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Research Article

Novel method to manage weeds in the rainfed groundnut (var. VRI 8 and TMV 14) using nano encapsulated herbicide formulations

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Abstract
The groundnut crop harbours heavy weed infestation due to its small stature and slow growing nature. The current weed management practices of hand weeding and use of commercial herbicides are unsuitable because of high labour cost and inadequate moisture availability to activate herbicides. In order to release the herbicide in a smart way, this experiment aimed to study the efficacy of encapsulated herbicides . Field experiments were conducted during *Kharif* 2021 and late *Rabi* 2022 under rainfed conditions in randomised block design with three replications. The treatments consisted of sulfentrazone, oxyfluorfen, diclosulam and metolachlor in both commercial and encapsulated form using two doses, hand weeding at 20 and 40 DAS, weed free plot and weedy check. Minimum weed density (28.33 and 17.30 No./m^2 at 90 DAS during Kharif and late Rabi respectively) and weed dry weight (65.33 and 61.25 g/m^2 at 90 DAS during Kharif and late Rabi respectively) were observed in hand weeding at 20 and 40 DAS (T_{19}) followed by diclosulam @ 25 g ha^{-1} with encapsulation (T_7). Maximum weed density and weed dry weight was observed in metolachlor @ 1 kg/ha with encapsulation (T_8). Higher productivity was observed in hand weeding at 20 and 40 DAS (T_{19}) (1802 kg ha^{-1} and 1753 kg ha^{-1} pod yield during Kharif and late Rabi respectively) and higher profitability was obtained in diclosulam @ 25 g ha^{-1} with encapsulation (T_7) (1.80 and 2.01 B:C ratio during (Kharif and late Rabi respectively). Nano-encapsulated herbicides can thus significantly improve weed control in rainfed groundnut.

Keywords: Encapsulated herbicides, Productivity, Profitability, Rainfed groundnut, Weed dynamics

INTRODUCTION

Groundnut (*Arachis hypogaea* L) is a prevalent oilseed crop grown in tropical and subtropical climates worldwide with wide adaptability to various climatic conditions. India occupies the first position under area coverage (4.73 million hectares) and ranks second in the production of groundnut (6.73 million tonnes), with an average yield of 1422 kg/ha in 2019 (Economics and Statistics, 2021).

Weed menace is one of the major bottlenecks, among other limitations that restrict productivity and limit the profit margin of groundnut in India. Despite its hardy nature, the groundnut crop harbours heavy weed infestation owing to its small stature and slow-growing nature. Numerous broad-leaved, grassy and sedge weeds emerge during various groundnut stages in heavy flushes that reduce the yield per unit area. Weeds compete with groundnut for resources like sunlight, space, moisture and nutrients, creating problems during harvest. Groundnut has a critical crop weed competition period of about 4-9 weeks (Everman *et al.*,

2008) and the yield loss due to weed interference range from 74 to 92% (Mishra, 2020).

In India, most groundnut production comes under rainfed conditions, and weed infestation is found to be more problematic due to the conducive environment (Jat *et al.*, 2011). Weed management is especially important in rainfed situations to make the most of available precipitation and reduce the competition by weeds. Manual weeding under rainfed conditions acts as an increasing expense, significantly reducing the profit. Hand weeding is also not optimal due to many reasons, including labour unavailability and damage to peg and pod formation (Korav *et al.*, 2020). It also causes the surge of weed flushes at later stages, which interferes during harvest, causing difficulties in digging the crop. Hence, chemical weed management using herbicides has become the predominant weed control practice owing to socioeconomic factors like limited time and labour. However, the rainfed condition usually causes disruption in the regular action of herbicides either through leaching in the case of heavy rainfall or inaction of herbicides in case of not enough moisture content in soil. This combined with the case of limited water supply under rainfed conditions for spraying leaves conventional pre emergence herbicide spraying options ineffective. Due to the lack of success of conventional herbicides under rainfed conditions, emphasis must be placed on exploring other venues to deliver herbicides effectively (Chandana *et al.*, 2021).

Encapsulation is the process in which a three-dimensional barrier is created around the active ingredient prolonging its interaction with the immediate chemical environment (Slattery *et al.*, 2019). It increases the herbicide efficiency by directing it specifically to the target and extending its release duration (Ghormade *et al.*, 2011). Using encapsulated herbicides under rainfed conditions, protects the herbicides from immediate volatilization, photodegradation and microbial decomposition (Daneshvari *et al.*, 2021). Further, encapsulating with hydrophilic polymers causes expansion of the polymer with the receipt of moisture through rain which leads to the release of the herbicide present inside. This release will coincide with the weed seed germination resulting in effective control of weeds (Mikkelsen, 1994).

The commercial form of pre-emergence herbicides sulfentrazone (Srimathi *et al.*, 2021), oxyfluorfen (Patel *et al.*, 2020), diclosulam (Sridhar *et al.*, 2021) and metolachlor (Ojelade *et al.*, 2018) has already been used in irrigated groundnut and shown varied levels of success in weed control. In this work, an attempt was made to formulate smart release herbicides of sulfentrazone, oxyfluorfen, diclosulam, metolachlor and to test its efficacy under rainfed groundnut (VRI 8 and TMV 14).

MATERIALS AND METHODS

Field experiments were conducted at the Eastern Block Farm of Agronomy Department, Tamil Nadu Agricultural University during *Kharif* 2021 and late *Rabi* 2022 under rainfed conditions. It is geographically situated at 11.0122° N, 76.9354° E at an altitude of 411 m above mean sea level. During *Kharif* 2021, the experimental soil was sandy clay loam in texture with soil pH of 8.34, EC of 0.27 dS m^{-1} organic carbon (0.46%), available N (196 kg ha^{-1}), available P_2O_5 (25 kg ha^{-1}) and available K (540 kg ha^{-1}). The rainfall received during the crop period was 547.3 mm. The crop was sown in the residual moisture from previous day rain, followed by life irrigation was given after 14 days of sowing since there was no rain and after lifesaving irrigation, the crop was fully maintained under the rainfed situation. During the late *Rabi* 2022, the experimental soil was sandy clay loam in texture with soil pH of 8.33, EC of 0.27 dS m^{-1} organic carbon (0.46%), available N (205 kg ha^{-1}), available P_2O_5 (28 kg ha^{-1}) and available K (527 kg ha^{-1}).

Soil pH and EC were calculated using pH meter and conductivity meter respectively (Jackson, 1973). Organic carbon was analysed based on the chromic acid wet digestion method by Walkley and Black (1934). Available Nitrogen, phosphorus and potassium was calculated following alkaline permanganate method (Subbaiah and Asija, 1956), Olsen's method (Olsen, 1954) and flame photometric method using neutral normal ammonium acetate extract (Stanford and English, 1949).

Groundnut was sown based on the rain forecast but due to rainfall failure supplemental irrigation was given at 5 DAS using rain gun. The rainfall was artificially simulated using rain gun, which was operated once every 15 days. The experiment was laid out in randomized block design and was replicated thrice. The treatment consisted of four pre-emergence herbicides sulfentrazone (T_2, T_3, T_{10} and T_{11}), oxyfluorfen (T_4, T_5, T_{12} and T_{13}), diclosulam (T_6, T_7, T_{14} and T_{15}) and metolachlor (T_8, T_9, T_{16} and T_{17}) in its commercial and encapsulated forms in two doses of 100% and 125% recommended doses. Weed-free check (T_1), weedy control (T_{18}) and hand weeding at 20 and 40 DAS were also included (T_{19}). The crop was maintained uniformly throughout the growth period except for weed management.

The herbicides were encapsulated through the solvent evaporation method. All the herbicides were coated with two hydrophilic polymers viz., poly allyl amine hydrochloride and polystyrene sulfonate. The solvent used were methanol for sulfentrazone and metolachlor. For oxyfluorfen and diclosulam, dichloromethane was used as a solvent. The solvents were chosen based on their compatibility. For coating with first polymer, an organic phase was prepared by mixing herbicide and water and mixing polymer and solvent separately in a magnetic stirrer for 5 minutes each. Both were then mixed together for another 5 minutes forming the organic phase. An aqueous phase was prepared by preparing a four per cent starch solution and stirring it in the magnetic stirrer for 1 hour. Then oil-water emulsion was prepared by adding the organic phase drop by drop to the aqueous phase while being stirred in a magnetic stirrer. It was then taken and centrifuged, followed by drying to get encapsulated particles. Since metolachlor alone did not settle into particles, so it was taken as liquid formulation. The next coating was done by repeating the above procedure with the resultant particles of the first coating. The particles were dried and used for field application (Kumar and Chinnamuthu, 2017).

Groundnut varieties VRI 8 and TMV 14 were used *Kharif* and late *Rabi* respectively, after treating with mancozeb at 2 g kg^{-1} and were sown at the rate of 144 kg ha^{-1} with a spacing of 30 × 10 cm. The plot size maintained was 6 × 4 m. The herbicides were mixed with sand and broadcasted on the day of sowing. Weed free plot was kept weed free by continuous hand weeding until harvest. Weedy control plot was maintained without any weed removal till harvest. Fertilizers were applied according to the recommendation *i.e.* 10 kg N, 10 kg P_2O_5 and 45 kg K_2O ha^{-1}. All fertilizers were applied basally. Gypsum was applied at the rate of 400 kg ha^{-1} (CPG, 2020). Weed density and weed dry weight were recorded in each plot by placing the quadrate of 0.25 m^2 randomly in four places in the plot. Weed dry weight was calculated by first air drying the samples for one week, followed by oven drying at 60□ for 2 days. Weed control efficiency was calculated following the formula suggested by Mishra and Misra (1997),

$$Weed\ control\ efficiency\ (WCE) = \frac{X-Y}{X} \times 100 \quad \text{Eq. 1}$$

Where,

X = Weed dry matter in weedy check (g). Y = Weed dry matter in respective treatment (g).

Weed index was calculated using the formula suggested by Gill (1969),

$$Weed\ index\ (WI) = \frac{X-Y}{X} \times 100 \quad \text{Eq. 2}$$

Where,

X = Crop yield from weed free plot. Y = Crop yield from the treated plot

Yield parameters and yield of groundnut were recorded by harvesting the net plot. The economics were computed by utilizing the prevailing local rates. Cost of cultivation for each treatment was obtained by tallying all the input costs in respective treatments with the unit market price of the input and expressed as Rs. ha-1. Gross return was worked out by multiplying the pod yield and haulm yield in each treatments with the respective unit price in the local market and expressed as Rs. ha-1. The net return was computed for all the treatments by deducting the cost of cultivation from the gross return and expressed as Rs. ha-1. The benefit-cost ratio of groundnut was computed using the below formula.

$$BCR = \frac{\text{Gross return}}{\text{Cost of cultivation}} \quad \text{Eq.3}$$

Economic parameters were not statistically analysed. The data on the weeds and yield were statistically analyzed, as suggested by Gomez and Gomez (1984). The data on weed density and weed dry weight were subjected to square root transformation √(x + 0.5) before analysis. The treatment differences were worked out at a five per cent probability level. The non-significant treatment differences were denoted as NS.

RESULTS AND DISCUSSION

Effect of different weed management practices on weed dynamics of rainfed groundnut

Different weed management practices significantly affected (0.05% level) both weed density and dry weight during both seasons at all stages of observation. Total weed density was lowest in hand weeding twice at 30 DAS, 60 DAS and 90 DAS during both seasons (Tables 1 and 2). This was followed by metolachlor @ 1.25 kg/ha without encapsulation at 30 DAS and diclosulam @ 25 g/ha with encapsulation 60 DAS. At 90 DAS, the application of diclosulam @ 25 g/ha was on par with hand weeding twice. The percent of decrease in weed density over weedy check due to the application of diclosulam @ 25 g/ha with encapsulation was 85.42% at 30 DAS, 77.20% at 60 DAS and 65.45% at 90 DAS during *Kharif* and 82.40% at 30 DAS, 69.52% at 60 DAS and 70.86% at 90 DAS during late *Rabi* respectively. This might have happened due to the fact that diclosulam after encapsulation lasted longer in soil enduring the losses and controlled weeds effectively which reduced the weed density throughout the crop period comparing to other weed management practices. Highest weed density was observed in metolachlor @ 1 kg/ha and 1.25 kg/ha with encapsulation, which was at par with diclosulam @ 20g/ha and 25 g/ha without encapsulation. This might be because the herbicides were inactivated during the first 14 days/5 days when the moisture content was insufficient during *Kharif* and late *Rabi* respectively. Due to this, there was significantly higher emergence of weeds form 30 DAS till 90 DAS.

Weed dry weight was equally lowest in hand weeding during both seasons in all observations. It was followed by metolachlor @ 1.25 kg/ha without encapsulation which was statistically on par with diclosulam @ 25 g/

Table 1. Influence of various weed management practices on weed dynamics of rainfed groundnut during *Kharif* 2021

Treatments	Total weed density (No./m²)			Total weed dry weight (g/m²)		
	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
T_1 - Weed free	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)
T_2 - Sulfentrazone @ 200 g/ha with encapsulation	108.67 (10.45)	96.00 (9.82)	78.00 (8.86)	2.60 (1.76)	165.41 (12.88)	291.18 (17.08)
T_3 - Sulfentrazone @ 250 g/ha with encapsulation	107.00 (10.37)	92.33 (9.63)	74.67 (8.67)	1.66 (1.47)	159.54 (12.65)	275.29 (16.61)
T_4 - Oxyfluorfen @ 200 g/ha with encapsulation	106.67 (10.35)	89.33 (9.48)	68.67 (8.32)	1.63 (1.46)	154.16 (12.44)	268.73 (16.41)
T_5 - Oxyfluorfen @ 250 g/ha with encapsulation	93.67 (9.70)	47.67 (6.94)	38.33 (6.23)	1.26 (1.33)	108.18 (10.42)	199.31 (14.14)
T_6 - Diclosulam @ 20 g/ha with encapsulation	85.00 (9.25)	42.33 (6.54)	48.00 (6.96)	1.03 (1.23)	87.45 (9.38)	189.12 (13.77)
T_7 - Diclosulam @ 25 g/ha with encapsulation	51.00 (7.18)	25.00 (5.05)	31.67 (5.67)	0.65 (1.07)	58.25 (7.66)	120.86 (11.02)
T_8 - Metolachlor @ 1 kg/ha with encapsulation	229.67 (15.17)	105.33 (10.29)	89.33 (9.48)	6.48 (2.64)	582.17 (24.14)	424.27 (20.61)
T_9 - Metolachlor @ 1.25 kg/ha with encapsulation	205.67 (14.36)	94.67 (9.76)	85.67 (9.28)	3.50 (2.00)	534.70 (23.13)	391.19 (19.79)
T_{10} - Sulfentrazone @ 200 g/ha without encapsulation	54.33 (7.40)	111.67 (10.59)	82.33 (9.10)	1.48 (1.41)	198.04 (14.09)	302.34 (17.40)
T_{11} - Sulfentrazone @ 250 g/ha without encapsulation	101.00 (10.07)	99.33 (9.99)	81.00 (9.03)	1.42 (1.39)	189.33 (13.78)	299.97 (17.33)
T_{12} - Oxyfluorfen @ 200 g/ha without encapsulation	98.67 (9.96)	85.67 (9.28)	55.33 (7.47)	1.38 (1.37)	137.62 (11.75)	262.91 (16.23)
T_{13} - Oxyfluorfen @ 250 g/ha without encapsulation	93.67 (9.70)	59.33 (7.73)	41.00 (6.44)	1.29 (1.34)	131.47 (11.49)	215.91 (14.71)
T_{14} - Diclosulam @ 20g/ha without encapsulation	214.00 (14.65)	101.33 (10.09)	88.33 (9.46)	5.35 (2.42)	567.69 (23.84)	411.41 (20.30)
T_{15} - Diclosulam @ 25g/ha without encapsulation	198.00 (14.09)	91.67 (9.60)	87.33 (9.37)	4.72 (2.28)	504.84 (22.48)	380.41 (19.52)
T_{16} - Metolachlor @ 1 kg/ha without encapsulation	84.00 (9.19)	52.67 (7.29)	49.67 (7.08)	0.71 (1.10)	110.75 (10.55)	200.82 (14.19)
T_{17} - Metolachlor @ 1.25 kg/ha without encapsulation	38.33 (6.23)	32.33 (5.73)	37.33 (6.15)	0.56 (1.03)	82.16 (9.09)	159.03 (12.63)
T_{18} - Weedy check	263.00 (16.23)	109.67 (10.50)	91.67 (9.60)	7.12 (2.76)	598.38 (24.47)	475.52 (21.82)
T_{19} - Hand weeding at 20 DAS and 40 DAS	7.67 (2.86)	12.67 (3.63)	28.33 (5.37)	0.15 (0.81)	35.97 (6.04)	65.33 (8.11)
Sed	0.51	0.42	0.38	0.08	0.69	0.76
Cd (0.05)	1.03	0.85	0.77	0.17	1.39	1.54

Data inside the parantheses are the square root transformed values

ha with encapsulation during 30 DAS. At 60 DAS and 90 DAS, hand weeding was followed by diclosulam @ 25 g/ha with encapsulation and Metolachlor @ 1.25 kg/ha without encapsulation. Diclosulam encapsulated form recording lower weed dry weight might be due to efficient and smart release of herbicides throughout the season. Steckel *et al.* (2002) have also reported that encapsulated herbicides of acetochlor in maize show efficient weed control when observed 56 days after planting. Metolachlor herbicides have been reported reducing weed density and dry matter accumulation in groundnut previously by Kanagam and Chinnamuthu (2009).

Among the four herbicides, diclosulam, oxyfluorfen and sulfentrazone have shown higher weed control in encapsulated forms than in commercial forms. This might be because the commercial formulation might have released the herbicide as a spot burst whereas encapsulated forms release the herbicide in a controlled manner. The encapsulated herbicide formulation of sulfentrazone requires limited moisture for activation, helps minimise crop injury, and can also prolong weed control for up to 40 days after sowing (Grichar *et al.*, 2015; Srimathi *et al.*, 2021). However, metolachlor herbicide

Table 2. Influence of various weed management practices on weed dynamics of rainfed groundnut during late *Rabi* 2022

Treatments	Total weed density (No./m^2)			Total weed dry weight (g/m^2)		
	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
T_1 - Weed free	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)
T_2 - Sulfentrazone @ 200 g/ha with encapsulation	56.67 (7.56)	86.67 (9.34)	60.32 (7.80)	29.35 (5.46)	217.67 (14.77)	243.16 (15.61)
T_3 - Sulfentrazone @ 250 g/ha with encapsulation	53.67 (7.36)	84.67 (9.23)	57.71 (7.63)	27.10 (5.25)	209.43 (14.49)	229.37 (15.16)
T_4 - Oxyfluorfen @ 200 g/ha with encapsulation	52.00 (7.25)	74.00 (8.63)	47.85 (6.95)	26.02 (5.15)	203.08 (14.27)	225.16 (15.02)
T_5 - Oxyfluorfen @ 250 g/ha with encapsulation	37.33 (6.15)	49.33 (7.06)	22.33 (4.78)	15.63 (4.02)	171.06 (13.10)	169.62 (13.04)
T_6 - Diclosulam @ 20 g/ha with encapsulation	34.00 (5.87)	53.33 (7.04)	20.30 (4.56)	12.46 (3.60)	160.55 (12.69)	151.98 (12.35)
T_7 - Diclosulam @ 25 g/ha with encapsulation	29.67 (5.49)	32.00 (7.34)	19.86 (3.22)	8.40 (2.98)	105.03 (10.27)	112.74 (10.64)
T_8 - Metolachlor @ 1 kg/ha with encapsulation	148.67 (12.21)	92.00 (9.62)	67.54 (8.25)	266.33 (16.34)	520.23 (22.82)	375.95 (19.40)
T_9 - Metolachlor @ 1.25 kg/ha with encapsulation	142.00 (11.94)	90.33 (9.53)	66.99 (8.22)	255.49 (16.00)	516.88 (22.75)	343.42 (18.55)
T_{10} - Sulfentrazone @ 200 g/ha without encapsulation	65.67 (8.13)	93.67 (9.70)	62.35 (7.93)	28.49 (5.38)	256.36 (16.03)	199.59 (14.15)
T_{11} - Sulfentrazone @ 250 g/ha without encapsulation	51.00 (7.18)	80.33 (8.99)	60.03 (7.78)	27.61 (5.30)	248.60 (15.78)	275.73 (16.62)
T_{12} - Oxyfluorfen @ 200 g/ha without encapsulation	70.00 (8.40)	62.00 (7.91)	29.00 (5.43)	24.76 (5.03)	197.99 (14.09)	269.29 (16.43)
T_{13} - Oxyfluorfen @ 250 g/ha without encapsulation	45.67 (6.79)	60.67 (7.82)	27.55 (5.30)	20.65 (4.60)	192.80 (13.90)	199.46 (14.14)
T_{14} - Diclosulam @ 20g/ha without encapsulation	132.33 (11.53)	89.00 (9.46)	66.41 (8.18)	233.56 (15.30)	496.57 (22.30)	337.22 (18.38)
T_{15} - Diclosulam @ 25g/ha without encapsulation	128.33 (11.35)	89.67 (9.50)	64.09 (8.04)	228.18 (15.12)	489.86 (22.14)	323.14 (17.99)
T_{16} - Metolachlor @ 1 kg/ha without encapsulation	36.00 (6.04)	56.00 (7.52)	24.36 (4.99)	10.33 (3.29)	188.02 (13.73)	176.57 (13.31)
T_{17} - Metolachlor @ 1.25 kg/ha without encapsulation	25.33 (5.08)	49.00 (5.70)	20.30 (4.56)	6.33 (2.61)	145.03 (12.06)	147.38 (12.16)
T_{18} - Weedy check	168.67 (13.01)	105.0 (10.37)	68.15 (8.29)	284.77 (16.89)	637.14 (25.25)	390.07 (19.76)
T_{19} - Hand weeding at 20 DAS and 40 DAS	4.33 (2.20)	27.33 (5.28)	17.30 (4.56)	1.44 (1.39)	40.86 (6.43)	61.25 (7.86)
Sed	0.40	0.43	0.32	0.36	0.79	0.71
Cd (0.05)	0.80	0.87	0.64	0.73	1.59	1.45

Data inside the parantheses are the square root transformed values

alone has shown higher weed control in its commercial form compared to the encapsulated form. The failure of encapsulation for metolachlor herbicides may be attributed to solvent, polymer, temperature maintained during encapsulation procedure or method of application.

Among the weed management practices, weed index was found highest in metolachlor @ 1 kg/ha with encapsulation and it was close to diclosulam @ 20 g/ha without encapsulation, diclosulam @ 25g/ha without encapsulationand metolachlor @ 1.25 kg/ha with encapsulation (Fig. 1). The lowest weed index was found in hand weeding at 20 DAS and 40 DAS followed by diclosulam @ 25 g/ha with encapsulation showcasing efficient weed control. Weed control efficiency was found to be higher in hand weeding twice at 30 DAS, 60 DAS and 90 DAS followed by diclosulam @ 25 g/ha with encapsulation during both seasons (Figs. 2 and 3). This is attributed to the efficient weed control found in both the treatments as seen through lower weed density and weed fry weight. Weed control efficiency was found to be lower in metolachlor @ 1 and 1.25 kg/ha with encapsulation and diclosulam @ 20 and 25 g/ha without encapsulation. This is due to the ineffective control of weeds by metolachlor as indicated previously by higher weed density and weed dry weight.

Effect of various weed management practices on yield parameters and yield of rainfed groundnut

A total number of pods per plant differed significantly among the different weed management practices during both seasons (Tables 3 and 4). Maximum pods were observed in weed-free plots (16.23 and 20.98 during *Kharif* and late *Rabi* respectively) which was on par with hand weeding (15.20 and 20.57 during *Kharif* and late *Rabi* respectively). This was followed by diclosulam @ 25 g/ha with encapsulation (14.20 and 17.59 during *Kharif* and late *Rabi* respectively). Higher number of pods in these treatments might be owed to the low weed density and low weed dry weight which

Table 3. Influence of various weed management practices on yield parameters and yield of rainfed groundnut during *Kharif* 2021

Treatment	Total no. of pods/plant	Pod yield (kg/ha)	Haulm yield (kg/ha)	Harvest index
T_1 - Weed free	16.23	1973	3979	0.33
T_2 - Sulfentrazone @ 200 g/ha with encapsulation	8.73	989	2196	0.31
T_3 - Sulfentrazone @ 250 g/ha with encapsulation	9.00	1002	2299	0.30
T_4 - Oxyfluorfen @ 200 g/ha with encapsulation	9.73	1023	2366	0.30
T_5 - Oxyfluorfen @ 250 g/ha with encapsulation	11.73	1407	2914	0.33
T_6 - Diclosulam @ 20 g/ha with encapsulation	12.93	1536	2996	0.34
T_7 - Diclosulam @ 25 g/ha with encapsulation	14.20	1683	3339	0.34
T_8 - Metolachlor @ 1 kg/ha with encapsulation	6.60	604	1672	0.27
T_9 - Metolachlor @ 1.25 kg/ha with encapsulation	6.87	754	1807	0.29
T_{10} - Sulfentrazone @ 200 g/ha without encapsulation	8.00	928	2061	0.31
T_{11} - Sulfentrazone @ 250 g/ha without encapsulation	8.53	953	2102	0.31
T_{12} - Oxyfluorfen @ 200 g/ha without encapsulation	10.07	1036	2374	0.30
T_{13} - Oxyfluorfen @ 250 g/ha without encapsulation	10.67	1159	2619	0.31
T_{14} - Diclosulam @ 20g/ha without encapsulation	6.80	630	1713	0.27
T_{15} - Diclosulam @ 25g/ha without encapsulation	6.93	797	1826	0.30
T_{16} - Metolachlor @ 1 kg/ha without encapsulation	11.13	1286	3038	0.30
T_{17} - Metolachlor @ 1.25 kg/ha without encapsulation	13.00	1562	3362	0.32
T_{18} - Weedy check	6.13	520	1531	0.25
T_{19} - Hand weeding at 20 DAS and 40 DAS	15.20	1802	3604	0.33
S Ed	0.57	58.33	127.47	0.02
Cd (0.05)	1.15	118.32	258.55	0.03

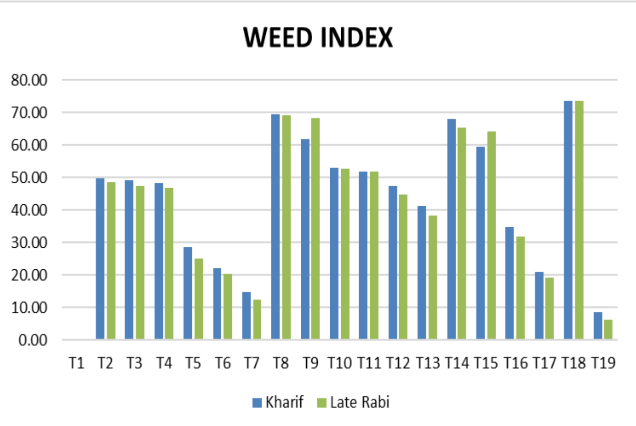

Fig. 1. *Weed index of various weed management practices*

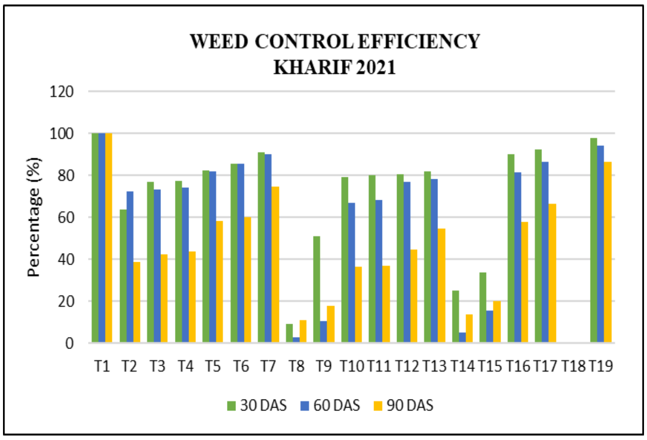

Fig. 2. *Weed control efficiency of various weed management practices at 30, 60 and 90 DAS during Kharif 2021*

Table 4. Influence of various weed management practices on yield parameters and yield of rainfed groundnut during late *Rabi* 2022

Treatment	Total no. of pods/plant	Pod yield (kg/ha)	Haulm yield (kg/ha)	Harvest index
T_1 - Weed free	20.98	1869	3503	0.35
T_2 - Sulfentrazone @ 200 g/ha with encapsulation	11.18	961	1865	0.34
T_3 - Sulfentrazone @ 250 g/ha with encapsulation	11.43	983	1939	0.34
T_4 - Oxyfluorfen @ 200 g/ha with encapsulation	12.17	996	1994	0.33
T_5 - Oxyfluorfen @ 250 g/ha with encapsulation	16.55	1401	2689	0.34
T_6 - Diclosulam @ 20 g/ha with encapsulation	14.90	1491	2795	0.35
T_7 - Diclosulam @ 25 g/ha with encapsulation	17.59	1636	3091	0.35
T_8 - Metolachlor @ 1 kg/ha with encapsulation	7.80	575	1367	0.30
T_9 - Metolachlor @ 1.25 kg/ha with encapsulation	7.79	594	1415	0.30
T_{10} - Sulfentrazone @ 200 g/ha without encapsulation	10.67	884	1798	0.33
T_{11} - Sulfentrazone @ 250 g/ha without encapsulation	12.89	903	1811	0.33
T_{12} - Oxyfluorfen @ 200 g/ha without encapsulation	10.16	1034	2008	0.34
T_{13} - Oxyfluorfen @ 250 g/ha without encapsulation	13.33	1153	2248	0.34
T_{14} - Diclosulam @ 20g/ha without encapsulation	8.02	647	1461	0.31
T_{15} - Diclosulam @ 25g/ha without encapsulation	8.11	667	1585	0.30
T_{16} - Metolachlor @ 1 kg/ha without encapsulation	13.92	1275	2647	0.33
T_{17} - Metolachlor @ 1.25 kg/ha without encapsulation	16.64	1513	3112	0.33
T_{18} - Weedy check	6.91	496	1216	0.29
T_{19} - Hand weeding at 20 DAS and 40 DAS	20.57	1753	3236	0.35
S Ed	0.70	55.09	113.67	0.02
Cd (0.05)	1.43	111.75	230.55	0.03

Table 5. Influence of various weed management practices on profitability of rainfed groundnut during *Kharif* 2021

Treatments	Cost of cultivation (Rs ha^{-1})	Gross returns (Rs ha^{-1})	Net returns (Rs ha^{-1})	Benefit: Cost ratio
T_1 - Weed free	77338	124358	47020	1.61
T_2 - Sulfentrazone @ 200 g/ha with encapsulation	61142	62634	1492	1.02
T_3 - Sulfentrazone @ 250 g/ha with encapsulation	62156	63568	1412	1.02
T_4 - Oxyfluorfen @ 200 g/ha with encapsulation	64571	64929	358	1.01
T_5 - Oxyfluorfen @ 250 g/ha with encapsulation	66242	88792	22549	1.34
T_6 - Diclosulam @ 20 g/ha with encapsulation	58526	96655	38128	1.65
T_7 - Diclosulam @ 25 g/ha with encapsulation	58863	105988	47126	1.80
T_8 - Metolachlor @ 1 kg/ha with encapsulation	78054	38749	-39306	0.50
T_9 - Metolachlor @ 1.25 kg/ha with encapsulation	83246	47951	-35295	0.58
T_{10} - Sulfentrazone @ 200 g/ha without encapsulation	57296	58783	1487	1.03
T_{11} - Sulfentrazone @ 250 g/ha without encapsulation	57348	60333	2985	1.05
T_{12} - Oxyfluorfen @ 200 g/ha without encapsulation	59726	65721	5995	1.10
T_{13} - Oxyfluorfen @ 250 g/ha without encapsulation	60386	73469	13083	1.22
T_{14} - Diclosulam @ 20g/ha without encapsulation	58044	40369	-17675	0.70
T_{15} - Diclosulam @ 25g/ha without encapsulation	58280	50559	-7721	0.87
T_{16} - Metolachlor @ 1 kg/ha without encapsulation	58788	81717	22929	1.39
T_{17} - Metolachlor @ 1.25 kg/ha without encapsulation	59213	98763	39550	1.67
T_{18} - Weedy check	57088	33519	-23569	0.59
T_{19} - Hand weeding at 20 DAS and 40 DAS	70588	113526	42938	1.61

Data not statistically analysed

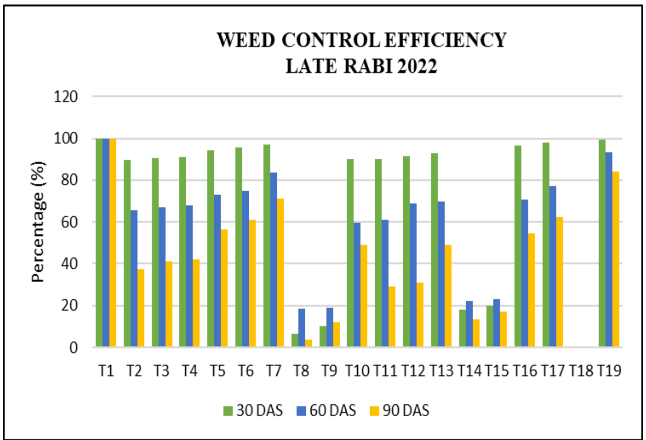

Fig. 3. *Weed control efficiency of various weed management practices at 30, 60 and 90 DAS during late Rabi 2022*

lessened the crop weed competition. Weedy check recorded the least number of pods per plant (6.13 and 6.91 during *Kharif* and late *Rabi* respectively) as the crop was completely covered by the weed foliage imposing severe stress on the plant.

There was a significant difference in the yield of groundnut among the different weed management practices. Higher pod yield was observed in weed-free plots (1973 kg ha^{-1} and 1869 kg ha^{-1} during Kharif and late Rabi respectively) followed by hand weeding at 20 and 40 DAS (1802 kg ha^{-1} and 1753 kg ha^{-1} during *Kharif* and late *Rabi* respectively). Higher haulm yield was observed in weed free plot (3979 kg ha^{-1} and 3503 kg ha^{-1} during *Kharif* and late *Rabi* respectively), which was followed by hand weeding at 20 and 40 DAS (3604 kg ha^{-1} and 3236 kg ha^{-1} during *Kharif* and late *Rabi* respectively), metolachlor @ 1.25 kg/ha without encapsulation (3362 kg ha^{-1} and 3112 kg ha^{-1} during *Kharif* and late *Rabi* respectively) and encapsulated diclosulam @ 25 g/ha (3339 kg ha^{-1} and 3091 kg ha^{-1} during *Kharif* and late *Rabi* respectively). This might be attributed to the lesser weed density, which lessens competition for light, space, nutrients and other resources. Aruna and Sagar (2018) also observed a higher yield in the treatment maintained as weed-free throughout the crop period of groundnut. Higher yield might be due to the protection offered by the polymers from volatilization, photodegradation and the controlled release of the formulation for a longer period. Sopeña *et al.* (2009) have reported that controlled release formulation of encapsulated herbicides delivers effective portions for longer.

Minimum dry pod yield (520 kg ha^{-1} and 496 kg ha^{-1}) and haulm yield (1531 kg ha^{-1} and 1216 kg ha^{-1}) were observed in the weedy check. This was on par with the

Table 6. Influence of various weed management practices on profitability of rainfed groundnut during late *Rabi* 2022

Treatments	Cost of cultivation (ha^{-1})	Gross returns (ha^{-1})	Net returns (ha^{-1})	B:C ratio
T_1 - Weed free	69588	117399	47811	1.69
T_2 - Sulfentrazone @ 200 g/ha with encapsulation	53392	60458	7066	1.13
T_3 - Sulfentrazone @ 250 g/ha with encapsulation	54406	61888	7482	1.14
T_4 - Oxyfluorfen @ 200 g/ha with encapsulation	56821	62751	5930	1.10
T_5 - Oxyfluorfen @ 250 g/ha with encapsulation	58492	88094	29601	1.51
T_6 - Diclosulam @ 20 g/ha with encapsulation	50776	93652	42876	1.84
T_7 - Diclosulam @ 25 g/ha with encapsulation	51113	102797	51685	2.01
T_8 - Metolachlor @ 1 kg/ha with encapsulation	70304	36550	-33754	0.52
T_9 - Metolachlor @ 1.25 kg/ha with encapsulation	75496	37762	-37734	0.50
T_{10} - Sulfentrazone @ 200 g/ha without encapsulation	49546	55737	6191	1.12
T_{11} - Sulfentrazone @ 250 g/ha without encapsulation	49598	56897	7298	1.15
T_{12} - Oxyfluorfen @ 200 g/ha without encapsulation	51976	65053	13077	1.25
T_{13} - Oxyfluorfen @ 250 g/ha without encapsulation	52636	72552	19916	1.38
T_{14} - Diclosulam @ 20g/ha without encapsulation	50294	40987	-9307	0.81
T_{15} - Diclosulam @ 25g/ha without encapsulation	50530	42398	-8132	0.84
T_{16} - Metolachlor @ 1 kg/ha without encapsulation	51038	80471	29433	1.58
T_{17} - Metolachlor @ 1.25 kg/ha without encapsulation	51463	95453	43990	1.85
T_{18} - Weedy check	49338	31559	-17779	0.64
T_{19} - Hand weeding at 20 DAS and 40 DAS	62838	110034	47196	1.75

Data not statistically analysed

metolachlor treatments encapsulated @ 1 kg ha^{-1} and diclosulam without encapsulation at 20 g ha^{-1} during Kharif 2021. During late Rabi 2022, metolachlor encapsulated @ 1 kg ha^{-1} and 1.25 kg ha^{-1} were on par with the weedy check. These treatments recorded maximum weed growth from the beginning. The inaction of diclosulam herbicide without encapsulation conceivably be because of the unavailability of moisture in the soil during the first 14 days/5 days during Kharif and late Rabi respectively. The unavailability of moisture would have prevented the herbicide's normal mode of action and during that time the herbicide might be subjected to various losses, such as volatilization and photodegradation. The weed growth in metolachlor encapsulated @ 1 and 1.25 kg ha^{-1} treatment possibly be attributed to an ineffective encapsulation mechanism. The solvent and polymers used might not have been suitable, leading to the inactive formulation. The heavy weed growth subsequently caused a drastic reduction in yield because of heavy crop-weed competition, poor peg formation and pod filling.

Effect of herbicides on profitability of rainfed groundnut

Economic indices were worked out for various weed management treatments (Tables 5 and 6). It indicated that the highest gross returns were obtained in weed-free plot followed by hand weeding at 20 DAS and 40 DAS because of its maximum pod and haulm yield in both seasons. Similar findings of higher gross returns from hand-weeding treatment in groundnut were reported by Kalhapure *et al.* (2013). However, highest net returns were observed in diclosulam @ 25 g/ha with encapsulation followed by weed-free and hand weeding at 20 and 40 DAS. This was because of the high cost of cultivation found in weed-free and hand weeding at 20 and 40 DAS. Higher labour cost for weeding in both these treatments significantly increased the cost of cultivation, subsequently decreasing the net returns despite its maximum yield. The findings of Sarin *et al.* (2021) support this observation where higher cultivation costs were observed in hand weeding. Whereas diclosulam showed increased returns and lesser cost of cultivation because of its low dose nature, less herbicide cost, and higher yield. Since it is a low-dose herbicide, the encapsulation charges were also low. Minimum gross return and cost of cultivation was obtained in weedy check, which may be explained because of the least yield and no weed management practice. Metolachlor @ 1 kg/ha with encapsulation recorded minimum net returns and B: C ratio, which may be owed to the herbicide and encapsulation cost and its poor weed management ability leading to lesser yield. When comparing commercial and encapsulated herbicides, diclosulam and oxyfluorfen both showed higher B: C ratio in encapsulated form at both doses compared to the commercial form. This was in line with the findings of Vikram *et al.* (2021), who used Sulfentrazone in blackgram and observed a higher B: C ratio (3.33) in encapsulated herbicide applied treatment. Meanwhile metolachlor herbicide recorded higher B: C ratio (1.67 and 1.85 during Kharif and late Rabi, respectively) in the commercial formulation at both doses than the encapsulated form indicating the ineffectiveness of encapsulated form. This might be because of the unsuitability of the solvent evaporation method of encapsulation for metolachlor.

Conclusion

The herbicides normally used under irrigated conditions are not suitable under rainfed conditions. Based on the findings, hand weeding at 20 and 40 DAS recorded minimum weed density and dry weight, followed by diclosulam @ 25 g/ha with encapsulation, which leads to higher productivity. Higher profitability (1.80 and 2.01 B:C ratio during (Kharif and late Rabi respectively) was obtained in diclosulam @ 25 g/ha with encapsulation followed by metolachlor @ 1.25 kg/ha without encapsulation since diclosulam is a low-dose herbicide, effectively decreasing the cost of cultivation.

Conflict of interest

The authors declare that they have no conflict of interest.

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