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Effect of drone-assisted sequential application of pre- and early post-emergence herbicides on weed density, weed control efficiency, growth and yield of groundnut (*Arachis hypogaea* L.)

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ABSTRACT

A field experiment was conducted during the Rabi season of 2025 at a farmer's field in Udupi to study the effect of drone-assisted sequential application of pre- and early post-emergence herbicides on weed density, weed control efficiency, growth and yield of groundnut (*Arachis hypogaea* L.) cv. DH-256. The experiment was laid out in a Randomized Complete Block Design (RCBD) with six treatments, replicated four times. The treatments consisted of a pre-emergence application of Pendimethalin 38.7% CS at 0-3 DAS, followed by an early post-emergence application of Imazethapyr 10% SL at 20-25 DAS. Herbicides were applied at the recommended dose through a knapsack sprayer (T_1) and through a drone at 100, 75, and 50 per cent of the recommended dose (T_2 , T_3 and T_4 , respectively), along with a weedy check (T_5) and a weed-free (T_6). Among the herbicidal treatments, T_2 (Pendimethalin 38.7% CS (2.25 l ha⁻¹) PE fb Imazethapyr 10% SL (750 ml ha⁻¹) EPoE - Drone (50 l ha⁻¹), 100% RDH) recorded the lowest total weed density (18.25, 27.75 and 30.50 m⁻²) and weed dry weight (2.82, 8.87 and 14.30 g m⁻²) at 30, 60 and 90 DAS, respectively, and remained statistically at par with T_1 (Pendimethalin 38.7% CS (2.25 l ha⁻¹) PE fb Imazethapyr 10% SL (750 ml ha⁻¹) EPoE-Knapsack sprayer (750 l ha⁻¹), 100% RDH). T_2 recorded the highest weed control efficiency (84.01, 78.05 and 70.11%) and the lowest weed index (5.49%) among the herbicidal treatments, with values statistically on par with T_1 (83.62, 77.81 and 69.90% W_{CE} ; 5.76% weed index). T_2 also recorded higher pod yield (2470 kg ha⁻¹), kernel yield (1723 kg ha⁻¹) and haulm yield (3292 kg ha⁻¹), along with higher plant height, number of branches, dry matter accumulation and leaf area index among the herbicidal treatments, and was statistically on par with T_1 . The results demonstrate that drone-assisted sequential application of the full recommended herbicide dose effectively managed weeds and maintained crop growth and yield in groundnut, with performance statistically on par with conventional knapsack spraying while reducing spray volume from 750 to 50 l ha⁻¹.

Keywords: Drone, Groundnut, Pendimethalin, Imazethapyr, Weed control efficiency, Growth, Yield

Introduction

Groundnut (*Arachis hypogaea* L.), popularly known as the "King of Oilseeds", is an important oilseed crop valued for its high oil (45-50%) and protein (25-30%) content. Globally, it is cultivated over 29.81 million hectares, producing 49.54 million tonnes with a productivity of 1.66 t ha⁻¹ (Anonymous, 2025) [1]. India produced 13.07 million tonnes from 5.95 million hectares during 2025-26, while Karnataka contributed about 0.38 million tonnes from 0.40 million hectares. Coastal districts such as Udupi, Dakshina Kannada and Uttara Kannada offer favourable conditions for Rabi groundnut following rice harvest (Narwal et al., 2024) [2].

Weeds are a major constraint to groundnut productivity due to its slow initial growth, prostrate habit and delayed canopy closure. Uncontrolled weeds may reduce pod yield by 15-75 per cent depending on weed density and duration of competition (Patel et al., 2020; Tripathi et al., 2022) [3, 4]. Labour scarcity and rising wages further limit manual weeding, while intercultivation after peg initiation may damage developing pegs and pods. Sequential application of pre- and early post-emergence herbicides can provide extended weed control by targeting successive weed flushes through different modes of action (Aruna et al., 2018) [5].

Drone-based spraying offers rapid application at substantially lower spray volumes, reducing water and labour requirements and operator exposure (Del Cerro et al., 2021; Dayana et al., 2022) [7, 6]. However, the effectiveness of sequential herbicide application through drones at reduced spray volumes and doses under coastal conditions remains inadequately documented. Therefore, the present investigation evaluated drone-assisted sequential application of Pendimethalin and Imazethapyr in Rabi groundnut in comparison with conventional knapsack spraying and reduced herbicide doses, with emphasis on weed flora, density, dry weight, weed control efficiency and weed index.

Material and Methods

The field experiment was conducted during late *Rabi* 2025-26 at a farmer's field in Padukere village, Kota Hobli, Udipi district (13.52014° N, 74.69154° E; 10 m amsl), located in the coastal zone (Zone-X) of *Karnataka*. The soil of the experimental site was sandy loam in texture, acidic in reaction (pH 5.19), with low electrical conductivity (0.04 dS m⁻¹), high organic carbon (1.23 g kg⁻¹).

The experiment was laid out in a Randomized Complete Block Design with six treatments, replicated four times, in a gross plot of 8 m × 7.5 m (net plot 7.10 m × 7.20 m). Groundnut cv. DH-256, a bunch-type variety, was sown on 12 December 2025 at a spacing of 30 cm × 10 cm with a seed rate of 120 kg ha⁻¹, and fertilized with 25:50:25 kg N:P₂O₅:K₂O ha⁻¹ along with zinc sulphate and borax @ 10 kg ha⁻¹ each and gypsum @ 500 kg ha⁻¹. The treatments comprised: T₁- pre-emergence (PE) Pendimethalin 38.7% CS @ 2.25 L ha⁻¹ (0-3 DAS) *fb* early post-emergence (EPOE) Imazethapyr 10% SL @ 750 mL ha⁻¹ (20-25 DAS) through a battery-operated knapsack sprayer at 750 L ha⁻¹ spray volume; T₂- pre-emergence (PE) Pendimethalin 38.7% CS @ 2.25 L ha⁻¹ (0-3 DAS) *fb* early post-emergence (EPOE) Imazethapyr 10% SL @ 750 mL ha⁻¹ (20-25 DAS) at 100% of the recommended herbicide dose applied through a drone at 50 L ha⁻¹ spray volume; T₃ - pre-emergence (PE) Pendimethalin 38.7% CS @ 1.68 L ha⁻¹ (0-3 DAS) *fb* early post-emergence (EPOE) Imazethapyr 10% SL @ 563 mL ha⁻¹ (20-25 DAS), applied through a drone at 50 L ha⁻¹ spray volume at 75% of the recommended herbicide dose; T₄ - pre-emergence (PE) Pendimethalin 38.7% CS @ 1.12 L ha⁻¹ (0-3 DAS) *fb* early post-emergence (EPOE) Imazethapyr 10% SL @ 375 mL ha⁻¹ (20-25 DAS), applied through a drone at 50 L ha⁻¹ spray volume at 50% of the recommended herbicide dose; T₅ - weedy check; and T₆ -weed-free treatment maintained by hand weeding at 20 and 35 DAS. For herbicide application, a battery-operated knapsack sprayer and an AGRIBOT drone were used as per the treatment schedule. The battery-operated knapsack sprayer had a tank capacity of 16 L and was fitted with a single hollow-cone nozzle. The spray was applied at a height of 20-30 cm above the crop, with a spraying width of 0.75-1.0 m and a spray volume of 750 L ha⁻¹. The AGRIBOT drone, having a tank capacity of 10 L, was fitted with four flat-fan nozzles (2020A-132 series). During spraying, the flight height was maintained at 1.5 m above the crop canopy, with a flying speed of 3 m s⁻¹ and a swath width of 3 m. The drone was operated by a trained operator, and a spray volume of 50 L ha⁻¹ was maintained for all drone-based herbicide treatments.

Weed flora in the experimental area was recorded on the basis of visual observation. Species-wise weed density was recorded from two randomly placed 1 m² quadrats per plot at 30, 60 and 90 DAS and categorized into grasses, sedges and broadleaved weeds (BLW). Weeds from the same quadrats were oven-dried at 65 ± 2 °C for 24 h to record dry weight (g m⁻²). Weed count and dry-weight data were subjected to $\sqrt{(x+0.5)}$ transformation prior to analysis (Blackman *et al.*, 1950) [8]; transformed values are reported with original values in parentheses. Weed control efficiency (W_{CE} , %) was calculated following formula suggested by Mani *et al.* (1973) [9]:

$$W_{CE} = \frac{(DMC - DMT)}{DMC} \times 100,$$

where DMC , dry matter production of weeds/m² in weedy check; DMT , dry-matter production of weeds/m² in the treatment to be compared

The weed index (W_I , %), the yield reduction attributable to weed competition relative to the weed-free check, was calculated as per Gill *et al.* (1969) [10]:

$$W_I = \frac{(X - Y)}{X} \times 100, \text{ where } X \text{ and } Y \text{ are the groundnut yield of the weed-free plot and the treatment plot, respectively. Data were analysed by Fisher's analysis of variance for RCBD (Gomez et al., 1984) [11]; treatment differences were tested for significance at } P = 0.05, \text{ and standard error of mean (S.E.m } \pm \text{) and critical difference (C.D.) are presented}$$

Results and Discussion

Weed density

The experimental field harboured a mixed weed flora comprising grasses (*Digitaria sanguinalis*, *Cynodon dactylon* and *Echinochloa colona*), a sedge (*Cyperus rotundus*) and broad-leaved weeds (*Cleome viscosa*, *Boerhavia diffusa*, *Cardiospermum halicacabum*, *Physalis minima*, *Phyllanthus niruri*, *Portulaca oleracea*, *Commelina benghalensis* and *Ageratum conyzoides*), similar to earlier reports from groundnut-growing tracts of coastal *Karnataka* (Narwal *et al.*, 2020; Maheswari *et al.*, 2022) [13, 12]. Total weed density differed significantly among treatments at all stages of crop growth (Table 1). The weedy check (T₅) recorded the highest weed density throughout the crop growth period, whereas the weed-free treatment (T₆) remained free of weeds. Among the herbicide treatments, Pendimethalin 38.7% CS (2.25 l ha⁻¹) PE *fb* Imazethapyr 10% SL (750 ml ha⁻¹) EPoE applied through drone (50 l ha⁻¹), 100% RDH, recorded the lowest total weed density of 18.25, 27.75 and 30.50 m⁻² at 30, 60 and 90 DAS, respectively, and was statistically on par with Pendimethalin 38.7% CS (2.25 l ha⁻¹) PE *fb* Imazethapyr 10% SL (750 ml ha⁻¹) EPoE applied through knapsack sprayer (750 l ha⁻¹), which recorded 19.25, 30.25 and 32.75 m⁻², respectively. Reduction in the drone-applied herbicide dose to 75 and 50 per cent resulted in a progressive increase in weed density. The lower weed density under Pendimethalin 38.7% CS (2.25 l ha⁻¹) PE *fb* Imazethapyr 10% SL (750 ml ha⁻¹) EPoE applied through drone (50 l ha⁻¹), 100% RDH, may be attributed to the adequate herbicide dose and low spray volume, which provided wider area coverage, greater droplet deposition on the soil surface and sufficiently uniform distribution of the herbicides over the target area. The uniform deposition of pendimethalin resulted in reduced weed germination through inhibition of cell division and mitosis in susceptible germinating weed seedlings (Sinchana *et al.*, 2023) [14]. The subsequent early post-emergence application of imazethapyr effectively controlled susceptible weeds that emerged after the pre-emergence application, thereby reducing weed population during the later stages of crop growth. The effectiveness of early post-emergence imazethapyr 10% SL in reducing total weed density and improving weed control efficiency in groundnut was also reported by Babu *et al.* (2013) [15]. Thus, the sequential action of pendimethalin on early-emerging weeds followed by imazethapyr on subsequently emerged weeds provided sustained suppression of weed emergence and establishment. The controlled flight height, speed and discharge rate of the drone further facilitated effective and relatively uniform droplet deposition, resulting in herbicide efficacy comparable with the corresponding high-volume knapsack application. These findings are consistent with earlier reports on sequential pendimethalin and imazethapyr application in groundnut (Pawar *et al.*, 2018; Vijay *et al.*, 2018; Patel *et al.*, 2021) [17, 18, 16] and UAV-based herbicide application in field crops (Pranaswi *et al.*, 2022; Paul *et al.*, 2023) [20, 19].

Weed dry weight

Total weed dry weight followed a trend similar to weed density (Table 2). Among the herbicide treatments, T₂ (Pendimethalin 38.7% CS (2.25 l ha⁻¹) PE *fb* Imazethapyr 10% SL (750 ml ha⁻¹) EPoE - Drone (50 l ha⁻¹), 100% RDH) recorded the lowest weed dry weight (2.82, 8.87 and 14.30 g m⁻² at 30, 60 and 90 DAS, respectively) and was statistically at par with T₁ (Pendimethalin 38.7% CS (2.25 l ha⁻¹) PE *fb* Imazethapyr 10% SL (750 ml ha⁻¹) EPoE - Knapsack sprayer (750 l ha⁻¹)), which recorded 2.89, 9.01 and 14.40 g m⁻², respectively. T₃ and T₄ recorded progressively higher weed biomass with reduction in herbicide dose. The lower biomass under T₁ and T₂ can be attributed to the complementary action of pendimethalin in suppressing early weed establishment followed by imazethapyr-mediated inhibition of ALS in susceptible weeds emerging subsequently, thereby restricting weed growth and biomass accumulation (Malunjar *et al.*, 2012; Patro *et al.*, 2014) [21, 22]. In T₂, application of the full recommended herbicide dose at a low carrier volume, coupled with rotor-induced downwash, likely enhanced downward transport and deposition of

spray droplets within the target zone. Such improved spray delivery can increase the probability of herbicide contact with susceptible weeds and thereby sustain the efficacy of the sequential treatment, contributing to lower weed biomass (Zhang *et al.*, 2020) [23]. The

comparable response of T₂ with the high-volume knapsack treatment indicates that the reduced carrier volume under drone application did not compromise weed biomass suppression when the recommended herbicide dose was maintained.

Table 1. Total weed density (no. m⁻²) of groundnut as influenced by drone-assisted sequential herbicide application

Treatments	Total weed density (no. m ⁻²)		
	30 DAS	60 DAS	90 DAS
T ₁ : Pendimethalin 38.7% CS (2.25 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (750 ml ha ⁻¹) EPoE - Knapsack sprayer (750 l ha ⁻¹)	4.44 (19.25)	5.55 (30.25)	5.77 (32.75)
T ₂ : Pendimethalin 38.7% CS (2.25 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (750 ml ha ⁻¹) EPoE -Drone (50 l ha ⁻¹), 100% RDH	4.33 (18.25)	5.31 (27.75)	5.57 (30.50)
T ₃ : Pendimethalin 38.7% CS (1.68 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (563 ml ha ⁻¹) EPoE -Drone (50 l ha ⁻¹), 75% RDH	5.10 (25.50)	6.32 (39.50)	6.61 (43.25)
T ₄ : Pendimethalin 38.7% CS (1.12 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (375 ml ha ⁻¹) EPoE - Drone (50 l ha ⁻¹), 50% RDH	6.32 (39.50)	7.45 (55.00)	7.62 (57.50)
T ₅ : Weedy check	7.98 (63.25)	9.33 (86.50)	9.62 (92.00)
T ₆ : Weed-free	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
SEm±	0.74	0.64	1.31
CD @ 5%	2.24	1.93	3.95

Note: Figures in parentheses are original values; data were subjected to $\sqrt{(x + 0.5)}$ transformation before analysis. DAS: Days after sowing; PE: Pre-emergence; EPoE: Early post-emergence; *fb*: followed by; RDH: Recommended dose of herbicide.

Weed control efficiency and weed index

Weed control efficiency (W_{CE}) and weed index further confirmed the effectiveness of the weed management treatments (Table 3). Pendimethalin 38.7% CS (2.25 l ha⁻¹) PE *fb* Imazethapyr 10% SL (750 ml ha⁻¹) EPoE applied through drone (50 l ha⁻¹), 100% RDH, recorded the highest W_{CE} of 84.01, 78.05 and 70.11 per cent at 30, 60 and 90 DAS, respectively, and the lowest weed index (5.49%) among the herbicide treatments, and was statistically on par with Pendimethalin 38.7% CS (2.25 l ha⁻¹) PE *fb* Imazethapyr 10% SL (750 ml ha⁻¹) EPoE applied through knapsack sprayer (750 l ha⁻¹), which recorded W_{CE} of 83.62, 77.81 and 69.90 per cent and weed index of 5.76 per cent, respectively. The higher W_{CE} under the full recommended herbicide dose was mainly due to the lower weed density and weed dry weight resulting from effective and sustained suppression of weeds by the sequential application of pendimethalin and imazethapyr. The lower weed population and biomass reduced weed

competition for moisture, nutrients, light and growing space, thereby resulting in greater suppression of weed growth and higher W_{CE} . The 50 l ha⁻¹ spray volume under drone application, together with controlled flight height, speed and discharge rate, facilitated wider coverage and adequate, relatively uniform droplet deposition over the target area, enabling effective herbicide utilization despite the low spray volume. Consequently, W_{CE} under drone application was comparable with the corresponding high-volume knapsack application. The lower weed index under the full recommended herbicide dose was associated with reduced weed competition and better crop growth and yield, resulting in pod yield closer to that of the weed-free treatment. The progressive decline in W_{CE} at later stages may be attributed to the emergence of late weed flushes and gradual decline in herbicidal activity, as reported by Devi *et al.* (2020) [24] and Supriya *et al.* (2021) [25]. In contrast, reduction of the herbicide dose to 75 and 50 per cent resulted in greater weed density and dry weight, leading to lower W_{CE} and greater yield reduction and, consequently, higher weed index.

Table 2. Total weed dry weight (g m⁻²) of groundnut as influenced by drone-assisted sequential herbicide application

Treatments	Total weed dry weight (g m ⁻²)		
	30 DAS	60 DAS	90 DAS
T ₁ : Pendimethalin 38.7% CS (2.25 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (750 ml ha ⁻¹) EPoE - Knapsack sprayer (750 l ha ⁻¹)	1.84 (2.89)	3.08 (9.01)	3.86 (14.40)
T ₂ : Pendimethalin 38.7% CS (2.25 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (750 ml ha ⁻¹) EPoE -Drone (50 l ha ⁻¹), 100% RDH	1.82 (2.82)	3.06 (8.87)	3.85 (14.30)
T ₃ : Pendimethalin 38.7% CS (1.68 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (563 ml ha ⁻¹) EPoE -Drone (50 l ha ⁻¹), 75% RDH	2.11 (3.96)	3.52 (11.86)	4.31 (18.05)
T ₄ : Pendimethalin 38.7% CS (1.12 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (375 ml ha ⁻¹) EPoE - Drone (50 l ha ⁻¹), 50% RDH	2.81 (7.40)	4.53 (20.04)	5.03 (24.82)
T ₅ : Weedy check	4.26 (17.64)	6.41 (40.62)	6.95 (47.84)
T ₆ : Weed-free	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
SEm±	0.24	0.34	0.53
CD @ 5%	0.74	1.04	1.60

Note: Figures in parentheses are original values; data were subjected to $\sqrt{(x + 0.5)}$ transformation before analysis. DAS: Days after sowing; PE: Pre-emergence; EPoE: Early post-emergence; *fb*: followed by; RDH: Recommended dose of herbicide.

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Table 3. Weed control efficiency (%) and weed index (%) of groundnut as influenced by drone-assisted sequential herbicide application

Treatments	Weed control efficiency (%)			Weed index (%)
	30 DAS	60 DAS	90 DAS	
T ₁ : Pendimethalin 38.7% CS (2.25 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (750 ml ha ⁻¹) EPoE - Knapsack sprayer (750 l ha ⁻¹)	83.62	77.81	69.90	5.76
T ₂ : Pendimethalin 38.7% CS (2.25 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (750 ml ha ⁻¹) EPoE -Drone (50 l ha ⁻¹), 100% RDH	84.01	78.05	70.11	5.49
T ₃ : Pendimethalin 38.7% CS (1.68 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (563 ml ha ⁻¹) EPoE -Drone (50 l ha ⁻¹), 75% RDH	77.55	70.80	62.27	11.29
T ₄ : Pendimethalin 38.7% CS (1.12 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (375 ml ha ⁻¹) EPoE - Drone (50 l ha ⁻¹), 50% RDH	58.05	50.66	48.12	26.17
T ₅ : Weedy check	0.00	0.00	0.00	47.70
T ₆ : Weed-free	100.00	100.00	100.00	0.00
SEm±	1.32	1.41	1.33	0.42
CD @ 5%	3.98	4.25	4.02	1.27

Note: DAS: Days after sowing; PE: Pre-emergence; EPoE: Early post-emergence; *fb*: followed by; RDH: Recommended dose of herbicide.

Growth parameters

Plant height, number of branches plant⁻¹, dry matter accumulation and leaf area index did not differ significantly at 30 DAS, but differences became evident from 60 DAS onwards. At 60 DAS, T₂ recorded 23.05 cm plant height, 8.12 branches plant⁻¹, 18.40 g plant⁻¹ dry matter and 3.17 LAI, which were statistically on par with T₁. At 90 DAS, T₂ maintained the highest values among the herbicidal treatments, with 27.34 cm plant height, 10.58 branches plant⁻¹, 36.08 g plant⁻¹ dry matter and 3.72 LAI, statistically on par with T₁. Leaf area duration was also higher under T₂ (57.00 and 103.35 days during 30-60 and 600-90 DAS, respectively) and remained on par with T₁. The higher growth attributes under T₂, with plant height of 27.34 cm, 10.58 branches plant⁻¹, dry matter accumulation of 36.08 g plant⁻¹ and LAI of 3.72 at 90 DAS, were statistically on par with T₁. The reason behind the higher growth attributes under T₂ was the combined effect of sequential application of pendimethalin at pre-emer-

gence followed by imazethapyr at early post-emergence at the full recommended herbicide dose through the drone. The drone enabled application of the full herbicide dose at a low spray volume of 50 L ha⁻¹, with effective spray distribution over the target area, thereby ensuring adequate weed suppression throughout the critical period of crop-weed competition. Consequently, reduced weed interference for nutrients, moisture, light and space favoured plant height, branching, dry matter accumulation and leaf area development. These findings were in accordance with Sudesh *et al.* (2019) [26], Hiremath *et al.* (2024) [27], Ramesh *et al.* (2024) [28] and Ashok *et al.* (2025) [29]. The overall similarity between the knapsack- and drone-sprayed full-dose treatments indicates that, once an adequate herbicide dose reaches the target, the delivery method exerts a comparatively minor influence on canopy development, which is also supported by the findings of Su *et al.* (2018) [30] and Ajay Pratap *et al.* (2025) [31], where UAV spraying performed similarly to conventional application under properly managed flight conditions.

Table 4. Plant height, number of branches plant⁻¹, dry matter accumulation and leaf area index of groundnut at 90 DAS, as influenced by drone-assisted sequential herbicide application

Treatments	Plant height (cm)	Number of branches plant ⁻¹	Dry matter (g plant ⁻¹)	Leaf area index
T ₁ : Pendimethalin 38.7% CS (2.25 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (750 ml ha ⁻¹) EPoE - Knapsack sprayer (750 l ha ⁻¹)	26.50	10.26	35.85	3.66
T ₂ : Pendimethalin 38.7% CS (2.25 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (750 ml ha ⁻¹) EPoE - Drone (50 l ha ⁻¹), 100% RDH	27.34	10.58	36.08	3.72
T ₃ : Pendimethalin 38.7% CS (1.68 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (563 ml ha ⁻¹) EPoE - Drone (50 l ha ⁻¹), 75% RDH	25.35	9.12	32.17	3.53
T ₄ : Pendimethalin 38.7% CS (1.12 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (375 ml ha ⁻¹) EPoE - Drone (50 l ha ⁻¹), 50% RDH	23.39	8.22	28.90	3.21
T ₅ : Weedy check	18.38	6.18	22.51	2.75
T ₆ : Weed-free	28.20	10.87	39.21	3.88
SEm±	0.04	0.31	1.40	0.11
CD @ 5%	3.14	0.95	4.21	0.34

Note: DAS: Days after sowing. DAS: Days after sowing; PE: Pre-emergence; EPoE: Early post-emergence; *fb*: followed by; RDH: Recommended dose of herbicide.

Yield parameters

Among the herbicide treatments, T₂ recorded the highest pod yield (2470 kg ha⁻¹) and was statistically on par with T₁ (2438 kg ha⁻¹) and next only to the weed-free treatment (2587 kg ha⁻¹). T₃ and T₄ recorded pod yields of 2295 and 1910 kg ha⁻¹, respectively, whereas

the weedy check recorded the lowest pod yield (1353 kg ha⁻¹). Kernel yield under T₂ (1723 kg ha⁻¹) was statistically comparable with T₁ (1710 kg ha⁻¹), while haulm yield under T₂ (3292 kg ha⁻¹) was also on par with T₁ (3285 kg ha⁻¹). The higher pod, kernel and haulm yields under T₂ may be attributed to the greater number of spray droplets and relatively uniform deposition of herbicides over

the target area, resulting in effective weed suppression throughout the crop growth period. The reduced crop-weed competition for moisture, nutrients, light and space favoured better crop growth and reproductive development, ultimately contributing to higher yield. Despite the substantially lower carrier volume of 50 L ha⁻¹, drone spraying under T₂ provided adequate herbicide deposition through effective droplet distribution and rotor-induced downwash, resulting in yield comparable with conventional knapsack spraying at 750 L ha⁻¹. Similar effectiveness of aerial herbicide application using small unmanned aerial

vehicles has been reported by Zhang *et al.* (2020) [23], who evaluated UAV-applied herbicides in wheat. Comparable yield responses to UAV-based herbicide application were also reported by Rabari *et al.* (2024) [32] and Ajay Pratap *et al.* (2025) [31]. The progressive reduction in yield under T₃ and T₄ with decreasing herbicide dose indicates that adequate herbicide dose is essential for maintaining effective weed suppression and crop productivity, in agreement with Mudigiri *et al.* (2024) [33].

Table 5. Yield parameters of groundnut as influenced by drone-assisted sequential herbicide application

Treatments	Yield parameters		
	Pod yield (kg ha ⁻¹)	Kernel yield (kg ha ⁻¹)	Haulm yield (kg ha ⁻¹)
T ₁ : Pendimethalin 38.7% CS (2.25 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (750 ml ha ⁻¹) EPoE - Knapsack sprayer (750 l ha ⁻¹)	2438	1710	3285
T ₂ : Pendimethalin 38.7% CS (2.25 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (750 ml ha ⁻¹) EPoE -Drone (50 l ha ⁻¹), 100% RDH	2470	1723	3292
T ₃ : Pendimethalin 38.7% CS (1.68 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (563 ml ha ⁻¹) EPoE -Drone (50 l ha ⁻¹), 75% RDH	2295	1602	3190
T ₄ : Pendimethalin 38.7% CS (1.12 l ha ⁻¹) PE <i>fb</i> Imazethapyr 10% SL (375 ml ha ⁻¹) EPoE - Drone (50 l ha ⁻¹), 50% RDH	1910	1287	2833
T ₅ : Weedy check	1353	902	2144
T ₆ : Weed-free	2587	1852	3401
SEm±	50.35	48.52	93.35
CD @ 5%	151.77	146.24	281.39

Note: DAS: Days after sowing; PE: Pre-emergence; EPoE: Early post-emergence; *fb*: followed by; RDH: Recommended dose of herbicide. NS: Non-significant.

Conclusion

Sequential application of pendimethalin 38.7% CS (pre-emergence) followed by imazethapyr 10% SL (early post-emergence) through an agricultural drone at the full recommended dose, using only 50 l ha⁻¹ spray volume, provided weed control, growth and yield of groundnut statistically comparable with the same dose applied through a conventional knapsack sprayer at 750 l ha⁻¹. Reducing the drone-applied herbicide dose to 75 or 50 per cent of the recommended level progressively reduced weed control efficiency and yield, indicating that maintaining the full recommended dose, rather than the spraying method per se, is critical for realising the yield potential of groundnut. Properly calibrated drone application of the recommended herbicide dose can therefore be adopted as an effective, water-saving alternative to conventional knapsack spraying for sequential pre- and early post-emergence weed management in groundnut.

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