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RESEARCH ARTICLE

Optimizing herbicide use: Can drone technology revolutionize weed management in rice

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Abstract

This study investigates the standardization of herbicide dosage for drone applications in rice cultivation, specifically for the herbicide mixture triafamone 20% + ethoxysulfuran 10%. It compares the efficacy of drone-applied herbicide at 70% of the recommended dose (RDH) with traditional knapsack sprayer applications, where 67.5 g a.i. ha^{-1} is considered the 100% dose. The research analyzes several factors, including growth parameters, rice yield, weed density, biomass, and weed control efficiency (WCE) at 30, 60, and 90 days after sowing (DAS). The study utilized a randomized block design with 10 treatments and three replicates, which included weed-free and weedy checks, along with varying herbicide doses. Results show that the weed-free check exhibited the lowest weed density and biomass with the highest WCE. Among drone-applied treatments, 70% RDH proved most effective, maintaining low weed densities and biomass similar to the weed-free check, and achieving WCE values of 94-95%. Higher doses (100%, 90%, 80% RDH) caused phytotoxicity, hindering initial crop growth and resulting in higher weed competition and lower WCE (71-73%). The study highlights that the 70% RDH spray via drone not only reduces herbicide costs by 30%, but also improves crop-weed dynamics, rice yield, net income, benefit-cost ratio, and energy efficiency, promoting sustainable agricultural practices in rice cultivation.

Keywords

rice; drone; herbicide; triafamone 20% + ethoxysulfuron 10%; sustainable production; farm profit

Introduction

Rice (*Oryza sativa* L.) is a staple food for more than half of the global population. In India, rice is cultivated across 45.77 million hectares, with a productivity of 2717 kg/ha and an annual production of 124.37 million tons in 2020-21. Odisha is one of the leading rice-producing states in India, contributing 8.82% of the area (4.04 million ha) and 7.08% of the production (8.81 million tons) of the country's total rice production. However, Odisha faces relatively low productivity (2182 kg/ha) compared to other states in 2020-21 (1). In Asia, wet tillage, which involves transplanting rice seedlings into puddled soil, is a predominant cultivation practice. While it supports rice growth, this method is resource-intensive, requiring large amounts of water, labor, and energy (2). As these resources become scarcer, the traditional wet tillage system is increasingly less economically viable (3). Consequently, the growing scarcity of agricultural land and water, combined with a labor shortage, is pushing for a shift toward direct-seeded rice (DSR) cultivation in the 21st century (4).

The main challenges to optimal rice productivity and quality in DSR are related to the simultaneous growth of rice and weed seedlings, which compete for resources in the early stages of growth. Transplanted rice seedlings have a competitive advantage over weeds due to their larger size and more advanced growth (5). During the early and tillering stages, rice is particularly vulnerable to weed competition, which can lead to significant yield losses. Despite rice being a crucial crop, India continues to face challenges in its production due to traditional farming practices, water scarcity, climate variability, pest infestations, and weed proliferation. Weeds in rice fields, especially in DSR systems, are particularly challenging to control, and herbicide application before or after weed emergence remains the most effective and economical means of weed management.

Wet seeding, which involves sowing pre-germinated rice seeds in puddled fields, offers advantages in terms of seed germination and crop establishment. In Odisha's wet-seeded rice (WSR) fields, grasses, sedges, and broad-leaved weeds (BLWs) dominate between 30 and 60 days after sowing (DAS), accounting for 27-35%, 37-42%, and 23-36% of the weed population, respectively (6). Yield losses in DSR can be as high as 70-80% (7), while in WSR, losses range from 45-66% (8-10). Among the various selective, premixed, and tank-mixed herbicides available, the combination of triafamone 20% + ethoxysulfuron 10% WG (ALS inhibitor herbicide mixture) applied at 67.5 g/ha at the 1-2 leaf stage of weeds in a spray volume of 300 liters/ha through a knapsack sprayer has been shown to effectively control a broad spectrum of weed species, significantly improving grain yield in both transplanted and wet-seeded rice systems (11-13).

Drones have emerged as a significant advancement in modern agriculture, particularly in India, where their use for agrochemical spraying is becoming increasingly prevalent. Traditionally, herbicides were applied using knapsack sprayers, which often made it difficult to maintain uniform application rates and herbicide deposition due to varying walking speeds and individual strengths, especially on muddy rice fields. In contrast, drones offer consistent spraying speed and pressure, ensuring a constant application rate (14, 15). Drones also require less energy input compared to knapsack sprayers, yet they can effectively spray liquids at low heights and over short distances (17). One major challenge with drone spraying is drift, which can be mitigated through operator control and proper calibration procedures for the specific liquid being applied (18, 19). Furthermore, drone spraying reduces the required spray volume to 20 liters per hectare and the chemical load, while improving efficiency (20). The herbicide mixture of 20% triafamone + 10% ethoxysulfuron, approved by the Government of India (Office Memorandum F.No. 13035/07/2022-PP-I, dated 18th April 2022), has a recommended dose of 67.5 g a.i. ha^{-1} for application via knapsack sprayer, using a spray volume of 300 liters per hectare. However, no official dosage recommendation exists for applying this herbicide mixture via drone, which uses a much lower spray volume of 20 liters per hectare. Applying the same dose via drone would increase the herbicide concentration by 15 times compared to the knapsack method, potentially causing phytotoxicity in rice (22). This raises the possibility that a reduced dose could effectively manage the complex weed flora in rice while minimizing the risks of phytotoxicity. By optimizing the herbicide dose for drone application, it may be possible to reduce herbicide costs, application time, and the chemical load on soil, while enhancing the productivity and profitability of rice cultivation with improved efficiency. This study aims to address this gap in research and explore the standardization of herbicide dosage for drone spraying to effectively control weeds in rice.

Materials and Methods

Experimental site

The field trial was conducted at the Post Graduate Research Farm (23°39' N latitude, 87°42' E longitude) of Centurion University of Technology and Management (CUTM), Odisha (Fig. 1A). The experimental site was characterized by sandy clay loam soil, and the region falls under a tropical hot and sub-humid climate. Meteorological data during the cropping period were obtained from the Agrometeorological Observatory of CUTM, Paralakhemundi (Fig. 2). The mean maximum temperature during the crop season ranged from 25.9 °C to 34.9 °C, while the minimum temperature varied between 20.2 °C and 26.5 °C. The mean maximum relative humidity ranged from 87% to 65.2%, and the minimum relative humidity fluctuated between 62.2% and 80.4%. The total rainfall received by the crop was 847 mm, with an average daily bright sunshine duration of 8.16 hours. Soil samples were collected from the experimental field at a depth of 0–30 cm using a soil auger. The physicochemical analysis revealed that the soil was sandy loam with a pH of 6.62 and an organic carbon content of 0.68%. The soil had low available nitrogen (263 kg.ha^{-1}), medium levels of available phosphorus (12.9 kg.ha^{-1}), and potassium (122.4 kg.ha^{-1}).

Experiment details

The experiment was conducted in the kharif season of 2023 using a randomized complete block design (RCBD) with ten treatments, each replicated three times. The recommended dose of the herbicide mixture triafamone 20% + ethoxysulfuran 10% (67.5 g a.i. ha^{-1}) applied via a knapsack sprayer was considered as the 100% recommended dose (RDH). The treatments included seven varying doses of the herbicide applied via drone (100%, 90%, 80%, 70%, 60%, 50%, and 40% RDH). Additionally, three other treatments were included: herbicide application at 100% RDH via a knapsack sprayer, a weed-free check, and a weedy check. The details of each treatment are provided in Table 1.

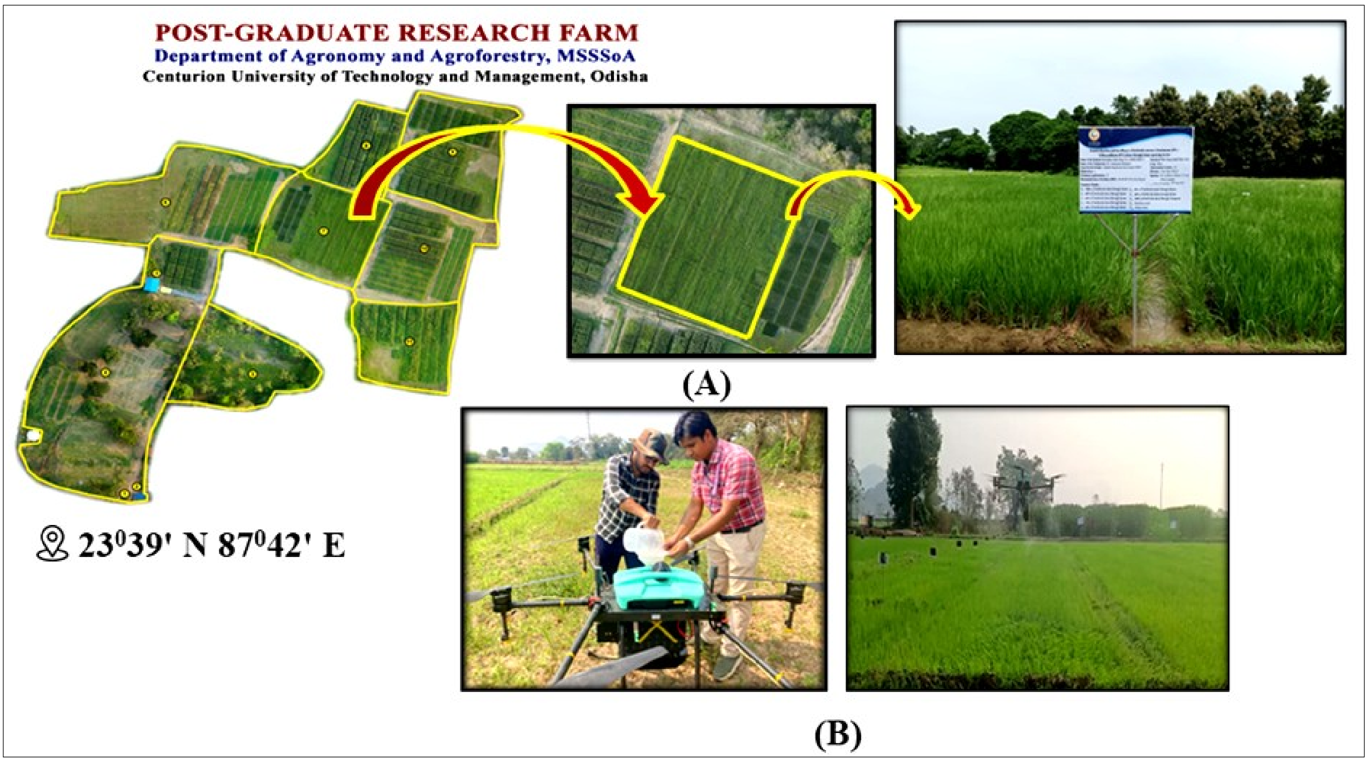

Fig. 1. (A) Experimental site; (B) Herbicide application through drone in the experiment.

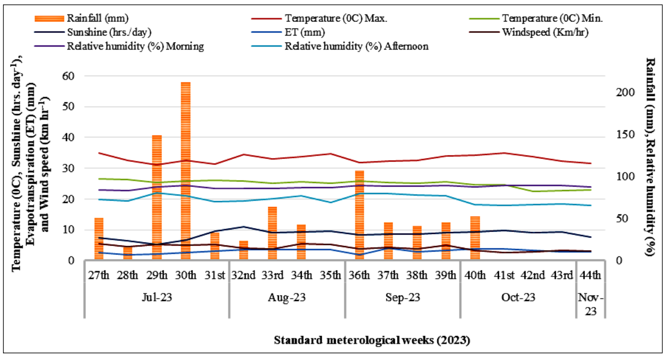

Fig. 2. Meteorological observation prevailed during the crop period (July 2023 to December 2023).

Table 1. Treatment details of the experiment

No.	Treatments
T_1	Drone spraying at 100% RDH (67.50 g a.i. ha^{-1})
T_2	Drone spraying at 90% RDH (60.75 g a.i. ha^{-1})
T_3	Drone spraying at 80% RDH (54.00 g a.i. ha^{-1})
T_4	Drone spraying at 70% RDH (47.25 g a.i. ha^{-1})
T_5	Drone spraying at 60% RDH (40.50 g a.i. ha^{-1})
T_6	Drone spraying at 50% RDH (33.75 g a.i. ha^{-1})
T_7	Drone spraying at 40% RDH (27.00 g a.i. ha^{-1})
T_8	Knapsack spraying at 100% RDH (67.50 g a.i. ha^{-1})
T_9	Weed-free check (Hand weeding at 20, 40, and 60 DAS)
T_{10}	Weedy check

RDH: Recommended dose of herbicide.

All herbicide applications were made at 18 DAS, based on weed emergence and favorable weather conditions for drone spraying. Each treatment plot covered an area of 108 m^2 (18 m x 6 m). Rice (var. RNR15084) was manually sown on 12th July 2023, with a spacing of 20 cm x 10 cm after land preparation, puddling, and layout. Hand weeding was performed three times at 20, 40, and 60 DAS for the weed-free check, while the weedy check was left undisturbed throughout the crop cycle. Two irrigations were provided as required, as adequate rainfall was received during the growing season. A fertilizer regimen of N:P2O5:K2O at 120:60:60 kg ha^{-1} was followed, with full doses of P2O5 and K2O applied as basal during final land preparation and N fertilizer applied in three equal splits at basal, 20, and 40 DAS.

The drone used in the experiment

The UAS class medium hexacopter drone "Krishak V1.0" by General Aeronautics having a payload capacity of 16 litres for 2 acres, spraying speed of 4-5 minutes acre^{-1} and spray swath 6 m with 6 spray nozzles, was used for herbicide spraying in the experiment (Fig. 1B) (23). The herbicide was sprayed at a height of 2.5 m above the ground.

Observations and calculations

Plant growth parameters, including plant height, number of tillers per square meter, dry matter accumulation, and leaf area index (LAI), were recorded at harvest. Yield attributes such as number of panicles per square meter, number of grains per panicle, sterility percentage, panicle weight, panicle length, and test weight were also measured. Grain and straw yields were determined at harvest. A 0.25 m^2 quadrat (0.5 m x 0.5 m) was placed randomly at three locations within the net plot area to assess weed density, categorized into grasses, sedges, and broadleaf weeds (BLWs), and expressed as weed density per square meter. The weeds were uprooted, root-cleaned, and sun-dried followed by oven-drying to a constant weight to determine weed biomass (g m^{-2}) for each category. Weed control efficiency (WCE) and weed index (WI) were calculated using Eqn. 1 (24) and Eqn. 2 (6), respectively. Phytotoxicity was measured using two methods: (i) visual observation (phytotoxic score) based on symptoms of wilting, chlorosis, necrosis, and leaf tip/surface injury (25); and (ii) chlorophyll content measurement using a chlorophyll content meter. Chlorophyll content was recorded at 1, 5, 10, 15, and 20 days after herbicide application (DHA). Visual observations on phytotoxicity were recorded at 1, 5, 10, 15, and 20 DHA, with mean values calculated for each plot. The phytotoxicity score was recorded using a 1–10 scale (where 1 = 1-10% damage and 10 = 91-100% damage). For chlorophyll content, ten randomly selected rice plants per plot were observed, and five leaves per plant were measured using a CCM-200 Plus Chlorophyll-meter at the aforementioned DHA intervals. Upon physiological maturity, crops from each net plot were harvested separately, and the grain and straw were separated by threshing. The weights of grain and straw were recorded separately and expressed in t ha^{-1}. Sterility percentage and harvest index were calculated using Eqn. 3 (26) and Eqn. 4 (27), respectively.

$$Weed\ control\ efficiency\ (\%) = \frac{\text{Weed dry weight in control plot} - \text{Weed dry weight in treated plot}}{\text{Weed dry weight in control plot}} \times 100$$
…….(Eqn. 1)

$$Weed\ index\ (\%) = \frac{\text{Yield from weed free plot} - \text{Yield from treated plot}}{\text{Yield from weed free plot}} \times 100$$
…….(Eqn. 2)

$$Sterility\ (\%) = \frac{\text{No.of unfilled grains per panicle}}{\text{Total no.of grains panicle per panicle}} \times 100$$
…….(Eqn. 3)

$$Harvest\ index\ (\%) = \frac{\text{Grain yield}}{\text{Grain yield} + \text{Straw yield}} \times 100$$
…….(Eqn. 4)

Economics

The total variable cost of cultivation was determined by summing all expenses associated with field operations (including tillage, seeding, irrigation, fertilizer and chemical applications, harvesting, and post-harvest activities) as well as input costs (such as seeds, fertilizers, and chemicals). Gross returns, representing the total revenue from the sale of produce, were calculated by adding the sale prices of both grain and straw. The grain price was based on the Minimum Support Price (MSP) for common-grade paddy, ₹2183 per quintal (28), while the straw price was derived from the prevailing market rate of ₹1 per kilogram for each treatment. The net returns for each treatment were calculated by subtracting the total cost of cultivation from the gross returns. The benefit-cost ratio (B:C ratio) was then calculated as the ratio of net returns to the total cost of cultivation.

Energetics

The input energy (MJ ha^{-1}) was calculated by multiplying the amount of each input consumed by its corresponding unit energy equivalent, following the methodology outlined by Yadav et al. (2017) (29), Kitani (1999) (30), Ghosh et al. (2021) (31), and Soni et al. (2018) (32). The average power consumption of the drone was determined using the following data: (i) battery capacity = 36,400 mAh, and (ii) average voltage drop per 10 acres = 10 V, as recorded in the logbook of the General Aeronautics Krishak Drone HanGAr, GTIDS Pvt. Ltd., Paralakhemundi, Odisha. Based on these values, the energy consumption per hectare was calculated to be 0.3235 MJ ha^{-1}. Energy output was determined by multiplying the energy equivalents of the main product (rice seed) and by-product (rice straw) as provided by Ghosh et al. (2021) (31). The following parameters were calculated: energy input (MJ ha^{-1}), energy output (MJ ha^{-1}), net energy return (MJ ha^{-1}), energy use efficiency, specific energy (MJ kg^{-1}), and energy productivity (kg MJ^{-1}), using the equations presented in Ghosh et al. (2021) (31) (Eqn. 5-10) (33).

$$Energy\ input = Ehl + Epr + Emt$$
…….(Eqn. 5)

$$Energy\ output = Emp + Ebp$$
…….(Eqn. 6)

$$Net\ energy\ return = Output\ energy - Input\ energy$$
…….(Eqn. 7)

$$Energy\ use\ efficiency = \frac{\text{Total output energy}}{\text{Total input energy}}$$
…….(Eqn. 8)

$$Specific\ energy = \frac{\text{Energy input}}{\text{Yield of rice}}$$
…….(Eqn. 9)

$$Specific\ energy = \frac{\text{Energy input}}{\text{Yield of rice}}$$
…….(Eqn. 10)

Where, Ehl, Epr and Emt refer to energy from human labour, energy from power and energy from materials *viz.* seed, fertilizer, irrigation, chemicals etc., respectively. Emp and Ebp refer to energy from the main product and energy from the bi-product.

Statistical analysis

The data recorded at various crop growth stages and at harvest were subjected to statistical analysis using Analysis of Variance (ANOVA) (34), with the F-value calculated at a 5% significance level. Weed density and biomass data were transformed using the square root [√(x+0.5)] transformation, and the transformed values were subsequently analyzed. Correlations between the number of panicles m^2, number of grains per panicle, 10-panicle weight, 1000-grain weight, weed biomass (grasses, sedges, broadleaf weeds (BLWs), and total at 60 DAS), as well as straw yield with grain yield, were assessed. All statistical analyses were performed using R software version 4.2.2 (2022-10-31 ucrt) (35).

Results and Discussion

Growth parameters of rice

ll treatments significantly influenced growth parameters, including plant height, the number of tillers per m^2, dry matter accumulation per m^2, and leaf area index (LAI) (Table 2). At harvest, the highest plant height was recorded in the weed-free check (124.6 cm), while the lowest was observed in the untreated weedy check (82.5 cm). Among drone-applied treatments, 70% RDH achieved the highest plant height (123.3 cm), statistically comparable to the 100% RDH applied via knapsack sprayer (120.4 cm) and 60% RDH applied through the drone (119.3 cm). Similar trends were observed in dry matter accumulation, the number of tillers per m^2, and LAI.

Table 2. Effect of different doses of herbicide (triafamone 20% + ethoxysulfuron 10%) through drone spraying on growth parameters of rice

Treatments	Plant height (cm)	No. of Tillers m^{-2}	Dry matter accumulation ($g\ m^{-2}$)	LAI
Drone 100% RDH (67.50 g a.i. ha^{-1})	111^{bcd}	306^{ef}	1099^{def}	3.77^{de}
Drone 90% RDH (60.75 g a.i. ha^{-1})	114^{abc}	314^{ef}	1156^{cde}	3.97^{cd}
Drone 80% RDH (54.00 g a.i. ha^{-1})	115^{abc}	342^{de}	1197^{cde}	4.07^{cd}
Drone 70% RDH (47.25 g a.i. ha^{-1})	123^{ab}	408^{ab}	1357^{ab}	4.56^{ab}
Drone 60% RDH (40.50 g a.i. ha^{-1})	119^{ab}	368^{cd}	1237^{bcd}	4.25^{bc}
Drone 50% RDH (33.75 g a.i. ha^{-1})	105^{cd}	279^{fg}	1058^{ef}	3.52^{e}
Drone 40% RDH (27.00 g a.i. ha^{-1})	101^{d}	266^{g}	989^{f}	3.35^{e}
Knapsack 100% RDH (67.50 g a.i. ha^{-1})	120^{ab}	380^{bc}	1255^{bc}	4.34^{bc}
Weed free	125^{a}	425^{a}	1427^{a}	4.80^{a}
Weedy check	82^{e}	200^{h}	681^{g}	2.45^{f}
SEM (±)	4	12	53	0.14
LSD (P=0.05)	13	37	157	0.44

The superior growth performance of the 70% RDH drone treatment, comparable to the weed-free check and the 100% RDH knapsack treatment, was attributed to its efficacy in suppressing weed pressure and reducing crop-weed competition, which improved resource utilization and enhanced crop growth. In contrast, the drone-applied higher doses (80%, 90%, and 100% RDH) showed significantly lower growth parameters due to increased phytotoxicity. The reduced spray volume in drone applications concentrated the solution up to 15-fold in 100% RDH, leading to adverse effects on crop growth at initial stages. This weakened growth allowed a second flush of weeds to flourish, intensifying crop-weed competition and further reducing growth parameters in these treatments (36–38). The untreated weedy check exhibited the lowest growth parameters due to severe crop-weed competition in the absence of any weed control measures.

Phytotoxicity observed in rice

Phytotoxicity score in rice

The visual phytotoxic symptoms on rice leaves, including wilting, chlorosis, necrosis, and leaf tip/surface injury, were systematically recorded in herbicide-treated plots applied via drones at 1, 5, 10, 15, and 20 days after herbicide application (DHA) (Table 3 and Fig. 3). The highest phytotoxicity scores for wilting, chlorosis, necrosis, and leaf tip/surface injury were observed in the 100% RDH drone application, with respective scores of 14, 12, 8, 5, and 2 across the observation period. This was followed by the 90% RDH treatment (scores of 12, 9, 7, 3, and 2) and the 80% RDH treatment (scores of 8, 6, 4, 1, and 0).

Minimal phytotoxic effects were observed in the 70% and 60% RDH drone treatments and the 100% RDH knapsack sprayer application, while no visible phytotoxic symptoms were recorded in the 50% and 40% RDH drone applications. Across all treatments, phytotoxic symptoms progressively diminished from 1 to 20 DHA. Chlorosis and

Table 3. Effect of different doses of herbicide (triafamone 20% + ethoxysulfuron 10%) through drone spraying on visual phytotoxicity score in rice

Treatments	1 DHA					5 DHA					10 DHA					15 DHA					20 DHA				
	W	C	N	I	T	W	C	N	I	T	W	C	N	I	T	W	C	N	I	T	W	C	N	I	T
T_1	2	6	2	4	14	1	6	2	3	12	0	5	1	2	8	0	3	0	2	5	0	1	0	1	2
T_2	2	5	1	4	12	1	4	1	3	9	0	4	1	2	7	0	2	0	1	3	0	1	0	1	2
T_3	1	4	0	3	8	0	3	0	3	6	0	3	0	1	4	0	1	0	0	1	0	0	0	0	0
T_4	0	2	0	1	3	0	1	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
T_5	0	2	0	1	3	0	1	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
T_6	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T_7	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
T_8	0	1	0	1	2	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

W: Wilting; **C**: Chlorosis; **N**: Necrosis; **I**: Injury in leaf tip/surface; **DHA**: Days after herbicide application.

Fig. 3. Phytotoxicity observed after application of different doses of the herbicide mixture (triafamone 20% + ethoxysulfuron 10%) through drone and knapsack sprayer in rice .

leaf tip injury were more pronounced than wilting and necrosis at all observation stages for each treatment. By 30 DHA, complete crop recovery was evident, and no residual phytotoxic symptoms were detected. These findings are consistent with those reported by Mahapatra et al. (2017) (25), Rosinger et al. (2012) (22), Pal et al. (2008) (39), and Park et al. (2017) (40).

CCM chlorophyll-meter readings in rice

The chlorophyll meter readings of rice recorded at 1, 5, 10, 15, and 20 DHA revealed significant differences among the treatments (Table 4). The weed-free check consistently exhibited the highest chlorophyll content across all intervals, with values of 6.36, 8.21, 10.17, 16.36, and 22.69, respectively. This superior performance can be attributed to the absence of crop-weed competition, allowing efficient utilization of growth resources by the crop. Among drone-applied treatments, 70% of the RDH performed exceptionally well, with readings of 5.65, 6.23, 8.33, 15.24, and 22.13, closely matching the weed-free check and the 100% RDH applied via knapsack sprayer, especially at later intervals. These results indicate minimal phytotoxic effects from the 70% RDH drone application, with rapid recovery observed within a short period. The knapsack sprayer application of 100% RDH also recorded high chlorophyll values of 5.52, 5.89, 7.58, 15.02, and 22.04, comparable to the top-performing drone treatments. Conversely, the weedy check consistently exhibited the lowest chlorophyll readings, underscoring the adverse impact of crop-weed competition on photosynthetic efficiency. These findings align with previous studies by Mahapatra et al. (2017) (25), Rosinger et al. (2012) (22), Pal et al. (2006) (39), and Park et al. (2017) (40), which also highlighted the detrimental effects of weed competition and the efficacy of optimized herbicide treatments.

Yield attributing characters of rice

The application of varying doses of herbicide through drones significantly influenced rice yield attributes, with marked differences observed across treatments, except for

Table 4. Effect of different doses of herbicide (triafamone 20% + ethoxysulfuron 10%) through drone spraying on CCM chlorophyll-meter readings of rice

	Treatments	1 DHA	5 DHA	10 DHA	15 DHA	20 DHA
T_1	Drone 100% RDH (67.50 g a.i. ha^{-1})	2.78^{d}	2.93^{d}	4.85^{g}	11.32^{bc}	19.37^{cd}
T_2	Drone 90% RDH (60.75 g a.i. ha^{-1})	3.02^{d}	3.29^{cd}	5.42^{fg}	12.17^{b}	19.49^{cd}
T_3	Drone 80% RDH (54.00 g a.i. ha^{-1})	3.45^{cd}	3.66^{c}	5.68^{ef}	12.43^{b}	19.77^{bcd}
T_4	Drone 70% RDH (47.25 g a.i. ha^{-1})	5.65^{b}	6.23^{b}	8.33^{b}	15.24^{a}	22.13^{a}
T_5	Drone 60% RDH (40.50 g a.i. ha^{-1})	5.89^{ab}	6.03^{b}	7.51^{c}	14.97^{a}	21.52^{abc}
T_6	Drone 50% RDH (33.75 g a.i. ha^{-1})	5.92^{ab}	6.12^{b}	6.49^{de}	11.45^{b}	18.76^{de}
T_7	Drone 40% RDH (27.00 g a.i. ha^{-1})	6.02^{ab}	6.15^{b}	6.52^{d}	11.57^{b}	18.31^{de}
T_8	Knapsack 100% RDH (67.50 g a.i. ha^{-1})	5.52^{b}	5.89^{b}	7.58^{bc}	15.02^{a}	22.04^{ab}
T_9	Weed-free check	6.36^{a}	8.21^{a}	10.17^{a}	16.36^{a}	22.69^{a}
T_{10}	Weedy check	3.73^{c}	3.85^{c}	3.97^{h}	9.82^{c}	16.66^{e}
SEM (±)		0.22	0.24	0.27	0.52	0.79
CD (P=0.05)		0.67	0.71	0.82	1.55	2.35

DHA: Days after herbicide application.

filled spikelets (%) and panicle length (Table 5). The weed-free check consistently achieved the highest values across parameters, including the number of panicles m^{-2} (282), spikelets per panicle (332), grains per panicle (294), filled spikelets (88.61%), test weight (21.10 g), panicle weight (3.75 g), and panicle length (22.0 cm). Among drone-applied treatments, the 70% recommended dose of herbicide (RDH) emerged as the most effective, delivering values of 280 panicles m^{-2}, 318 spikelets per panicle, 280 grains per panicle, 88.39% filled spikelets, 21.07 g test weight, 3.73 g panicle weight, and 21.8 cm panicle length. These results were comparable to those achieved with the 100% RDH applied via knapsack sprayer and closely aligned with the weed-free check. Conversely, higher doses of herbicide (80%, 90%, and 100% RDH) applied through drones exhibited phytotoxic effects, impeding early crop growth. This early growth inhibition allowed for increased weed growth in later stages, leading to intensified competition for growth resources. Consequently, the performance of these treatments in key yield attributes was notably lower compared to the optimal 70% RDH and the weed-free check (36-39, 41, 42).

Yield of rice

The analysis of yield, harvest, and weed indices revealed significant differences across treatments (Table 6). The weed-free check demonstrated superior performance, achieving the highest grain yield (5.9 t ha^{-1}), straw yield (6.9 t ha^{-1}), and biological yield (12.8 t ha^{-1}), along with the lowest weed index (0%) and a harvest index of 46.2%. Among drone-applied treatments, the 70% recommended dose of herbicide (RDH) performed notably well, recording grain yield (5.6 t ha^{-1}), straw yield (6.4 t ha^{-1}), biological yield (12.0 t ha^{-1}), and a low weed index (4.4%), closely aligning with the performance of the knapsack sprayer. Early-stage suppression of weeds allowed the rice crop to grow vigorously, preventing subsequent weed proliferation, which resulted in enhanced yield attributes and productivity. Conversely, higher doses such as 100% and 90% RDH applied via drone resulted in lower grain yields (4.4 and 4.9 t ha^{-1}, respectively) and higher weed indices (26% and 16%). This was attributed to early-stage phytotoxicity, which adversely affected crop growth, increasing weed competition at later stages and ultimately reducing

Table 5. Effect of different doses of herbicide (triafamone 20% + ethoxysulfuron 10%) through drone spraying on yield attributing characters of rice

	Treatments	No. of panicles m^{-2}	No. of spikelets $panicle^{-1}$	No. of grains $panicle^{-1}$	Filled spikelets (%)	Test weight (g)	Panicle Weight (g)	Panicle length (cm)
T_1	Drone 100% RDH (67.50 g a.i. ha^{-1})	235^{def}	247^{cd}	216^{de}	87.55	19.37^{cd}	2.90^{cde}	20.6^{de}
T_2	Drone 90% RDH (60.75 g a.i. ha^{-1})	243^{cde}	266^{cd}	226^{de}	86.78	19.71^{c}	3.05^{cde}	20.8^{d}
T_3	Drone 80% RDH (54.00 g a.i. ha^{-1})	257^{bcd}	273^{bc}	235^{cd}	88.14	20.32^{b}	3.26^{bcd}	20.9^{d}
T_4	Drone 70% RDH (47.25 g a.i. ha^{-1})	280^{ab}	318^{ab}	280^{ab}	88.39	21.07^{a}	3.73^{a}	21.8^{ab}
T_5	Drone 60% RDH (40.50 g a.i. ha^{-1})	259^{abc}	283^{bc}	241^{bcd}	85.19	20.43^{b}	3.31^{abc}	21.4^{c}
T_6	Drone 50% RDH (33.75 g a.i. ha^{-1})	233^{ef}	237^{cd}	211^{de}	88.88	19.07^{d}	2.81^{de}	20.3^{e}
T_7	Drone 40% RDH (27.00 g a.i. ha^{-1})	216^{f}	222^{de}	191^{e}	85.84	18.88^{d}	2.71^{e}	20.2^{e}
T_8	Knapsack 100% RDH (67.50 g a.i. ha^{-1})	273^{ab}	314^{ab}	273^{abc}	87.18	20.47^{b}	3.70^{ab}	21.5^{bc}
T_9	Weed free	282^{a}	332^{a}	294^{a}	88.61	21.10^{a}	3.75^{a}	22.0^{a}
T_{10}	Weedy check	164^{g}	177^{e}	141^{f}	79.67	18.03^{e}	2.14^{f}	19.5^{f}
SEM (±)		7.6	16.01	13.9	6.6	0.2	0.1	0.1
CD (P=0.05)		22.8	47.5	41.3	NS	0.5	0.4	NS

Table 6. Effect of different doses of herbicide (triafamone 20% + ethoxysulfuron 10%) through drone spraying on yield, harvest and weed index (WI) of rice

	Treatments	Yield			Harvest index (%)	Weed Index (%)
		Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Biological yield (t ha^{-1})		
T_1	Drone 100% RDH (67.50 g a.i. ha^{-1})	4.4^{d}	5.5^{c}	9.8^{de}	44.3	26.0
T_2	Drone 90% RDH (60.75 g a.i. ha^{-1})	4.9^{c}	5.8^{bc}	10.8^{cd}	45.9	16.0
T_3	Drone 80% RDH (54.00 g a.i. ha^{-1})	5.1^{bc}	5.9^{bc}	11.0^{bc}	46.2	13.4
T_4	Drone 70% RDH (47.25 g a.i. ha^{-1})	5.6^{ab}	6.4^{ab}	12.0^{ab}	46.8	4.4
T_5	Drone 60% RDH (40.50 g a.i. ha^{-1})	5.3^{bc}	5.9^{bc}	11.2^{bc}	47.2	10.2
T_6	Drone 50% RDH (33.75 g a.i. ha^{-1})	4.3^{d}	5.4^{c}	9.6^{de}	44.5	27.3
T_7	Drone 40% RDH (27.00 g a.i. ha^{-1})	4.1^{d}	5.2^{c}	9.3^{e}	44.0	30.7
T_8	Knapsack 100% RDH (67.50 g a.i. ha^{-1})	5.5^{ab}	6.5^{ab}	12.0^{ab}	46.0	6.3
T_9	Weed free	5.9^{a}	6.9^{a}	12.8^{a}	46.2	0.0
T_{10}	Weedy check	2.9^{e}	4.0^{d}	6.9^{f}	42.8	49.9
SEM (±)		0.2	0.3	0.4	1	-
CD (P=0.05)		0.5	0.9	1.2	NS	-

yields (41, 42). The lowest grain yield was observed in the weedy check treatment. The higher dry matter accumulation observed at 60 DAS and harvest under effective weed management treatments likely contributed to increased yields by promoting greater tiller production. Reduced weed competition during critical growth stages led to more grain-bearing tillers, as also noted in similar findings by Kumar et al. (2018) (43). These results emphasize the critical role of optimal herbicide dosages in managing crop-weed dynamics and maximizing rice productivity.

Effect on weed density in rice

The analysis of weed density at 30, 60, and 90 DAS (Table 7) revealed significant differences among treatments. The weed-free and weedy checks consistently demonstrated the lowest and highest weed densities, respectively, across all weed categories (grasses, sedges, and broad-leaved weeds, BLWs). Among drone-applied treatments, the 70% recommended dose of herbicide (RDH) emerged as the most effective, maintaining weed densities comparable to the weed-free check. This treatment recorded total weed densities of 0.0, 13.3, and 13.3 m^{-2} at 30, 60, and 90 DAS, respectively. It significantly reduced weed competition during early growth stages, enabling vigorous crop development. Conversely, higher doses (100% and 90% RDH) applied via drone, though effective in reducing weed density at 30 DAS due to disruption of protein synthesis in weeds, resulted in increased weed densities at 60 and 90 DAS. This indicates potential phytotoxic effects that suppressed initial crop growth, thereby allowing subsequent weed resurgence. These findings underscore the importance of optimizing herbicide dosage, as exceeding the 70% RDH threshold leads to reduced efficacy at later stages due to compromised early crop growth and intensified weed competition. Drone-based application at lower concentrations showed superior weed control compared to traditional knapsack sprayers using higher concentrations, emphasizing the efficiency of precision spraying technologies.

Effect on weed biomass and WCE in rice

The analysis of weed biomass and WCE at 30, 60, and 90 DAS revealed significant differences among treatments (Table 8). The weed-free check consistently exhibited the lowest weed biomass and the highest WCE (100%) across all stages, as manual hand weeding was performed at 20, 40, and 60 DAS. Among drone-applied treatments, the 70% RDH demonstrated superior efficacy, with weed biomass values of 7.8, 13.4, and 10.2 g m^{-2} at 30, 60, and 90 DAS, respectively, and WCE values of 94% and 95% at 60 and 90 DAS, respectively. This indicates that the 70% RDH application through drones effectively controlled early-stage weed growth, allowing the rice crop to establish vigorous growth and subsequently suppress weed competition. In contrast, higher doses (100%, 90%, and 80% RDH) applied via drones resulted in greater weed biomass at later stages, attributed to initial phytotoxicity that impeded crop growth, thereby increasing weed competition. These treatments recorded lower WCE values, ranging from 71% to 78%. These findings emphasize the critical importance of optimizing herbicide doses to achieve high WCE, minimize weed biomass, and ensure favorable crop-weed competition dynamics for improved rice yield outcomes.

Table 7. Effect of different doses of herbicide (triafamone 20% + ethoxysulfuron 10%) through drone spraying on weed density (m^{-2}) in rice

Treatments	30 DAS				60 DAS				90 DAS			
	Grasses	Sedges	BLWs	Total	Grasses	Sedges	BLWs	Total	Grasses	Sedges	BLWs	Total
Drone 100% RDH (67.50 g a.i. ha^{-1})	0.7^{e} (0.0)	0.7^{d} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	5.3^{c} (28.0)	5.3^{c} (28.0)	3.1^{c} (9.0)	8.1^{d} (65.0)	5.8^{c} (33.3)	4.8^{c} (22.7)	3.0^{c} (8.3)	8.0^{c} (64.3)
Drone 90% RDH (60.75 g a.i. ha^{-1})	0.7^{e} (0.0)	0.7^{d} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	5.1^{c} (25.3)	4.9^{cd} (24.0)	2.9^{c} (7.7)	7.6^{de} (57.0)	5.6^{c} (30.7)	4.7^{c} (21.3)	2.7^{c} (7.0)	7.7^{cd} (59.0)
Drone 80% RDH (54.00 g a.i. ha^{-1})	0.7^{e} (0.0)	0.7^{d} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	4.9^{c} (24.0)	4.5^{d} (20.0)	2.7^{cd} (6.7)	7.1^{e} (50.7)	4.9^{c} (24.0)	4.5^{c} (20.0)	2.7^{cd} (6.7)	7.2^{d} (50.7)
Drone 70% RDH (47.25 g a.i. ha^{-1})	0.7^{e} (0.0)	0.7^{d} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	2.4^{d} (5.3)	2.4^{e} (5.3)	1.8^{f} (2.7)	3.7^{h} (13.3)	2.4^{d} (5.3)	2.7^{d} (6.7)	1.3^{e} (1.3)	3.7^{f} (13.3)
Drone 60% RDH (40.50 g a.i. ha^{-1})	2.4^{c} (5.3)	1.6^{c} (2.7)	2.1^{c} (4.0)	3.5^{c} (12.0)	3.0^{d} (8.7)	3.0^{e} (8.7)	2.4^{de} (5.3)	4.8^{f} (22.7)	3.0^{d} (8.3)	3.0^{d} (8.7)	2.3^{d} (5.0)	4.7^{e} (22.0)
Drone 50% RDH (33.75 g a.i. ha^{-1})	4.4^{b} (20.0)	4.0^{b} (16.0)	3.1^{b} (9.3)	6.7^{b} (44.0)	6.3^{b} (38.7)	6.1^{b} (37.3)	3.9^{b} (15.0)	9.6^{c} (91.0)	6.9^{b} (46.7)	6.0^{b} (36.0)	3.7^{b} (13.0)	9.8^{b} (95.7)
Drone 40% RDH (27.00 g a.i. ha^{-1})	4.5^{b} (18.7)	4.2^{b} (17.3)	3.3^{b} (10.7)	7.0^{b} (48.0)	6.7^{b} (45.3)	6.3^{b} (40.0)	4.3^{b} (18.0)	10.2^{b} (103.3)	7.2^{b} (52.0)	6.3^{b} (40.0)	4.0^{b} (15.7)	10.4^{b} (107.7)
Knapsack 100% RDH (67.50 g a.i. ha^{-1})	1.6^{d} (2.7)	0.7^{d} (0.0)	1.3^{d} (1.3)	2.0^{d} (4.0)	2.7^{d} (6.7)	2.7^{e} (7.0)	2.1^{ef} (4.0)	4.3^{g} (17.7)	2.7^{d} (6.7)	2.8^{d} (7.3)	1.7^{e} (2.30)	4.1^{ef} (16.3)
Weed free	0.7^{e} (0.0)	0.7^{d} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	0.7^{f} (0.0)	0.7^{g} (0.0)	0.7^{i} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	0.7^{f} (0.0)	0.7^{g} (0.0)
Weedy check	7.6^{a} (57.3)	6.5^{a} (41.3)	4.6^{a} (20.7)	10.9^{a} (119.3)	10.9^{a} (120.0)	9.2^{a} (84.0)	5.3^{a} (28.0)	15.2^{a} (232.0)	11.3^{a} (128.0)	9.5^{a} (90.0)	5.1^{a} (25.7)	15.6^{a} (243.7)
SEM (±)	0.2	0.2	0.1	0.2	0.2	0.2	0.1	0.1	0.3	0.2	0.1	0.2
CD (P=0.05)	0.7	0.6	0.3	0.6	0.8	0.8	0.4	0.5	1.02	0.8	0.3	0.6

Figures in parentheses are the original values. The data was transformed to square root $[\sqrt{(x+0.5)}]$ before analysis; DAS: Days after sowing; RDH: Recommended dose of herbicide.

Table 8. Effect of different doses of herbicide (triafamone 20% + ethoxysulfuron 10%) through drone spraying on weed biomass (g m^{-2}) and WCE (%) in rice

Treatments	30 DAS				60 DAS					90 DAS				
	Grasses	Sedges	BLWs	Total	Grasses	Sedges	BLWs	Total	WCE	Grasses	Sedges	BLWs	Total	WCE
Drone 100% RDH (67.50 g a.i. ha^{-1})	0.7^{e} (0.0)	0.7^{d} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	5.2^{c} (26.2)	3.1^{c} (9.2)	1.4^{cd} (1.6)	6.1^{c} (37.0)	71	5.0^{c} (23.9)	3.0^{c} (9.3)	1.4^{cd} (1.5)	5.9^{c} (34.0)	73
Drone 90% RDH (60.75 g a.i. ha^{-1})	0.7^{e} (0.0)	0.7^{d} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	5.0^{c} (24.8)	2.8^{c} (7.7)	1.4^{cd} (1.4)	5.8^{c} (33.8)	73	4.8^{c} (22.4)	2.7^{c} (8.7)	1.3^{de} (1.2)	5.6^{c} (30.8)	74
Drone 80% RDH (54.00 g a.i. ha^{-1})	0.7^{e} (0.0)	0.7^{d} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	2.4^{d} (5.5)	1.6^{d} (2.0)	1.0^{f} (0.6)	2.9^{e} (8.1)	75	1.7^{e} (2.7)	1.4^{d} (2.9)	0.9^{g} (0.3)	2.2^{e} (4.4)	78
Drone 70% RDH (47.25 g a.i. ha^{-1})	2.5^{c} (5.6)	1.3^{c} (1.4)	1.2^{c} (0.8)	2.9^{c} (7.8)	3.1^{d} (9.0)	2.0^{d} (3.3)	1.3^{de} (1.1)	3.7^{d} (13.4)	94	2.6^{d} (6.5)	1.8^{d} (3.8)	1.2^{ef} (0.9)	3.3^{d} (10.2)	95
Drone 60% RDH (40.50 g a.i. ha^{-1})	4.5^{b} (19.7)	3.0^{b} (8.3)	1.6^{b} (2.0)	5.5^{b} (30.0)	6.4^{b} (40.4)	3.9^{b} (14.4)	1.9^{b} (3.2)	7.6^{b} (58.0)	90	6.2^{b} (38.3)	3.8^{b} (15.7)	1.9^{b} (3.1)	7.5^{b} (55.4)	92
Drone 50% RDH (33.75 g a.i. ha^{-1})	4.6^{b} (21.1)	3.1^{b} (9.0)	1.7^{b} (2.3)	5.7^{b} (32.3)	6.9^{b} (47.4)	4.0^{b} (15.4)	2.1^{b} (3.8)	8.2^{b} (66.6)	58	6.7^{b} (45.4)	3.9^{b} (17.5)	2.1^{b} (3.8)	8.0^{b} (64.2)	59
Drone 40% RDH (27.00 g a.i. ha^{-1})	1.7^{d} (2.8)	0.7^{d} (0.0)	0.9^{d} (0.3)	1.8^{d} (3.09)	2.7^{d} (6.9)	1.8^{d} (2.7)	1.2^{f} (0.8)	3.3^{de} (10.4)	51	2.2^{de} (4.3)	1.6^{d} (3.2)	1.0^{fg} (0.6)	2.7^{de} (7.0)	54
Knapsack 100% RDH (67.50 g a.i. ha^{-1})	0.7^{e} (0.0)	0.7^{d} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	0.7^{g} (0.0)	0.7^{f} (0.0)	92	0.7^{f} (0.0)	0.7^{e} (0.0)	0.7^{h} (0.0)	0.7^{f} (0.0)	93
Weed free	0.7^{e} (0.0)	0.7^{d} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	0.7^{e} (0.0)	0.7^{g} (0.0)	0.7^{f} (0.0)	100	0.7^{f} (0.0)	0.7^{e} (0.0)	0.7^{h} (0.0)	0.7^{f} (0.0)	100
Weedy	7.8^{a} (60.4)	4.7^{a} (21.4)	2.2^{a} (4.4)	9.3^{a} (86.2)	9.9^{a} (99.0)	5.7^{a} (32.3)	2.5^{a} (5.9)	11.7^{a} (137.2)	0	9.8^{a} (97.2)	5.7^{a} (39.3)	2.7^{a} (7.0)	11.7^{a} (136.4)	0
SEM (±)	0.2	0.1	0.05	0.2	0.2	0.1	0.06	0.1	-	0.2	0.1	0.06	0.2	-
CD (P=0.05)	0.7	0.4	0.1	0.6	0.8	0.4	0.1	0.5	-	0.8	0.5	0.1	0.6	-

Figures in parentheses are the original values. The data was transformed to square root $[\sqrt{(x+0.5)}]$ before analysis; DAS: Days after sowing; RDH: Recommended dose of herbicide; WCE: Weed control efficiency (%).

Correlation of yield attributes, weed biomass, straw and grain yield

Rice yield attributes, including the number of panicles per square meter, panicle weight (10 panicles), number of grains per panicle, 1000-grain weight, and straw yield, exhibited strong positive correlations with grain yield, with correlation coefficients ranging from 0.84 to 0.90. These findings underscore the significant contribution of yield components to grain yield (Fig. 4). Conversely, the biomass of grasses, sedges, BLWs, and total weed biomass at 60 DAS showed a highly negative correlation with grain yield, with coefficients ranging from -0.91 to -0.92, indicating the adverse impact of weed competition on rice productivity. Similar observations were reported by Ansari et al. (2017) (44). The data reveal that weed competition significantly limits resource availability for rice crops, resulting in lower yields in unweeded plots. Uncontrolled weed growth in wet-seeded rice (WSR) can lead to grain yield reductions of

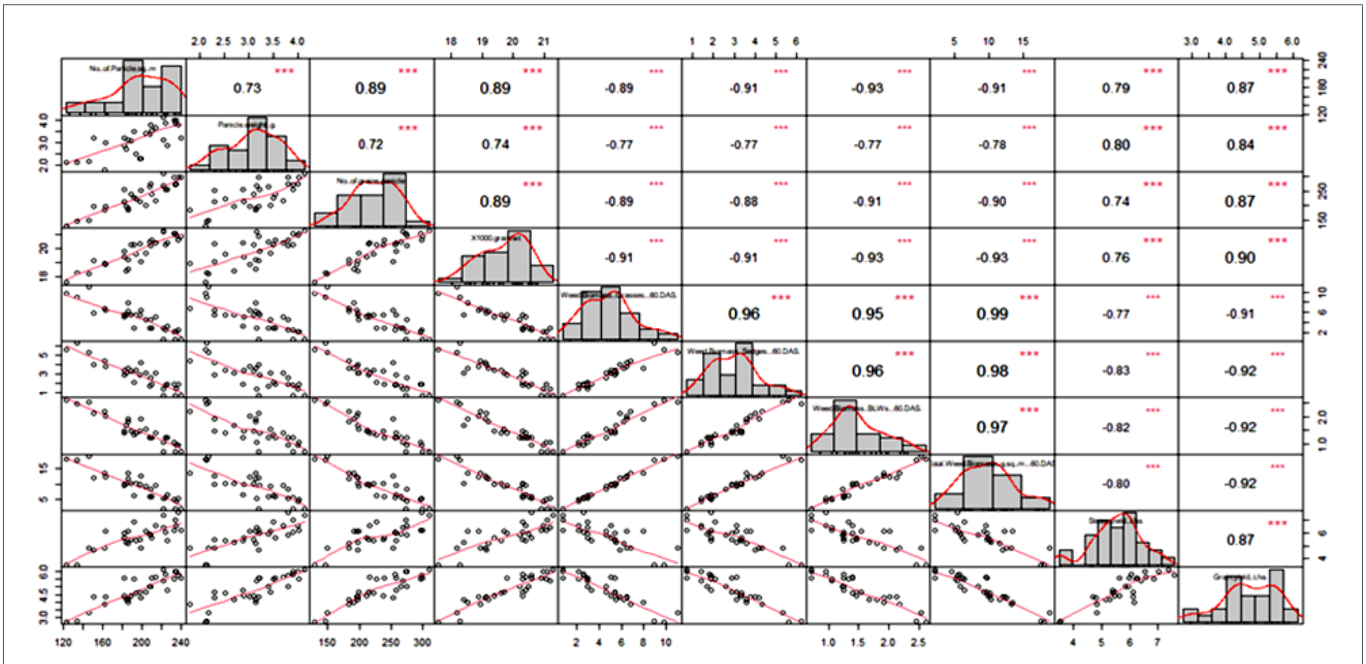

Fig. 4. Correlation plots of rice yield attributes (no. of panicles m^{-2}, 10 panicle weight, no. of grains panicle^{-1}, 1000-grain weight), weed biomass (grasses, sedges, BLWs and total at 60 DAS), straw and grain yield.

up to 50%. These findings align with those reported by Kumar et al. (2018) (43), highlighting the critical importance of effective weed management in optimizing rice yield potential.

Economics

The economic analysis of herbicide application treatments via drone demonstrated significant variations in the cost of cultivation, gross returns, net returns, and benefit-cost (B:C) ratio (Table 9). Among drone-based treatments, the application of 70% of the recommended dose of herbicide (RDH) emerged as the most economically efficient approach. This treatment achieved the highest gross return (₹129,290 ha^{-1}), net return (₹82,528 ha^{-1}), and B:C ratio (1.8), indicating an optimal balance between herbicide efficiency and application cost. Higher-dose drone applications, such as 100% and 90% RDH, resulted in reduced net returns of ₹52,969 ha^{-1} and ₹66,541 ha^{-1}, respectively, with corresponding B:C ratios of 1.1 and 1.4. These findings suggest excessive costs and possible phytotoxicity that limited economic returns. Lower doses, including 60% and 50% RDH via drone, also underperformed economically, with net returns of ₹74,936 ha^{-1} and ₹52,614 ha^{-1} and B:C ratios of 1.6 and 1.1, respectively. The traditional knapsack sprayer at 100% RDH provided competitive financial outcomes, with a gross return of ₹127,022 ha^{-1}, net return of ₹79,931 ha^{-1}, and a B:C ratio of 1.7, closely aligning with the 70% RDH drone treatment. The weed-free check yielded the highest gross return (₹135,452 ha^{-1}) but had a lower net return (₹70,991 ha^{-1}) and B:C ratio (1.1) due to elevated cultivation costs (₹64,461 ha^{-1}). Conversely, the weedy check incurred the lowest economic efficiency, with a net return of ₹24,899 ha^{-1} and a B:C ratio of 0.6, underscoring the economic necessity of effective weed control strategies.

Energetics

The study on the energetics of different herbicide doses applied via drones revealed significant variations in key energy metrics, including additional energy input, energy output, net energy, energy use efficiency, specific energy, and energy productivity (Table 10). The 70% recommended dose (RDH) applied through drone exhibited the most favorable energetics, with an energy output of 162,599 MJ ha^{-1}, a net energy of 146,535 MJ ha^{-1}, and an energy use efficiency of 10.12. This treatment required a relatively low additional energy input (19.22 MJ ha^{-1}) and had a specific energy of 2.85 and energy productivity of 0.35, indicating optimal resource utilization. In contrast, higher doses of 100% and 90% RDH through drone, although showing substantial energy outputs of 132,440 MJ ha^{-1} and 145,640 MJ ha^{-1}, respectively, exhibited lower energy use efficiencies (8.24 and 9.06) due to higher additional energy inputs (27.32 MJ ha^{-1} and 24.62 MJ ha^{-1}). The 50% and 40% RDH

Table 9. Effect of different doses of herbicide (triafamone 20% + ethoxysulfuron 10%) through drone spraying on economics in rice

Treatments	Cost of Cultivation (₹ ha^{-1})	Gross return (₹ ha^{-1})	Net return (₹ ha^{-1})	B:C Ratio
Drone 100% RDH (67.50 g a.i. ha^{-1})	47641	100609	52969	1.1
Drone 90% RDH (60.75 g a.i. ha^{-1})	47348	113889	66541	1.4
Drone 80% RDH (54.00 g a.i. ha^{-1})	47055	117283	70228	1.5
Drone 70% RDH (47.25 g a.i. ha^{-1})	46762	129290	82528	1.8
Drone 60% RDH (40.50 g a.i. ha^{-1})	46469	121405	74936	1.6
Drone 50% RDH (33.75 g a.i. ha^{-1})	46176	98789	52614	1.1
Drone 40% RDH (27.00 g a.i. ha^{-1})	45883	94280	48398	1.1
Knapsack 100% RDH (67.50 g a.i. ha^{-1})	47091	127022	79931	1.7
Weed-free	64461	135452	70991	1.1
Weedy	43461	68360	24899	0.6

Table 10. Effect of different doses of herbicide (triafamone 20% + ethoxysulfuron 10%) through drone spraying on energetics in rice

Treatments	Additional energy input (MJ ha^{-1})	Energy output (MJ ha^{-1})	Net energy (MJ ha^{-1})	Energy use efficiency	Specific energy (MJ kg^{-1})	Energy productivity (kg MJ^{-1})
Drone 100% RDH (67.50 g a.i. ha^{-1})	27.32	132440	116369	8.24	3.69	0.27
Drone 90% RDH (60.75 g a.i. ha^{-1})	24.62	145640	129571	9.06	3.25	0.31
Drone 80% RDH (54.00 g a.i. ha^{-1})	21.92	149345	133279	9.30	3.15	0.32
Drone 70% RDH (47.25 g a.i. ha^{-1})	19.22	162599	146535	10.12	2.85	0.35
Drone 60% RDH (40.50 g a.i. ha^{-1})	16.52	152085	136024	9.47	3.04	0.33
Drone 50% RDH (33.75 g a.i. ha^{-1})	13.82	129879	113820	8.09	3.75	0.27
Drone 40% RDH (27.00 g a.i. ha^{-1})	11.12	125340	109285	7.81	3.94	0.25
Knapsack 100% RDH (67.50 g a.i. ha^{-1})	46.60	162644	146553	10.11	2.91	0.34
Weed-free	753.60	172496	155698	10.27	2.85	0.35
Weedy	0.00	92984	76940	5.80	5.44	0.18

Common input energy for WSR in *kharif* = 16044 MJ ha^{-1}.

through drone treatments yielded reduced energy outputs and net energies, along with lower energy use efficiencies (8.09 and 7.81). The 100% RDH through knapsack sprayer had an energy output (162,644 MJ ha^{-1}) and net energy (146,553 MJ ha^{-1}) comparable to the 70% RDH through drone treatment but required significantly higher additional energy input (46.60 MJ ha^{-1}). The weed-free check recorded the highest energy output (172,496 MJ ha^{-1}) and net energy (155,698 MJ ha^{-1}) with an energy use efficiency of 10.27. However, its exceptionally high additional energy input (753.60 MJ ha^{-1}) adversely affected its specific energy and energy productivity (2.85 and 0.35). The weedy check, on the other hand, had the lowest energy output (92,984 MJ ha^{-1}) and net energy (76,940 MJ ha^{-1}), underscoring the negative impact of poor weed management on energy efficiency. Similar findings were reported by Paul et al. (2023) (16).

Conclusion

This comprehensive study evaluates the effectiveness of drone-applied herbicide treatments in rice cultivation, with a focus on the optimal 70% recommended dose of herbicide (RDH) at 47.25 g a.i. ha^{-1}, compared to the full 100% RDH (67.5 g a.i. ha^{-1}) applied using a traditional knapsack sprayer. The 70% RDH treatment exhibited minimal phytotoxicity, ensuring robust early crop growth, which contributed to improved crop-weed competition and consistently lower weed density and biomass throughout the growing season. As a result, this treatment achieved the highest weed control efficiency (WCE) and significantly improved key yield parameters and overall yield. Economically, the 70% RDH treatment provided the highest net returns and the best benefit-cost (B:C) ratio, demonstrating its financial viability. In terms of energy efficiency, it also showed the most favorable energy use efficiency and net energy, highlighting optimal resource utilization. These findings emphasize the potential of precision agriculture technologies, such as drone applications, to reduce herbicide use while enhancing economic returns, energy efficiency, and crop productivity. This approach not only supports sustainable agricultural practices but also offers a scientifically sound recommendation for farmers seeking to optimize herbicide application in rice cultivation.

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Authors' contributions

BM carried out the research taking the observations. AM formulated the research problem and design of the experiment. TM participated in drone spraying. CS participated in drone management and phytotoxicity studies. SS contributed to reviewing the research and manuscript. RSK contributed to crop management and coordination. VKG helped in data analysis. DSR participated in designing and coordination. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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