimal operation and uniform crop establishment.

The agriculture sector has recently experienced a tech-driven transformation using drones for precision farming (7). Various applications of drones in agriculture have emerged, including the spraying of nutrients (8), herbicides (9), pesticides (10), crop imaging and monitoring (11), drought and flood assessment (12), and seeding (13). Drone seeding technology not only reduces the cost of crop establishment and labor requirements but also enables coverage of larger areas in a shorter time (14). Additionally, it ensures uniform seed distribution, promotes optimal plant population and minimizes seed wastage (15). Drone seeding offers significant advantages by decreasing the need for skilled labor in broadcasting and providing optimal plant density, resulting in better yield and higher resource use efficiency (16). In India, rice is cultivated over vast areas with shorter sowing windows during the monsoon season, necessitating advanced crop establishment techniques like drone seeding. However, information regarding drone seeding of rice and its seed rate requirements is currently lacking. Therefore, this study aims to evaluate the feasibility of using drones for rice seeding compared to conventional rice establishment methods and to optimize the seed rate for drone seeding of rice.

Materials and Methods

Experimental site

The field study was conducted during the Rabi season of 2023-24 at a farmer's field in Kadambangudi village, Thiruverumbur, Tiruchirappalli, Tamil Nadu, India. The experimental site is located at 10° 48'N latitude and 78° 52'E longitude, with an altitude of 85 m above mean sea level (MSL). The location of the experimental site is depicted in Fig. 1. The soil at the site was sandy loam in texture, exhibiting moderate drainage. It had slightly alkaline characteristics, with a pH value of 8.1 and an electrical conductivity (EC) of 0.28 dS/m. The available nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) levels in the soil were 112.3, 28.1 and 214.5 kg ha^{-1}, respectively.

Experimental design and field management

The field trial was conducted using a Randomized Block Design (RBD) with seven treatments, each replicated three times. Four different seed rates for drone seeding were compared with three established methods of rice cultivation: drum seeding, manual broadcasting and transplanting. The

Fig. 1. Experimental site location

treatments used in this experiment were as follows: T1 - Drum Seeding; T2 - Manual Broadcasting; T3 - Transplanting; T4 - Drone Seeding at 30 kg ha^{-1}; T5 - Drone Seeding at 40 kg ha^{-1}; T6 - Drone Seeding at 50 kg ha^{-1}; T7 - Drone Seeding at 60 kg ha^{-1}. The area for each treatment was 100 m^2 (25 m × 4 m). The various establishment methods employed in the experiment are illustrated in Fig. 2.

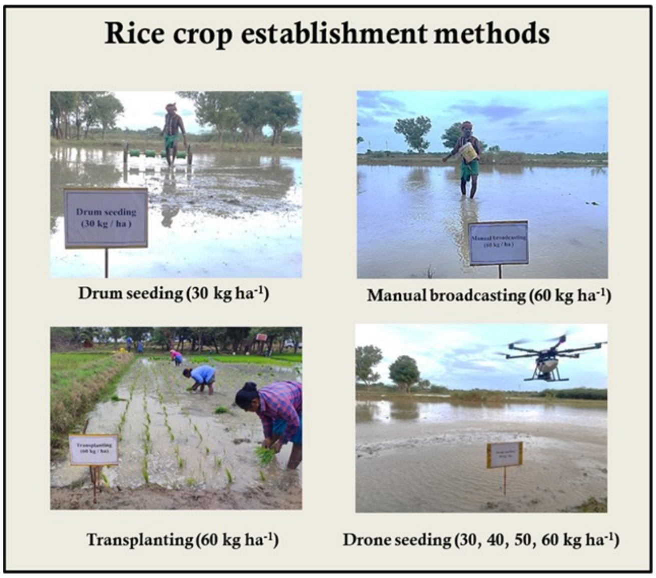

Fig. 2. Different establishment methods used in the study to evaluate the performance of drone seeding of rice

The rice variety used in this study was "TRY 5," a short-duration, saline and sodic-tolerant variety. Before sowing, the experimental field was thoroughly puddled twice using a tractor-drawn cage wheel and leveled with a leveling board to ensure a uniform slope. The study employed the HX8SDR model agricultural drone (dimensions: 1720 mm × 1500 mm × 556 mm) for seeding. A trained operator pre-determined and controlled the flight height (2.0 m), swath width (2.0 m) and GPS settings. Before drone seeding, the drone was calibrated for different seed rates by adjusting the spreader settings, including the hopper outlet size, spinner disc rotation speed and drone speed. The drone speed was set at 3 m/s with a hopper outlet opening of 20% for a 30 kg ha^{-1} seed rate and 25% for a 40 kg ha^{-1}. For seed rates of 50 and 60 kg ha^{-1}, a drone speed of 2 m/s was maintained, with 30% and 40% hopper outlet openings, respectively. The spreader had a payload capacity of 10 kg, and the spinner disc rotation speed was set at 307 RPM. In the direct seeding method, seeds were sown using a drum seeder with a row spacing of 20 cm and manually broadcast. During sowing, a water depth of 2.5 cm was maintained, which was drained the following morning. A saturated condition was maintained for five days to promote better seed germination. After the standing water disappeared, a water depth of 5.0 cm was irrigated and maintained throughout the cropping period. For the transplanting method, 25-day-old seedlings were planted at 2-3 seedlings per hill with a spacing of 20 x 15 cm by manual laborers. The recommended seed rates were 30 kg ha^{-1} for drum seeding and 60 kg ha^{-1} for transplanting and manual broadcasting. The detailed methodology for drone seeding is illustrated in Fig. 3.

Data recorded and analysis.

Plant population and the number of tillers were recorded using a 0.25 m^2 quadrat at three random locations in each plot 15 days after sowing (DAS) and during the tillering stage, respectively. Plant height was measured in centimeters from the base to the tip of the panicle on ten randomly selected plants to obtain the mean value. Dry matter production (DMP) was estimated by collecting samples from five random plants in the border rows of each plot. These samples were dried in the shade and dried in a hot air oven at 80°C for 72 hours until a constant weight was achieved. The dry weight was recorded and expressed in kg ha^{-1}. The leaf area index (LAI) was calculated at the flowering stage using leaf length, width, the number of leaves, and the land area occupied by the plants. Chlorophyll content in the leaves was measured at the flowering stage using a Soil Plant Analysis Development (SPAD) chlorophyll meter (17). Root characteristics and morphology were studied using an Epson photo scanner (Epson Perfection V800). Images of the scanned roots were analyzed using the WinRHIZO Pro image system to estimate total root length (cm), root surface area (cm^2), average root diameter (mm) and root volume (cm^3).

Yield attributes and grain and straw yields (kg ha^{-1}) were recorded at harvest time. The cost of cultivation was calculated based on the prevailing market prices of inputs. Net return was determined by deducting the cost of production from the gross returns. The benefit-cost ratio (BCR) was calculated by dividing the gross returns by the cost of cultivation. All recorded data were statistically analyzed using a randomized block design (18). The critical difference at a 5% probability level was assessed to ascertain the significance between treatments. Correlation analysis between crop parameters was conducted using R software version 4.1.2 to identify significant correlations between growth, yield parameters and grain yield ($p < 0.01$).

Results

Plant population

Drone seeding at 60 kg ha^{-1} (T7) recorded a significantly higher number of plants per unit area (119 plants m^{-2}) than other seed rates and sowing methods. However, it was statistically comparable to manual broadcasting at 60 kg ha^{-1} (T2) and drone seeding at 50 kg ha^{-1} (T6). Drum seeding (T1) exhibited a plant population of 38 plants m^{-2}, which was statistically similar to transplanting (T3), which had a significantly lower population of 34 plants m^{-2} compared to the other treatments (Table 1).

Growth parameters

Growth attributes were significantly influenced by different rice establishment methods (Table 1). Transplanted rice (T3) exhibited the tallest plants (92.3 cm), the highest number of tillers (432 tillers m^{-2}) and the greatest dry matter production (DMP) at 12,708 kg ha^{-1} compared to other methods. Following transplanting, drum-seeded rice (T1) displayed superior growth characteristics, including a plant height of 90.5 cm, a tiller population of 400 tillers m^{-2} and a DMP of 11,504 kg ha^{-1}, outperforming manual broadcasting (T2). Drum seeding (T1) was comparable to drone seeding at

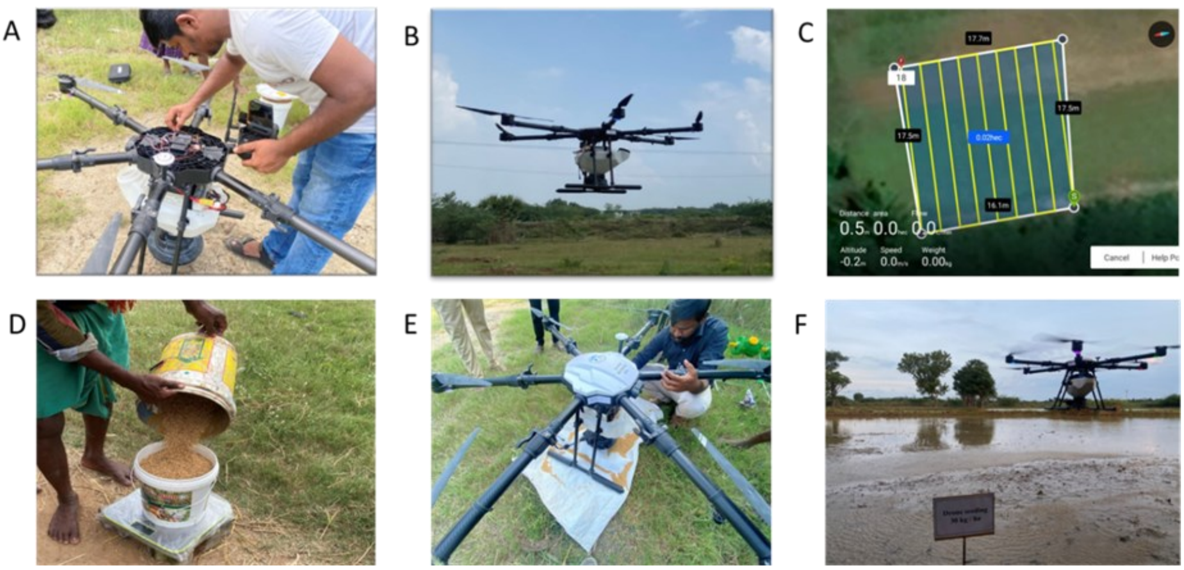

Fig. 3. Methodology of drone seeding - (A) Assembling and adjustments of drone and spreader mechanism; (B) Calibration of drone for effective flight and seeding; (C) Mapping of flight path and area to be sown; (D) Weighing of seeds based on the seed rate requirement; (E) Filling of seeds in the spreader tank; (F) Drone seeding in puddled field

Table 1. Effect of different establishment methods on growth parameters of rice

Treatment	Plant population (Nos. m^{-2})	Tillers (Nos. m^{-2})	Plant height (cm)	DMP (kg ha^{-1})
T_1 - Drum seeding	38 (±0.58)	400 (±6.11)	90.5 (±1.38)	11504 (±175.7)
T_2 - Manual broadcasting	112 (±1.71)	294 (±4.49)	76.8 (±1.17)	10220 (±156.1)
T_3 – Transplanting	34 (±1.22)	432 (±15.57)	92.3 (±3.32)	12708 (±458.1)
T_4 - Drone seeding 30 kg ha^{-1}	75 (±1.98)	355 (±9.39)	88.2 (±2.33)	10676 (±282.4)
T_5 -Drone seeding 40 kg ha^{-1}	84 (±0.84)	392 (±3.92)	87.7 (±0.87)	11184 (±111.8)
T_6 -Drone seeding 50 kg ha^{-1}	104 (±1.58)	368 (±5.62)	84.5 (±1.29)	10816 (±162.2)
T_7 -Drone seeding 60 kg ha^{-1}	119 (±3.82)	306 (±9.83)	77.8 (±2.50)	10535 (±338.6)
LSD (p=0.05)	5.49	3.21	15.18	461.65

(Significant at $P < 0.05$; *LSD* test) (DMP - Dry matter production)

40 kg ha^{-1} (T5) regarding growth parameters, such as the number of tillers (392 tillers m^{-2}) and DMP (11,184 kg ha^{-1}). In terms of plant height, drone seeding at 30 kg ha^{-1} (T4) produced taller plants (88.2 cm), which was comparable to drone seeding at 40 kg ha^{-1} (T5) with a height of 87.7 cm and drone seeding at 50 kg ha^{-1} (T6) at 84.5 cm. Manual broadcasting (T2) and drone seeding at 60 kg ha^{-1} (T7) resulted in significantly shorter plants (76.8 cm and 77.8 cm, respectively), fewer tillers (294 and 306 tillers m^{-2}) and lower DMP (10,220 kg ha^{-1} and 10,535 kg ha^{-1}, respectively). The influence of different establishment methods on rice growth at the panicle initiation and flowering stages is presented in Fig. 4.

Root growth parameters

Rice root growth parameters varied significantly across different rice establishment methods and seed rates in drone seeding techniques (Table 2). Among the establishment methods, transplanted rice (T3) exhibited the highest total root length (877.5 cm), root surface area (1657.7 cm^2) and root volume (99.7 cm^3) compared to other methods. Drum seeding (T1) was the next best treatment, recording a total root length of 435.3 cm, a root surface area of 843.7 cm^2, a root diameter of 0.62 mm and a root volume of 52.0 cm^3. This was followed by drone seeding at 40 kg ha^{-1} (T5), which recorded a total root length of 383.1 cm, a root surface area of 710.6 cm^2, a root

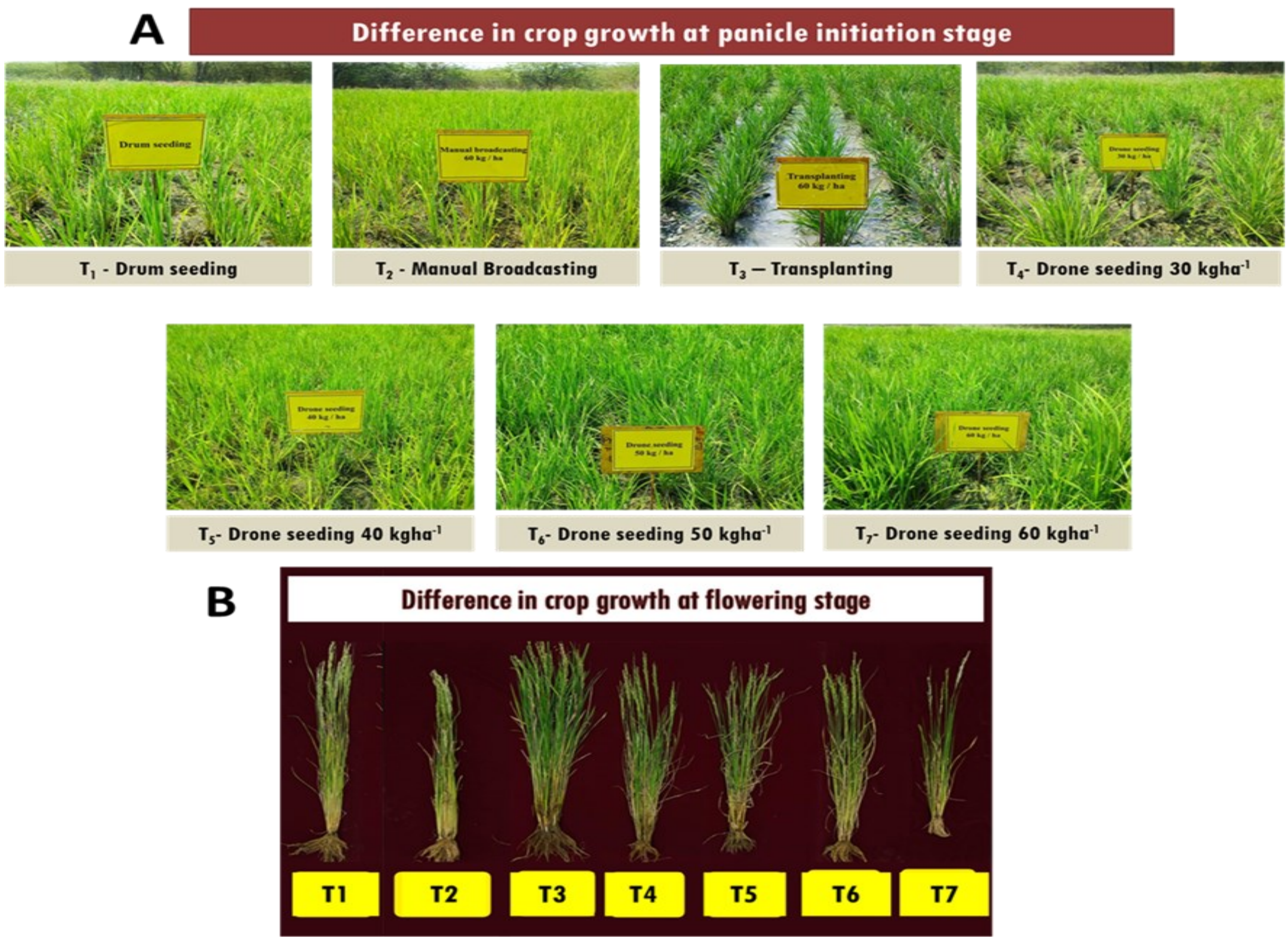

Fig. 4. Influence of different rice establishment methods on the growth of rice at (A) Panicle initiation stage and (B) Flowering stage (T_1 - Drum seeding; T_2 - Manual Broadcasting; T_3 - Transplanting; T_4 - Drone seeding at 30 kg ha^{-1}; T_5 - Drone seeding at 40 kg ha^{-1}; T_6 - Drone seeding at 50 kg ha^{-1}; T_7 - Drone seeding at 60 kg ha^{-1})

Table 2. Effect of different establishment methods on root parameters of rice at panicle initiation stage

Treatments	Panicle initiation stage			
	Total root length (cm)	Root surface area (cm²)	Average root diameter (mm)	Root volume (cm³)
T_1 - Drum seeding	435.31 (±6.64)	843.71(±12.8)	0.62 (±0.009)	52.06 (±0.79)
T_2 - Manual Broadcasting	281.50 (±4.29)	430.91(±6.58)	0.49 (±0.007)	21.00 (±0.32)
T_3 - Transplanting	877.56 (±31.64)	1657.70(±59.7)	0.60(±0.021)	99.71 (±3.59)
T_4 - Drone seeding 30 kg ha^{-1}	337.42 (±8.92)	672.89 (±17.8)	0.63 (±0.016)	42.72 (±1.13)
T_5 - Drone seeding 40 kg ha^{-1}	383.18 (±3.83)	710.65 (±7.10)	0.59 (±0.005)	41.96 (±0.41)
T_6 - Drone seeding 50 kg ha^{-1}	323.92 (±4.94)	568.64 (±8.68)	0.56 (±0.008)	31.78 (±0.48)
T_7 - Drone seeding 60 kg ha^{-1}	289.04 (±9.29)	472.27 (±15.1)	0.52 (±0.016)	24.56 (±0.78)
LSD (p=0.05)	31.7	60.3	0.02	3.66

(Significant at $P < 0.05$; *LSD* test)

diameter of 0.59 mm, and a root volume of 41.96 cm^3. Drone seeding at 30 kg ha^{-1} (T4) showed comparable root surface area and root volume to 40 kg ha^{-1} (T5) and comparable total root length to drone seeding at 50 kg ha^{-1} (T6). In contrast, manual broadcasting (T2) exhibited shorter roots (281.5 cm), a smaller root surface area (430.9 cm^2), a root diameter of 0.49 mm and a root volume of 21 cm^3, which was statistically comparable to drone seeding at 60 kg ha^{-1} (T7) for total root length (289 cm), root surface area (472.2 cm^2) and root volume (24.5 cm^3). The influence of rice establishment methods on root morphology at the panicle initiation stage is depicted in Fig. 5.

Physiological parameters

Both leaf area index (LAI) and leaf chlorophyll (measured by SPAD meter values) exhibited similar trends across the different methods of rice establishment (Fig. 6). Transplanting (T3) recorded the highest LAI of 5.14 and a SPAD value of 39.67, which was comparable to drum seeding (T1), which registered an LAI of 5.03 and a SPAD value of 39.45. Drone seeding at 40 kg ha^{-1} (T5) also produced a higher LAI of 4.94 and a SPAD value of 38.97 compared to higher seed rates. In contrast, manual broadcasting (T2) exhibited the lowest LAI of 4.25 and a SPAD value of 36.85, comparable to drone seeding at 60 kg ha^{-1} (T7).

Yield attributes and yield

Significant variations in yield attributes and rice yield were observed under different establishment methods and various seed rates for drone seeding (Fig. 7). Among the establishment methods, transplanting of rice (T3) produced the highest number of panicles (356 m^2), filled grains per panicle (121), grain yield (4,868 kg ha^{-1}) and straw yield (7,632 kg ha^{-1}), outperforming all other sowing methods. Drum seeding (T1) was the next best treatment, yielding 4,602 kg ha^{-1} of grain and 7,038 kg ha^{-1} of straw, with 331 panicles per square meter and 117 filled grains per panicle. However, its performance was statistically comparable to drone seeding at 40 kg ha^{-1}. Among the different seed rates used in drone seeding, the 40 kg ha^{-1} rate (T5) produced significantly more panicles (326 m^2), filled grains per panicle (114), grain yield (4,566 kg ha^{-1}) and straw yield (6,880 kg ha^{-1}) than the other seed rates. In contrast, manual broadcasting (T2) exhibited poor yield attributes, with a significantly lower grain yield of 4,010 kg ha^{-1} compared to the other methods and was comparable to drone seeding at 60 kg ha^{-1} (T7).

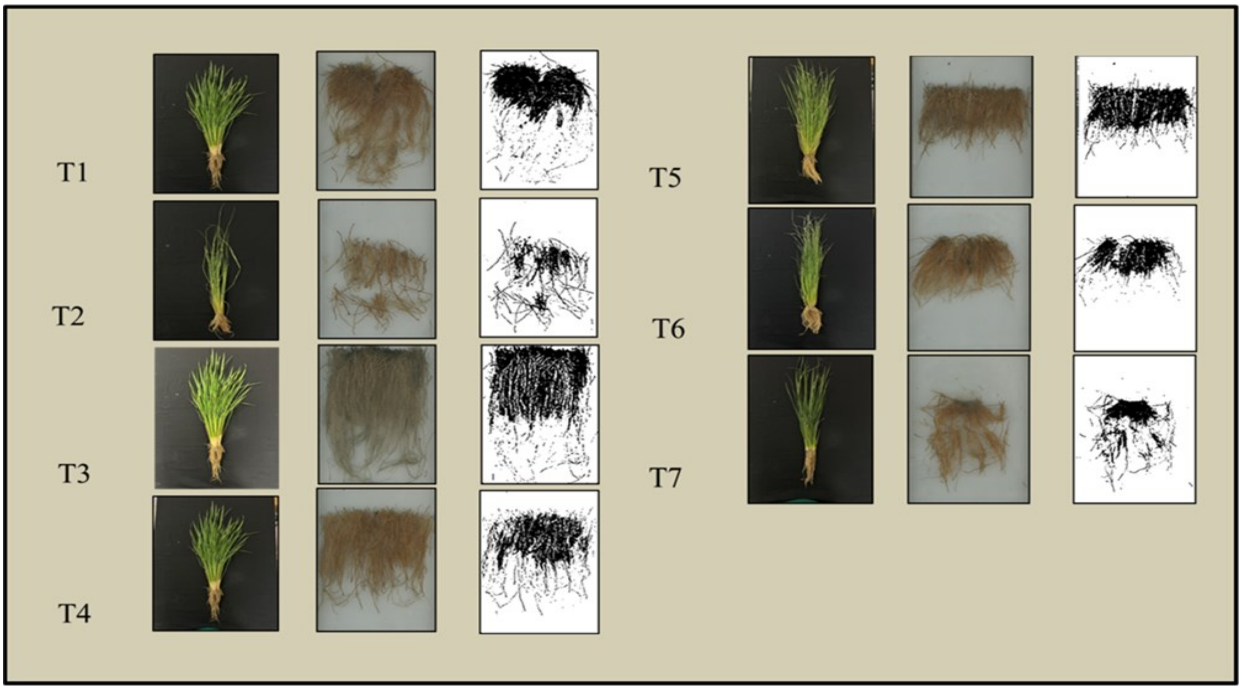

Fig. 5. Influence of different rice establishment methods on the root morphology of rice at the panicle initiation stage (T_1 - Drum seeding; T_2 - Manual Broadcasting; T_3 - Transplanting; T_4 - Drone seeding 30 kg ha^{-1}; T_5 - Drone seeding 40 kg ha^{-1}; T_6 - Drone seeding 50 kg ha^{-1}; T_7 - Drone seeding 60 kg ha^{-1})

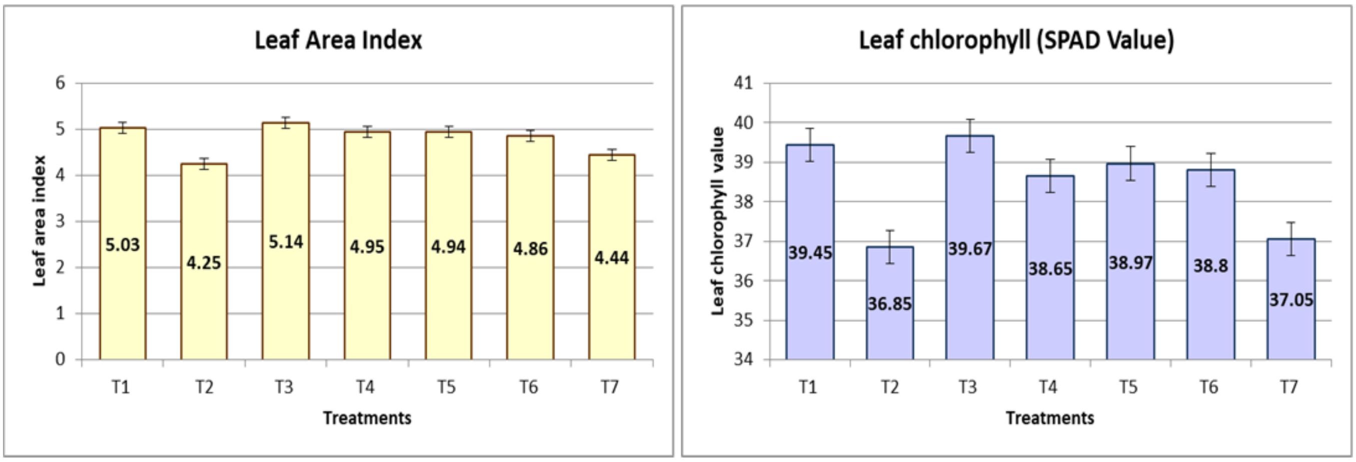

Fig. 6. Effect of different crop establishment methods on physiological parameters of rice (T_1 - Drum seeding; T_2 - Manual Broadcasting; T_3 – Transplanting; T_4 - Drone seeding 30 kg ha^{-1}; T_5 - Drone seeding 40 kg ha^{-1}; T_6 - Drone seeding 50 kg ha^{-1}; T_7 - Drone seeding 60 kg ha^{-1})

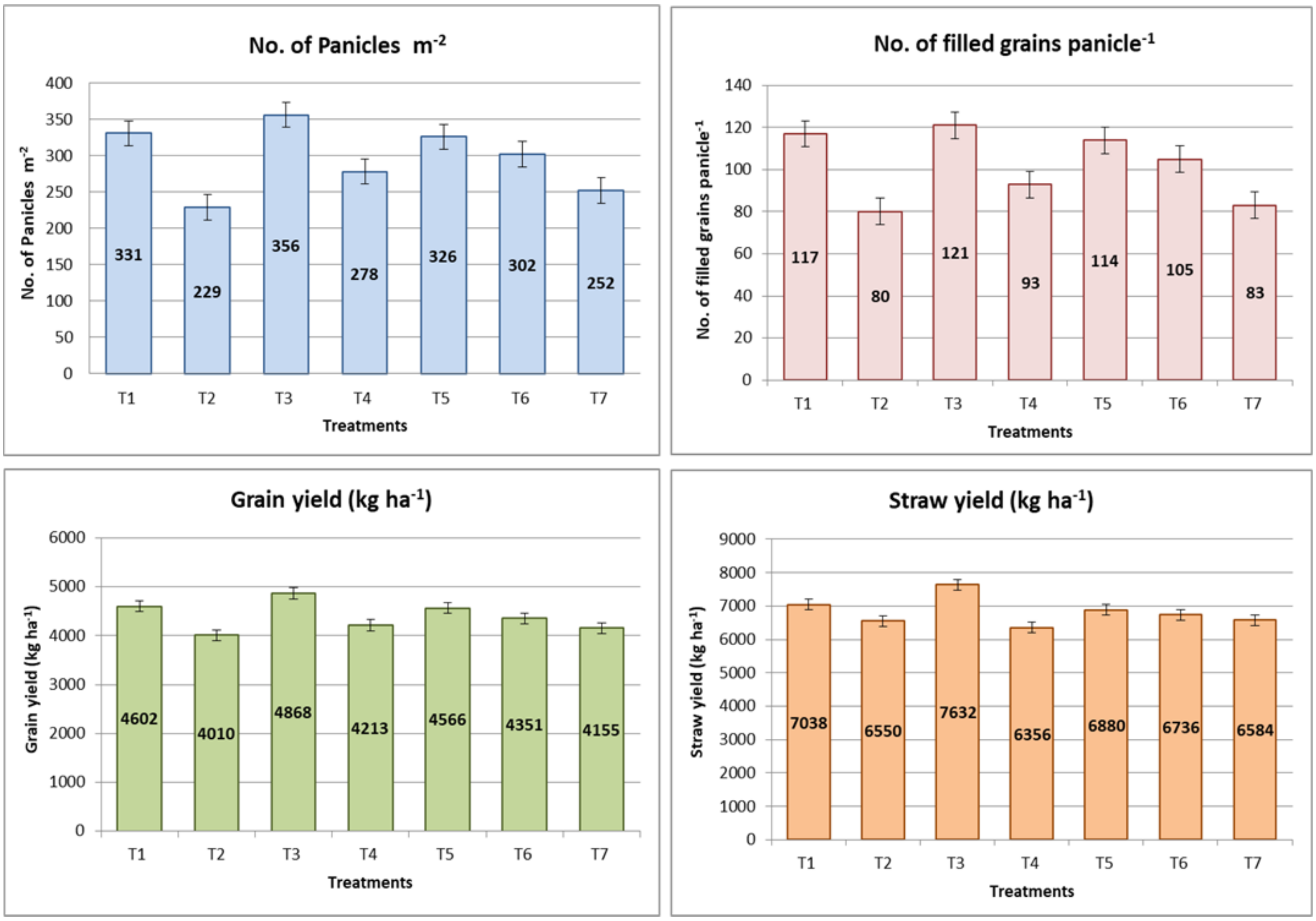

Figure 7. Effect of different crop establishment methods on yield parameters and yield of rice (T_1 - Drum seeding; T_2 - Manual Broadcasting; T_3 - Transplanting; T_4 - Drone seeding 30 kg ha^{-1}; T_5 - Drone seeding 40 kg ha^{-1}; T_6 - Drone seeding 50 kg ha^{-1}; T_7 - Drone seeding 60 kg ha^{-1})

Economics

The economics of rice cultivation varied across different seeding techniques and seed rates (Fig. 8). Drum seeding of rice (T1) yielded the highest net returns of 73,470 per hectare and a benefit-cost ratio (BCR) of 2.66, outperforming other treatments (Fig. 6). This was closely followed by drone seeding at 40 kg per hectare (T5), which achieved a net return of 71,480 per hectare and a BCR of 2.59. Transplanted rice (T3) recorded a lower net return of 70,358 per hectare and a BCR of 2.28 compared to both drone seeding (T5) and drum seeding (T1). Manual broadcasting (T2) showed the lowest net returns at 58,494 per hectare and a BCR of 2.29 among all methods.

Correlation between grain yield and different parameters of rice

Correlation analysis between crop growth, yield parameters and grain yield revealed significant correlations among these factors ($p < 0.01$) (Fig. 9). The number of panicles per square meter (0.98), number of tillers per square meter (0.96), dry matter production (0.96) and number of filled grains per panicle (0.96) exhibited high positive correlations with grain yield. This was followed by the SPAD value (0.92), total root length (0.92), straw yield (0.91), root surface area (0.91), root volume (0.88), leaf area index (0.85) and plant height (0.83). The correlation coefficients for yield parameters with grain yield were higher than those for growth parameters.

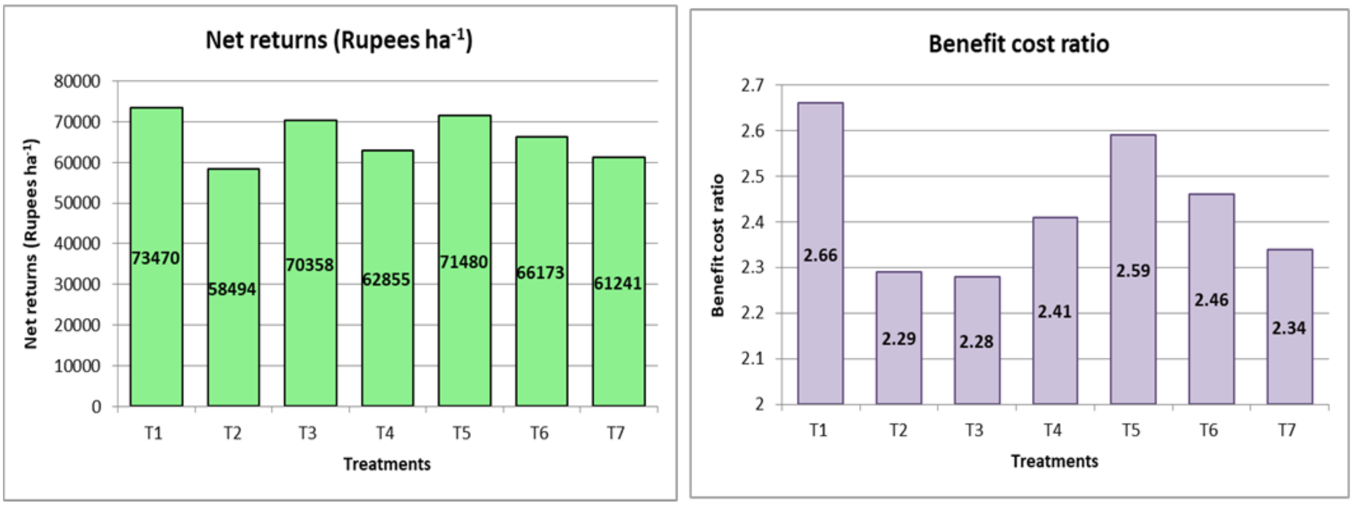

Fig. 8. Effect of different crop establishment methods on the economics of rice (T_1 - Drum seeding; T_2 - Manual Broadcasting; T_3 - Transplanting; T_4 - Drone seeding 30 kg ha^{-1}; T_5 - Drone seeding 40 kg ha^{-1}; T_6 - Drone seeding 50 kg ha^{-1}; T_7 - Drone seeding 60 kg ha^{-1})

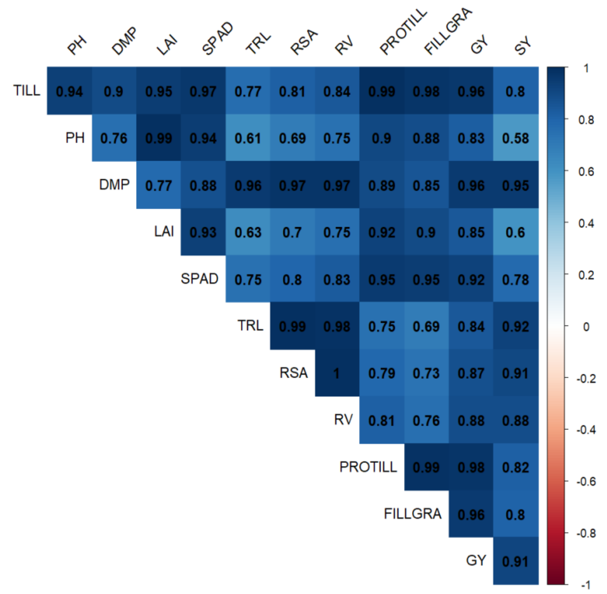

Fig. 9. Correlation between different growth, yield parameters and yield (TILL - No. of tillers m^{-2}; PH - Plant height; DMP - Dry matter production, LAI - Leaf area index; SPAD - Leaf chlorophyll value; TRL - Total root length; RSA - Root surface area; RV - Root volume; PROTILL - Productive tillers m^{-2}; FILLGRA - filled grains per panicle; GY - Grain yield; SY - Straw yield)

Discussion

Effect of rice establishment methods on growth parameters

The plant population strongly correlates with seed rates in rice cultivation. Increased seed rates yield a markedly larger plant population than reduced seed rates. An optimal plant population is essential for the effective utilization of resources. Although a higher population was observed with drone seeding at 60 kg ha^{-1}, a 40 kg ha^{-1} seed rate yielded better results. Increased plant population can negatively impact crop growth by intensifying competition among plants for available resources. The defined row spacing in drum seeding and transplanting contributes to a lower plant population than manual and drone seeding methods.

Better planting geometry in transplanted rice minimizes competition for sunlight and nutrients. Similar increases in plant height (19) and tiller population (20) under transplanted rice compared to direct-seeded rice have been recorded in earlier studies. Following transplanting, drum-sown rice exhibited superior growth characteristics, including 17.8% taller plants, 36% more tillers and 12.5% higher dry matter production (DMP) than manual broadcasting. These enhanced growth attributes can be attributed to uniform spacing and optimal plant population achieved through drum seeding (21). Greater canopy coverage and increased solar radiation interception in drum-sown rice resulted in higher DMP (22). Among the various seed rates used in drone seeding, a seed rate of 40 kg ha^{-1} performed best in terms of tiller population and DMP compared to other seed rates. Precise seed placement at lower seed rates with drone seeding optimizes plant spacing, minimizing competition for nutrients, light and space during critical growth stages. This can enhance crop performance by ensuring sufficient leaf area coverage, nitrogen absorption and photosynthetic efficiency. Drone seeding at 40 kg ha^{-1} produced 14% taller plants, 33% more tillers and 9.4% higher dry matter than manual broadcasting. These findings align with other researchers (1, 15, 23, 24) who reported better seed distribution by drones than by manual sowing. Conversely, manual broadcasting and drone seeding at 60 kg ha^{-1} resulted in fewer tillers and shorter plants, reflecting the negative effects of higher plant population and competition among plants.

The root system directly influences crop vigor and productivity, which is crucial for nutrient absorption. In transplanting, a well-developed root system with a greater root volume forms due to optimal spacing, which reduces competition for essential resources such as water, nutrients, and sunlight. This allows crops to allocate more resources to root growth (25, 26). Placing seeds at optimal spacing in drum seeding provides adequate space for plants to develop their roots, facilitating better resource utilization. This finding is consistent with earlier studies (27). Optimal spacing reduces competition for essential resources, enabling crops to develop longer and more extensive root systems. Increased root growth enhances soil exploration and nutrient uptake, resulting in greater root volume and dry weight (25, 26). Drone seeding at 40 kg ha^{-1} demonstrated significant root growth characteristics, with roots that were 36.1% longer, had a 64% larger surface area and were 20.4% thicker compared to manual broadcasting. The precise and uniform distribution of seeds through drones over the field (28), combined with adequate spacing, improves root proliferation compared to manual seeding. Treatments that utilized higher seed rates, such as manual broadcasting and drone seeding at 60 kg ha^{-1}, exhibited lower root growth characteristics primarily due to the higher plant population and resulting competition among the plants.

Effect of rice establishment methods on physiological parameters

The leaf area index (LAI) is a key indicator of leaf coverage within a crop ecosystem, significantly influencing photosynthesis processes (29). Transplanted rice, drum seeding, and drone seeding at 40 kg ha^{-1} recorded LAI values that were higher by 20.1%, 18.4% and 16.5%, respectively, along with leaf chlorophyll values that were 7.6%, 7.0% and 5.8% greater than those observed with manual broadcasting. This enhancement is primarily attributed to better resource utilization under optimal population densities, which increased leaf area and chlorophyll content. The optimal spacing achieved in transplanted rice, drum seeding and drone seeding at lower seed rates (30 and 40 kg ha^{-1}) improved solar radiation capture and nutrient uptake, ultimately enhancing plant physiology. These findings align with the findings of other studies (21, 30-32).

Effects of rice establishment methods on yield attributes and yield

Significant improvements in rice yield attributes were observed under transplanting, primarily due to optimal plant spacing and population, facilitating effective resource utilization. Transplanted rice produced more productive tillers, increasing grain yield (33). Similarly, higher yield attributes were noted under drum seeding, which resulted in reduced competition among plants, thereby enhancing nutrient uptake, increasing the number of productive tillers and improving other yield components. This finding is supported by previous research (34, 35). Compared to manual broadcasting, drone seeding at 40 kg ha^{-1} resulted in more productive tillers (42.3%) and filled grains per panicle (42.5%). Earlier studies (36, 37) have also confirmed that drone seeding contributes to improved yield attributes in rice.

Compared to manual broadcasting, transplanting of rice resulted in a 21% higher grain yield due to uniform crop establishment and optimal spacing among plants. This arrangement minimized crop-to-crop competition for available inputs, leading to increased nutrient availability, improved light infiltration, better water availability, and enhanced aeration, all contributing to superior crop growth and yield. These findings align with the study by Ramesh et al., 2023 (38), who reported that transplanted paddy yielded 5.5% more than direct seeding. Similarly, the uniform crop establishment achieved through drum seeding and drone seeding at 40 kg ha^{-1} reduced crop-to-crop competition for available inputs, thus increasing nutrient availability, light penetration, water access and aeration, resulting in better crop growth and yield. Previous researchers have documented the advantages of drum seeding over other establishment methods (39, 40). Drone seeding at 40 kg ha^{-1} outperformed manual broadcasting, yielding 13.8% more grain and 5% more straw. This improvement was primarily due to the uniform dispersal of the optimal number of seeds per unit area using drones, resulting in less competition among plants and greater resource availability, enhancing yield parameters and overall yield. Similar results regarding the yield performance of drone seeding have been reported in various studies (14, 24, 37). In contrast, manual broadcasting and drone seeding at 60 kg ha^{-1} increased competition among plants for resources, resulting in lower grain yields. Higher seed rates and uneven crop stands associated with manual broadcasting negatively affected crop yield.

Effect of rice establishment methods on economics

Despite its superior yield performance, transplanting was economically less favorable than direct seeding methods, primarily due to higher establishment costs. Transplanted rice showed a lower benefit-cost ratio (BCR) compared to drone seeding at a rate of 40 kg ha^{-1} and drum seeding, mainly due to the increased labor costs associated with nursery preparation, raising and pulling seedlings and the transplanting process (38). Drum seeding of rice yielded higher net returns and BCR than other methods, attributed to its lower establishment costs and higher grain yield. This finding is supported by researchers who reported that the benefit-cost ratio, labor productivity and labor use efficiency are superior in direct sowing compared to transplanting (41). However, drum seeding faces challenges such as a scarcity of skilled labor, higher labor demands and increased time consumption when seeding large areas.

In contrast, drone seeding allows for uniform seed distribution over large areas quickly, resulting in reduced labor requirements, operational costs and higher net returns than conventional methods (14). Drone seeding precisely and uniformly delivers seeds, reducing the seed rate, improving crop establishment (42) and lowering production costs (28). Additionally, drone seeding at a rate of 40 kg ha^{-1} achieved 22% higher net returns than manual broadcasting. These findings are consistent with the results of other researchers (37, 43).

Effect of rice establishment methods on the correlation between growth, yield parameters and grain yield

Rice grain yield is closely related to several morphological characteristics associated with plant development and architecture. Correlation analysis aids in understanding the relationships between yield and various agronomic parameters of rice (44). Plant height demonstrated a significant positive correlation with yield and yield attributes, a relationship also observed in earlier studies (45). Yield attributes, such as the number of productive tillers and filled grains, exhibited a stronger positive correlation with grain yield than growth parameters, as they directly contribute to yield. Higher correlations were found between grain yield and productive tillers (46), tiller population (47) and filled grains per panicle (48). Positive correlations were also noted between leaf chlorophyll, root length and root volume with yield. Similar findings were reported by researchers in previous studies (49).

Conclusion

This study concludes that drones can be effectively used for the direct seeding of rice under puddled lowland conditions, showing comparable performance to drum seeding and superior results compared to manual broadcasting. A 40 kg ha^{-1} seed rate for drone seeding was optimal for achieving higher grain yields and better economic returns. This method saves 20 kg ha^{-1} of seed and increases the yield by up to 13% compared to manual broadcasting at 60 kg ha^{-1}. Transplanting performed well across most growth, physiological and yield parameters, producing higher yields than other methods. However, drone seeding at 40 kg ha^{-1} yielded higher net returns and benefit-cost ratios (BCR) than transplanting. Therefore, drone seeding with a seed rate of 40 kg ha^{-1} is recommended as a forward-looking and viable method for crop establishment, considering its labor-saving advantages, timely operation and economic benefits.

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Authors' contributions

AK and RT conceptualized and used methodology for the experiment. AK collected data, analyzed it and wrote the first draft of the manuscript. TR did overall supervision of the experiment and reviewed and edited the manuscript. RS did a second revision and edited the manuscript. VC and RK administered and validated the project. AK, RT, and RS did the final revision of the manuscript. All authors have read and agreed to the published version of the manuscript.

Compliance with ethical standards

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