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Assessment of encapsulated herbicide for sustained release, weed control and crop productivity as a tool for agro-ecosystem biosafety

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Abstract

A significant amount of herbicide is applied in agricultural ecosystems to control weeds, which can pose risks to these environments. The encapsulated pyrazosulfuron ethyl and pretilachlor with zeolite, polycaprolactone and water-soluble polymer had impacts on weed control and productivity of rice and minimized the herbicidal hazard to the environmental impact. Weed control treatments showed a significant and inverse relationship with weed density, weed biomass and increased growth, yield attributes and yield of rice. Pyrazosulfuron ethyl entrapped zeolite reduced weed density by 56.26 % in 2022 and 53.91 % in 2023 at 45 DAS and the weed biomass was 2.10 times lower in 2022 and 2.85 times lower in 2023 than pretilachlor, which positively influenced the growth, yield attributes, grain and straw yield (5333 kg ha-1 and 6107 kg ha-1 in 2022 and 5123 kg ha-1 and 5803 kg ha-1 in 2023). It was on par with pyrazosulfuron ethyl encapsulated with polycaprolactone. Herbicide activity assay also resulted in better rice growth. Thus, the study showed that the encapsulated herbicides have a significant impact on weed control, growth and productivity of rice in a sustainable manner.

Keywords

crop productivity; controlled release; herbicide activity; wet direct-seeded rice; zeolite

Introduction

Globally, rice is one of the staple food crops produced on around 165.25 million ha and yields 787.29 million MT annually (1). India is a significant producer and consumer of rice, contributing up to 15.79 % of the world's production and 27.27 % of the cultivated area (45.07 million ha) (2). The world's growing population needs 40 % more global rice demand by 2050 (3). Because of the rising production costs, higher cropping intensity, labour and water scarcity, rice cultivation techniques have undergone periodic change (4). In the wake of labour and water shortages, wet direct-seeded rice is an effective alternative to the puddled transplanted rice system (5). A total of USD 11 billion is lost due to weeds in India's ten main crops, of which 21.4 % and 13.8 % are in direct seeded and transplanted rice respectively (6).

Wet direct-seeded rice (WDSR) is a planting method where pre-germinated seeds are directly sown onto the surface of puddled soil (5). These systems possess the capacity to decrease water expenses and thus decrease the labour demands in planting actions, including land preparation, seedling care, transportation and transplanting, as compared to puddled transplanted rice

(7). In wet direct-seeded rice, fields were drained for extended durations, creating an ideal environment for the concurrent growth of weeds along with the crop later on as a competitor for the resources. Hence, weeds provide the most significant limitation to WDSR and prompt weed control is essential for enhancing productivity of rice (8). In contemporary times, field workers are transitioning to non-agricultural occupations, making herbicide use the sole choice for efficient and economical weed management in WDSR. This is due to its reduced worker requirements, simple application and prompt output (9).

Herbicides are now extensively utilized in modern agriculture to control weeds. Only a small fraction of the herbicide is absorbed by the plant, while the rest is lost through processes such as photo-degradation, chemical breakdown, volatilization, leaching, microbial degradation and run-off. These losses result in the herbicide being transported off-site, contaminating groundwater and ecosystems, which reduces its effectiveness at the target site. (10). However, the persistent use of herbicides can lead to the development of resistance in weeds (11).

Herbicide encapsulation is an innovative approach that delivers the active ingredient to the target environment in a controlled manner, thus protecting the active ingredient from environmental vulnerability and reducing the residual effect of herbicides. It ultimately induced in prolonged period of weed control and increased crop productivity. Therefore, nanotechnology is an innovative approach for agricultural systems that includes advancements such as the creation of efficient monitoring tools, the development of smart agrochemicals, nano-based herbicides, nano-enhanced formulations and various other applications (12). Nano-herbicides represent a cutting-edge approach that provides valuable opportunities to enhance weed management in WDSR (Wet Direct Seeded Rice) (5). It reduces the effects of environmental contamination and boosts productivity. Encapsulation ensures prolonged weed control by protecting the active ingredient and minimizing its release into the environment (13). Thus, it reduces the accumulation of residues in the soil (14). Therefore, developing encapsulated herbicides is crucial for reducing herbicide pollution in the environment and enhancing effective weed control. The objective of the experiment was to evaluate the effect of nano-encapsulated herbicides on weed biomass, growth and productivity of wet direct-seeded rice (WDSR).

Materials and Methods

The experiments were carried out at V.O.C Agricultural College and Research Institute, Killikulam (8°46' *N latitude and 77°42' E longitude* and at an altitude of 40 m above MSL), Tamil Nadu in *Kharif* 2022 and 2023 (Fig. 1). Surface layer samples (20 cm) were collected to examine the initial physicochemical properties of the soil (Table 1). The weather during the crop growth period of 2022 and 2023 was variable. In 2022, the average maximum and minimum temperatures were 36.2 °C and 21.0 °C respectively, while in 2023, they rose to 37.4 °C and 21.5 °C. Total precipitation was recorded at 5.33 mm in 2022, decreasing to 3.95 mm in 2023. The average number of sunshine hours per standard meteorological week was 7.25 in 2022 and increased to 8.61 in 2023. Relative humidity was 61.78 % in 2022, slightly decreasing to 61.05 % in 2023 (Fig. 2 a, b). The experiments were laid out in a randomised block design with 11 treatments and 3 replications. The treatment details comprised of T1 - Commercial formulation of Pretilachlor at 0.75 kg a.i. ha-1, T2 - Pretilachlor loaded with Zeolite at 0.75 kg a.i. ha-1, T3 - Pretilachlor encapsulated with Polycaprolactone (PCL) at 0.75 kg a.i. ha-1, T4 - Pretilachlor encapsulated with water-soluble polymer (Poly allylamine hydrochloride (PAH) + Sodium Poly (styrene sulfonate) (PSS)) at 0.75 kg a.i. ha-1, T5 - Commercial formulation of Pyrazosulfuron ethyl at 25 g a.i. ha -1, T6 - Pyrazosulfuron ethyl loaded with Zeolite at 25 g a.i. ha-1, T7 - Pyrazosulfuron ethyl encapsulated with Polycaprolactone (PCL) at 25 g a.i. ha-1, T8 - Pyrazosulfuron ethyl encapsulated with water-soluble polymer (Poly allylamine hydrochloride (PAH) + Sodium Poly (styrene sulfonate) (PSS) at 25 g a.i. ha-1, T9 - PE Pretilachlor at 0.75 kg a.i ha-1, fb EPoE Bispyribac sodium at 25 g a.i. ha-1 on 20 DAS, T10 - Weed free check, T11 - Weedy check. The test variety of ASD 16 was soaked in the water for over 24 h and then kept in a dark room for 48 h to promote sprouting. A drum seeder

Fig. 1. Overview of the field experiment.

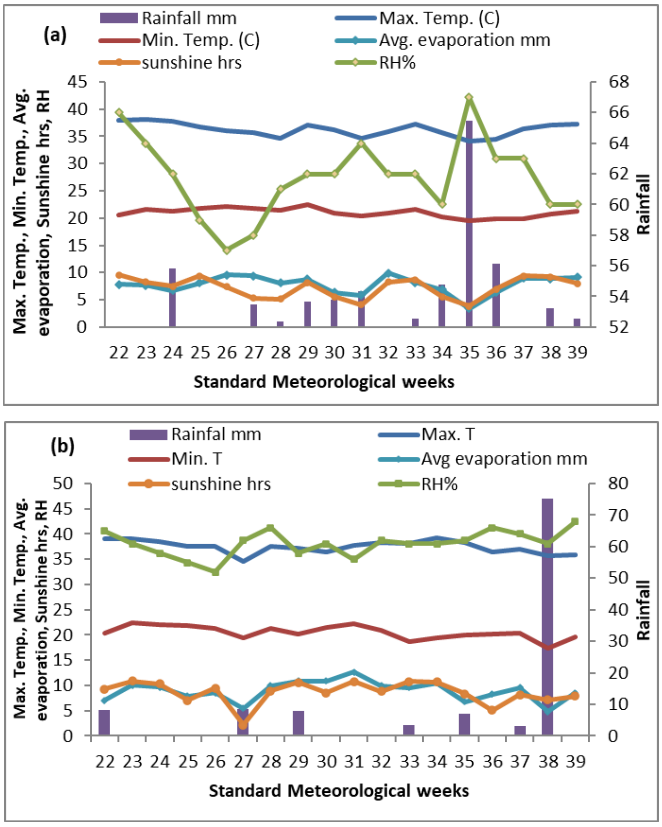

Fig. 2. Weather data during the crop growth season of Kharif 2022 (a) and 2023 (b).

Table 1. Initial physicochemical properties of the experimental field in *Kharif* 2022 and 2023.

Soil property	Value	
	2022	2023
Mechanical Analysis		
Sand (%)	27.5	27.5
Silt (%)	27.7	27.7
Clay (%)	44.8	44.8
Texture	Sandy Clay loam	Sandy Clay loam
Chemical Analysis		
pH	6.82	6.91
EC (ds m^{-1})	0.11	0.15
Organic carbon (g kg^{-1})	6.5	6.2
Available N (kg ha^{-1})	282	252
Available P_2O_5 (kg ha^{-1})	24	19
Available K_2O (kg ha^{-1})	290	246

with four rows evenly spaced 20 cm apart was used for sowing the seeds. The crop management practices were taken during the experiments. The biometric observation was recorded on five randomly selected plants from the net plots of each treatment. In each plot, weed samples were consistently collected from each of the four 0.25 m2 random sampling zones. Total weed density and weed dry weight were recorded at 15, 30 and 45 days after sowing (DAS) by standard procedures. The observations were recorded on plant growth parameters, *viz.,* height, leaf area index, dry matter production and yield parameters like number of productive tillers per hill, panicle length and panicle weight to assess the crop growth and yield of wet direct seeded rice. Before statistical analysis, the square root transformation of weed density and biomass was performed. The data was statistically analysed with SAS software version 9.3 (SAS Institute Inc., Cary, NC, USA), the Proc-GLIMMIX technique was used to do the analysis of variance (ANOVA) and proc sort data was used to separate the means. Before that, the Shapiro-Wilk test (PROC UNIVARIATE) was used to determine whether the data residuals were normal. Linear regression analyses were performed to assess the relationships between weed parameters and yield using Microsoft Excel.

Results and Discussion

Weed density and weed biomass

The predominated weed species observed were bermuda grass (*Cynodon dactylon),* barnyard grass *(Echinochloa crusgalli)*, jungle grass (*Echinochloa colona),* red sprangle top *(Leptochloa chinensis)*, umbrella plant (*Cyperus difformis)* and nut sedge (*Cyperus rotundus)*, silver cock's comb (*Celosia argentia),* false daisy *(Eclipta alba),* 4 leaf clover *(Marsilea quadrifolia)* and east Indian globe thistle (*Sphaeranthus indicus)*.

Encapsulated pretilachlor and pyrazosulfuron ethyl formulations confirmed significant differences in weed density and weed biomass at 15, 30 and 45 DAS. At all crop growth stages, weed-free checks exhibited the lowest weed density and biomass. Among the herbicide applications, lesser weed density was recorded on pyrazosulfuron ethyl entrapped zeolite at 25 g a.i. ha-1. It was on par with pyrazosulfuron ethyl encapsulated with polycaprolactone (Fig. 3 a, b). The modified release of pyrazosulfuron ethyl by zeolite improved the herbicide efficacy and better uptake of herbicides, which led to lower weed growth and minimised the impact of herbicide on the agroecosystem. Similar findings were obtained in earlier research (15-18). The highest weed density was recorded under the weedy check due to high competition between crop and weed.

Among the herbicide treatments, Pyrazosulfuron ethyl loaded with zeolite recorded 3.59- and 2.77-, 3.44- and 2.83-, 2.10- and 2.85-times lower weed dry weight at 15, 30 and 45 DAS in 2022 and 2023 respectively, as compared to pretilachlor at 0.75 kg a.i. ha-1 (Fig. 3 c, d). It could be because the herbicides entrapped in zeolite have enhanced sorption and reduced herbicide dissipation in soil. This assists in the herbicide's gradual release throughout the growing season, destroying the weed seed's food sources and reducing weed regeneration and biomass. Similar findings were reported in earlier research (19, 20). The highest weed dry weights of 39.76, 76.25 and 105.51 g m-2 in 2022 and 42.41, 78.96 and 110.31 g m-2 in 2023 during 15, 30 and 45 DAS respectively, were recorded in the weedy check. It could be attributed to the persistent proliferation of weeds during the crop's production cycle.

Crop phytotoxicity

Enhanced release and targeted delivery of the nano-encapsulated herbicides did not exhibit any adverse impact on rice. Similar confirmation was also obtained during earlier research (17).

Plant height

The rice height at active tillering, panicle initiation and harvest stages were significantly influenced by encapsulated pretilachlor and pyrazosulfuron ethyl formulations (Table 2).

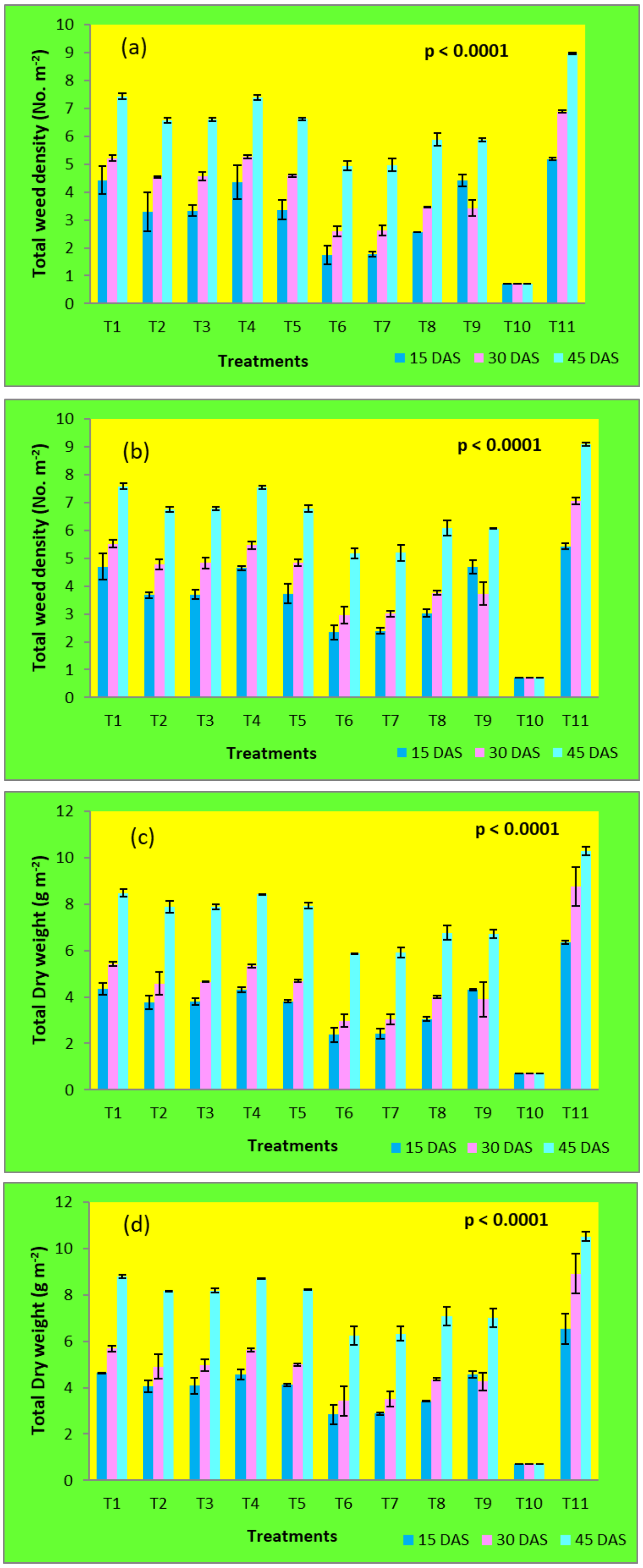

Fig. 3. Different weed management practices on total weed density during 2022 (a) and 2023 (b) ± S. E and total weed biomass during 2022 (c) and 2023 (d) ± S. E.

The height of the rice plant at the active tillering stage varied from 31.60 to 54.67 cm and 28.61 to 52.00 cm; at the panicle initiation stage, it was from 39.10 to 92.50 cm and 34.10 to 88.17 cm and at the harvest stage 64.70 to 128.07 cm and 54.70 to 118.07 cm were obtained during the year 2022 and 2023 respectively. The weed-free check recorded higher plant height. Among the herbicidal treatments, application of pyrazosulfuron ethyl loaded with zeolite (T6) recorded plant height of 48.73 and 37.11 % at active tillering, 29.35 and 31.65 % at panicle initiation and 51.43 and 58.71 % at harvest stage were obtained in 2022 and 2023 respectively, over pretilachlor (T1) alone. It was on par with pyrazosulfuron ethyl encapsulated with polycaprolactone (T7). This effect can be attributed to the better weed-free conditions attained by weed management and efficient use of existing resources, leading to enhanced crop growth and increased plant height. Earlier research suggests that the application of a nanoparticle herbicide significantly influenced the plant height due to the weed-free environment, which enhanced crop growth (21). The least plant height was recorded under the weedy check (T11).

Number of tillers m-2

Encapsulated pretilachlor and pyrazosulfuron ethyl formulations performed well on the number of tillers m-2. There was a steady increase in the total number of tillers m-2 up to the panicle initiation stage; thereafter, a slight reduction was observed at the harvest stage. Weed-free check recorded a maximum number of tillers than all other treatments. Among the herbicides, pyrazosulfuron ethyl loaded with zeolite (T6) recorded a higher tiller number and was found to be on par with pyrazosulfuron ethyl encapsulated with polycaprolactone (T7). The treatment T6 recorded a higher tiller number of 1.39 times at active tillering, 1.40 times at panicle initiation and 1.23 times at harvest stage in 2022 (Table 3). Whereas in 2023, the same treatment was recorded 1.43 times at active tillering, 1.44 times at panicle initiation and 1.34 times at harvest stage, compared to the application of pretilachlor alone. The minimum tiller number was recorded in the weedy check. Zeolites act as a soil-enriching substance, having a good herbicide holding capacity, so they better release the herbicide active ingredient, which leads to better weed control. The weed reduction due to weed control treatments allowed the crop to grow to its potential, thereby increasing tillers per meter square.

Dry matter production

Adoption of different treatments had a significant influence on the dry matter production of rice at active tillering, panicle initiation and harvest stages. Generally, as crop growth progressed to harvest, the dry matter content increased and attained its highest level. The highest DMP was obtained in the weed-free check. With respect to the herbicide practices evaluated, pyrazosulfuron ethyl loaded with zeolite (T6) resulted in significantly higher DMP of 1430, 7365, 10901 kg ha -1 and 1350, 7161, 10705 kg ha-1 at active tillering, panicle initiation and harvest stage during 2022 and 2023 respectively (22). It was on par with the pyrazosulfuron ethyl encapsulated with polycaprolactone (T7) recorded at 1403, 7267, 10688 kg ha-1 and 1340, 7067, 10495 kg ha-1 at active tillering, panicle initiation and harvest stage in 2022 and 2023, respectively (Table 4). The increase of plant DMP under these 2 treatments ranged from 51.02–53.93 %, 31.79–33.56 % and 43.07–45.93 % at different stages in 2022. In 2023, it ranged from 50.22 to 51.34 %, 34.68 to 36.47 % and 45.21 to 48.12 % at active tillering, panicle initiation and harvest stage respectively, compared with the pretilachlor. This might be due to the fact that herbicides not only exhibited significantly lesser toxicity to rice seedlings but also controlled the weeds effectively,

Table 2. Effect of encapsulated pretilachlor and pyrazosulfuron ethyl formulations on plant height (cm) of wet direct-seeded rice.

Treatments	Plant height (cm)					
	2022			2023		
	Active tillering	Panicle Initiation	Harvest	Active tillering	Panicle Initiation	Harvest
T_1	33.57 ± 0.73e	63.83 ± 0.61e	77.90 ± 0.68e	30.61 ± 0.76e	59.17 ± 17e	67.90 ± 0.68e
T_2	35.90 ± 0.35d	70.50 ± 0.47d	94.37 ± 1.05d	33.13 ± 0.36d	65.83 ± 0.32d	84.37 ± 1.05d
T_3	35.87 ± 0.54d	69.80 ± 0.89d	92.47 ± 1.25d	33.08 ± 0.38d	65.23 ± 0.32d	82.47 ± 1.25d
T_4	33.63 ± 0.86e	65.07 ± 0.73e	79.47 ± 0.88e	30.64 ± 0.86e	60.40 ± 0.96e	69.47 ± 0.88e
T_5	35.70 ± 0.50d	69.57 ± 0.55d	91.73 ± 0.66d	32.66 ± 0.46d	65.13 ± 0.88d	81.73 ± 0.66d
T_6	49.93 ± 0.20b	82.57 ± 1.09b	117.97 ± 1.73b	41.97 ± 0.50b	77.90 ± 0.81b	107.77 ± 1.23b
T_7	44.97 ± 0.50b	82.20 ± 0.75b	117.77 ± 1.23b	40.92 ± 0.22b	77.53 ± 0.49b	105.97 ± 1.73b
T_8	38.63 ± 0.84c	74.77 ± 0.70c	101.57 ± 1.27c	36.29 ± 0.95c	70.10 ± 0.86c	91.57 ± 1.27c
T_9	39.73 ± 0.88c	75.97 ± 0.92c	104.5 ± 1.15c	36.71 ± 0.90c	71.30 ± 0.61c	94.50 ± 1.15c
T_{10}	54.67 ± 0.51a	92.50 ± 0.87a	128.07 ± 0.76a	52.00 ± 0.84a	88.17 ± 0.58a	118.07 ± 0.76a
T_{11}	31.60 ± 0.43f	39.10 ± 0.20f	64.70 ± 0.61f	28.61 ± 0.47f	34.10 ± 0.2f	54.70 ± 0.61f
p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

leading to an increase in DMP. This is due to the effective and sustained release of herbicides against a wider weed flora. The increased dry matter production in plants was attributed to reduced competition between crops and weeds, which led to more vigorous growth and enhanced nutrient availability for wet direct-seeded rice (WDSR) under effective weed management. Similar results were obtained in earlier research (19). The least amount of DMP was recorded in the weedy check.

Leaf area index

The encapsulated pretilachlor and pyrazosulfuron ethyl formulations imposed a significant influence on the leaf area index of rice and it progressively increased from active tillering to the panicle initiation stage of the crop. Weed-free check obtained a maximum LAI than all other treatments. Among the herbicide treatments, application of pyrazosulfuron ethyl loaded with zeolite (T6) recorded a greater LAI of 3.55 and 3.49 during 2022 and 4.64 and 4.63 during 2023 at active tillering and panicle initiation stages respectively. It was found to be on par with the pyrazosulfuron ethyl encapsulated with polycaprolactone (Table 5). Shading to lower leaves of the crop due to weeds caused the crop senescence and death, but herbicide application led to a reduction in weed growth, which favoured the crop to get good light, water and nutrients resulting in higher LAI. Herbicides entrapped in zeolite and PCL increased herbicide activity towards a target species. Similar findings were obtained in previous works (23). The least LAI was obtained under a weedy check.

Table 3. Effect of encapsulated pretilachlor and pyrazosulfuron ethyl formulations on tillers (No. m^{-2}) of wet direct-seeded rice.

Treatments	Tillers (No. m^{-2})					
	2022			2023		
	Active tillering	Panicle Initiation	Harvest	Active tillering	Panicle Initiation	Harvest
T_1	139.00 ± 2.08e	231.33 ± 5.78e	285 ± 6.35e	124.00 ± 2.08e	211.33 ± 5.78e	271.67 ± 8.45e
T_2	160.00 ± 2.64d	270.33 ± 1.45d	315.33 ± 4.06d	145.00 ± 2.65c	250.33 ± 1.45d	308.67 ± 12.53d
T_3	157.33 ± 1.45d	265.33 ± 5.04d	314.33 ± 4.48d	142.33 ± 1.45d	245.33 ± 5.04d	304.33 ± 4.48d
T_4	141.00 ± 1.53e	240.00 ± 0.57e	293.67 ± 5.36e	126.00 ± 1.53e	220.00 ± 0.58e	273.67 ± 16.79e
T_5	155.00 ± 1.15d	258.00 ± 4.04d	309.67 ± 4.05d	140.00 ± 1.15d	238.00 ± 4.04d	303.00 ± 3.46d
T_6	193.66 ± 2.33b	323.33 ± 4.06b	350.67 ± 2.91b	177.00 ± 3.05b	302.33 ± 5.78b	363.67 ± 2.33b
T_7	188.67 ± 1.76b	321.00 ± 5.51b	348.33 ± 3.18b	173.67 ± 1.76b	297.67 ± 6.69b	362.67 ± 5.23b
T_8	172.33 ± 2.60c	287.67 ± 5.55c	330.67 ± 3.84c	157.33 ± 2.60c	267.67 ± 5.55c	334.33 ± 6.01c
T_9	177.67 ± 2.33c	298.00 ± 3.78c	331.00 ± 2.89c	162.67 ± 2.33c	278.00 ± 3.79c	335.33 ± 5.36c
T_{10}	208.33 ± 2.40a	337.00 ± 4.20a	364.67 ± 4.05a	193.33 ± 2.40a	317.00 ± 5.20a	391.33 ± 4.81a
T_{11}	123.3 ± 2.03f	215.33 ± 5.78f	263.67 ± 6.01f	108.33 ± 2.03f	195.33 ± 5.78f	243.67 ± 6.01f
p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table 4. Effect of encapsulated pretilachlor and pyrazosulfuron ethyl formulations on dry matter production (kg ha^{-1}) of wet direct-seeded rice.

Treatments	DMP (kg ha^{-1})					
	2022			2023		
	Active tillering	Panicle Initiation	Harvest	Active tillering	Panicle Initiation	Harvest
T_1	929 ± 13.05e	5514 ± 65.85e	7470 ± 121.30e	892 ± 6.17e	5247 ± 94.95e	7227 ± 49.77e
T_2	1130 ± 4.98d	6293 ± 60.18d	8873 ± 125.22d	1072 ± 24.45d	6093 ± 60.18d	8683 ± 137.42d
T_3	1122 ± 20.61d	6243 ± 22.1d	8723 ± 142.85d	1071 ± 14.19d	6076 ± 54.77d	8583 ± 77.83d
T_4	966 ± 4.25e	5592 ± 35.03e	7621 ± 139.47e	917.67 ± 3.29e	5392 ± 35.03e	7442 ± 141.86e
T_5	1109 ± 21.85d	6224 ± 2.89d	8617 ± 128.66d	1060 ± 21.87d	6051 ± 24.54d	8413 ± 128.97d
T_6	1430 ± 14.97b	7365 ± 47.70b	10901 ± 114.01b	1350 ± 30.35b	7161 ± 44.37b	10705 ± 106.05b
T_7	1403 ± 14.97b	7267 ± 21.60b	10689 ± 106.32b	1340 ± 34.18b	7067 ± 21.61b	10495 ± 97.61b
T_8	1237 ± 12.41c	6680 ± 58c	9648 ± 165.81c	1198 ± 7.51c	6480 ± 57.77c	9454 ± 156.36c
T_9	1241 ± 16.29c	6792 ± 12.33c	9796 ± 93.40c	1200 ± 4.04c	6592 ± 12.33c	9596 ± 93.79c
T_{10}	1546 ± 11.41a	7676 ± 19.67a	11659 ± 143.15a	1503 ± 5.69a	7476 ± 19.67a	11459 ± 147.98a
T_{11}	815 ± 6.25f	5095 ± 18.46f	6457 ± 115.24f	798 ± 7.96f	4962 ± 53.82f	6257 ± 119.49f
p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table 5. Effect of encapsulated pretilachlor and pyrazosulfuron ethyl formulations on LAI and productive tillers of wet direct-seeded rice.

Treatments	2022		2023		2022	2023
	AT	PI	AT	PI	Productive tillers	Productive tillers
T_1	2.26 ± 0.039e	3.27 ± 0.059e	2.19 ± 0.049e	3.26 ± 0.06e	171 ± 2.309e	161.33 ± 2.96e
T_2	2.54 ± 0.04d	3.77 ± 0.052d	2.44 ± 0.054d	3.76 ± 0.043d	195.67 ± 3.48d	185.67 ± 9.24d
T_3	2.48 ± 0.036d	3.75 ± 0.055d	2.45 ± 0.055d	3.74 ± 0.067d	190.67 ± 1.45d	180.67 ± 6.44d
T_4	2.27 ± 0.063e	3.34 ± 0.073e	2.21 ± 0.07e	3.31 ± 0.085e	175 ± 3.46e	161.67 ± 4.60e
T_5	2.47 ± 0.056d	3.66 ± 0.043d	2.40 ± 0.04d	3.64 ± 0.038d	190 ± 3.78d	178.33 ± 5.81d
T_6	3.55 ± 0.053b	4.64 ± 0.06b	3.49 ± 0.03b	4.63 ± 0.056b	236.67 ± 3.18b	226.67 ± 7.96b
T_7	3.43 ± 0.069b	4.55 ± 0.063b	3.43 ± 0.069b	4.55 ± 0.07b	232.37 ± 4.26b	225 ± 4.16b
T_8	2.75 ± 0.052c	3.98 ± 0.055c	2.68 ± 0.025c	4.24 ± 0.105c	211.67 ± 2.33c	204 ± 3.05c
T_9	2.83 ± 0.066c	4.10 ± 0.11c	2.76 ± 0.041c	4.25 ± 0.079c	219.00 ± 3.21c	207.33 ± 4.7c
T_{10}	3.79 ± 0.012a	4.97 ± 0.057a	3.75 ± 0.04a	4.90 ± 0.015a	254 ± 3.46a	244 ± 8.08a
T_{11}	2.09 ± 0.069f	2.743 ± 0.042f	2.026 ± 0.07f	2.69 ± 0.0176f	160 ± 2.08f	143.33 ± 1.85f
p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Number of productive tillers m-2

The encapsulated herbicide formulations had a substantial impact on the number of productive tillers m-2. The productive tiller ranged from 160 to 254 m-2 in 2022 and 143 to 244 m-2 in 2023. Weed-free checks resulted in the production of more productive tillers than other treatments. Among the herbicide formulations-based weed management practices, the application of pyrazosulfuron ethyl loaded with zeolite (T6) recorded a maximum number of productive tillers of 1.38 times in 2022 and 1.41 times in 2023. This was found to be on par with pyrazosulfuron ethyl encapsulated with polycaprolactone (T7), which recorded 1.35 and 1.39 times higher productive tiller in 2022 and 2023 respectively (Table 5). Both treatments were compared with the application of pretilachlor. The least number of productive tillers m-2 was obtained in the weedy check. The improved efficiency of nano herbicides in controlling weed populations, allowed the rice plants to thrive without any competition for essential resources, which led to improved productive tillers of rice. Similar results were also reported earlier (13).

Panicle length and weight

The encapsulation of herbicide significantly influenced the panicle length and weight. The weed-free check attained the first position compared to others. The second position was occupied by pyrazosulfuron ethyl loaded with zeolite (T6), which recorded 34.99 and 38.86 % of panicle length in 2022 and 2023 respectively. Whereas the same treatment recorded 49.77 and 50.51 % of panicle weight in 2022 and 2023 respectively, when compared with pretilachlor (Table 6). The treatment pyrazosulfuron ethyl encapsulated with

Table 6. Effect of encapsulated pretilachlor and pyrazosulfuron ethyl formulations on panicle length, panicle weight, grain and straw yield of wet direct-seeded rice.

Treatments	2022				2023			
	Panicle length (cm)	Panicle weight (g)	Grain yield (t/ha)	Straw yield (t/ha)	Panicle length (cm)	Panicle weight (g)	Grain yield (t/ha)	Straw yield (t/ha)
T_1	18.09 ± 0.10e	1.97 ± 0.0063e	3.483 ± 43.33e	4.355 ± 116.7e	16.70 ± 0.72e	1.96 ± 0.064e	3.260 ± 45.82e	4.048 ± 113.6e
T_2	21.47 ± 0.21d	2.33 ± 0.038d	4.167 ± 38.30d	5.172 ± 115d	19.81 ± 0.19d	2.31 ± 0.037d	4.024 ± 12.49d	4.866 ± 117.5d
T_3	21.22 ± 0.06d	2.31 ± 0.018d	4.087 ± 56.45d	5.161 ± 202.4d	19.56 ± 0.40d	2.31 ± 0.02d	3.877 ± 56.45d	4.854 ± 200d
T_4	18.42 ± 0.009e	2.03 ± 0.012e	3.552 ± 62.24e	4.435 ± 107e	17.09 ± 0.109e	2.02 ± 0.01e	3.342 ± 65.25e	4.158 ± 137.93e
T_5	21.19 ± 0.15d	2.31 ± 0.026d	3.992 ± 178.12d	4.974 ± 114d	18.86 ± 0.29d	2.30 ± 0.03d	3.782 ± 178.12d	4.670 ± 114.37d
T_6	24.42 ± 0.012b	2.95 ± 0.018b	5.333 ± 31.67b	6.107 ± 117b	23.19 ± 0.128b	2.95 ± 0.015b	5.123 ± 31.67b	5.803 ± 119.5b
T_7	24.19 ± 0.048b	2.91 ± 0.017b	5.199 ± 53.05b	5.982 ± 81.5b	22.71 ± 0.35b	2.91 ± 0.015b	5.022 ± 86.36b	5.676 ± 80.20b
T_8	21.92 ± 0.024c	2.62 ± 0.012c	4.609 ± 96c	5.547 ± 102c	21.38 ± 0.26c	2.62 ± 0.0057c	4.399 ± 96.20c	5.243 ± 101c
T_9	22.12 ± 0.07c	2.65.62 ± 0.009c	4.723 ± 54.28c	5.589 ± 113c	21.41 ± 0.31c	2.64 ± 0.0057c	4.513 ± 54.28c	5.282 ± 117c
T_{10}	25.07 ± 0.34a	3.21 ± 0.017a	5.750 ± 140a	6.482 ± 111a	24.20 ± 0.09a	3.20 ± 0.0176a	5.540 ± 140a	6.172 ± 111.2a
T_{11}	16.27 ± 0.089f	1.63 ± 0.012f	2.661 ± 106f	3.680 ± 85.01f	15.12 ± 0.153f	1.62 ± 0.009f	2.451 ± 105.95f	3.374 ± 81.97f
p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

polycaprolactone (T7) obtained the third position compared to other treatments. The least panicle length and weight were recorded in weedy check. The prolonged release of nano herbicides could contribute to a more sustained reduction in weed density over time, allowing the crop to achieve optimal growth conditions via weed-free conditions and potentially enhancing the yield attributes of rice. Similar findings were also reported earlier (24).

Yield

The encapsulated nano-herbicides formulation significantly influenced the yield of wet direct-seeded rice. The highest grain yield was achieved with weed-free check, followed by pyrazosulfuron ethyl loaded with zeolite and pyrazosulfuron ethyl encapsulated with polycaprolactone, which proved herbicide encapsulation can result in better weed management and improves yield than commercial formulations. Among the herbicide formulations, pre-emergence application of pyrazosulfuron ethyl loaded with zeolite recorded the highest grain yield of 5333 and 5123 kg ha-1 and straw yield of 6107 and 5803 kg ha-1 in 2022 and 2023 respectively. It was on par with pyrazosulfuron ethyl encapsulated with polycaprolactone with grain yields of 5199 and 5982 kg ha-1 and straw yields of 5022 and 5676 kg ha-1 in both the years respectively (Table 6). This might be due to the effective weed control by the encapsulated herbicide over a sustained period, which led to maintaining a weed-free environment. Thus, providing an ideal situation for efficient crop growth and development leads to improved crop yield. Similar results were corroborated in earlier work (16). A higher grain yield under herbicidal application owing to the effective control of weeds enhanced the values of yield attributes and ultimately increased the grain yield (25). Weedy check showed the realistic representation of the threatening nature of weeds on the rice yield. The lowest grain and straw yields were recorded in the control plot. This might be due to the fact that the weeds germinated along with the crop, grew vigorously and competed for natural resources throughout the crop period, resulting in reduced crop productivity.

Regression analysis of weed density and weed dry weight with grain yield

Weed density indicates a significant and negative relationship with grain yield. The coefficient of determination (R2 p ≤ 0.05) between grain yield and weed density was 0.8122 in 2022 and 0.7851 in 2023 at 45 days after sowing (Fig. 4 a, b). It indicated that about 81.22 % in 2022 and 78.51 % in 2023 of the grain yield was decreased due to weed density. The relationship between weed density and grain yield revealed that with an increase of every 10 weeds m-2, there was 0.391 kg of grain yield m-2 decrease in 2022 and 0.381 kg of grain yield m-2 in 2023. This analysis showed the supporting impact on weed control and grain yield. A similar result was reported earlier (26). Grain yield also shows a significant and negative relationship with weed dry weight. The coefficient of determination (R2 p ≤ 0.05) between the grain yield and weed density was 0.7839 in 2022 and 0.7493 in 2023 at 45 DAS (Fig. 4 c, d). This means that 78.39 % in 2022 and 74.93 % in 2023 of the variation in grain yield could be explained negatively by weed biomass. The relationship revealed that with an increase of every 50 g of weed dry weight m-2, there was a reduction of 0.3304 kg m-2 and 0.3167 kg m-2 in grain yield during 2022 and 2023 respectively. The findings highlighted the effectiveness of encapsulated herbicide formulations in controlling weed populations while improving crop yield. Similar results were reported earlier (27, 28).

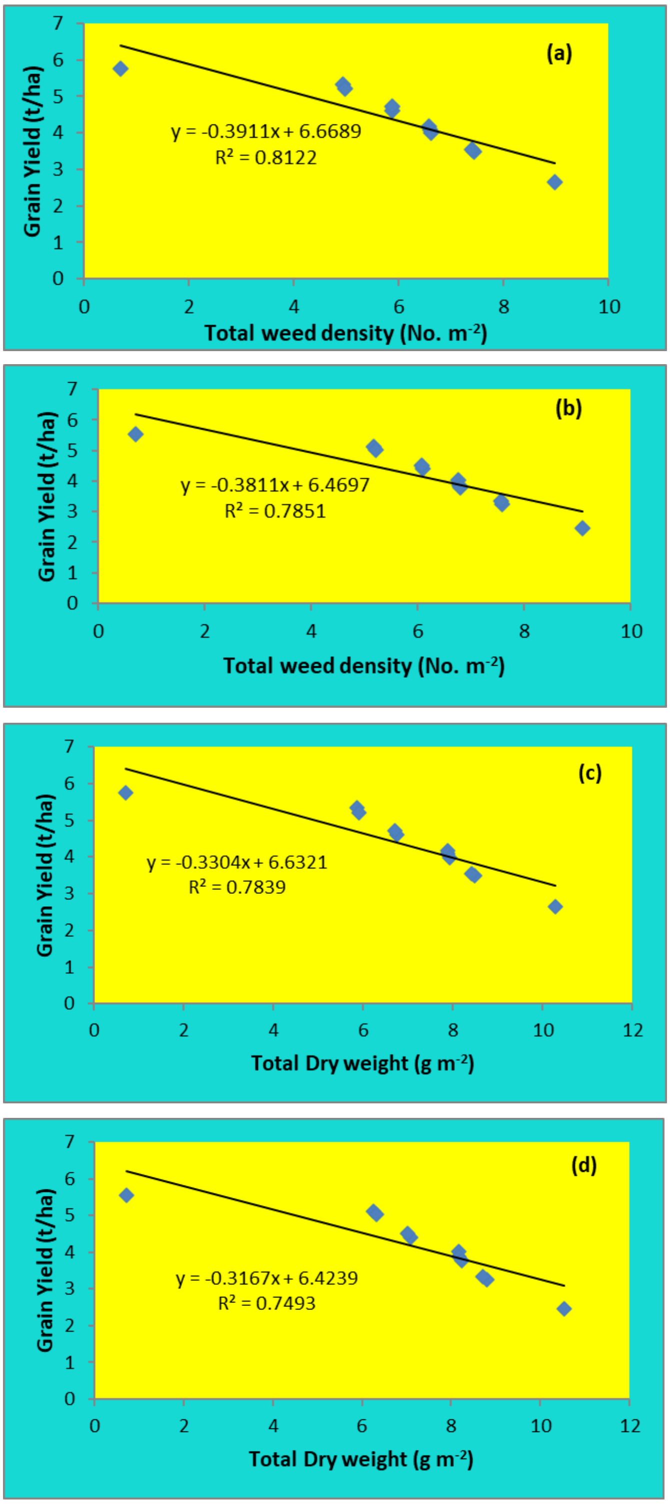

Fig. 4 a and b. Regression analysis between grain yield and weed density at 2022 (a) and 2023 (b)
c and d. Regression analysis between grain yield and weed dry weight in 2022 (c) and 2023 (d).

Conclusion

The weed-free check produces the highest grain yield, whereas the weedy check results in the lowest yield due to greater pressure from weeds in terms of biomass and density. Among the herbicide applications, pyrazosulfuron ethyl entrapped zeolite recorded lower weed density and biomass and increased growth and yield attributes of WDSR. The controlled release of encapsulated herbicide successfully regulates the herbicide movement within the soil column, by preventing the herbicide losses into the ecosystem. This process keeps an enormous amount of the active compound in the upper soil layer, which effectively controls the weed seeds that are actively present, emerge and compete with the crop. Through this process, there will be a decrease in the overall number of herbicide applications, which mitigates the inappropriate use of herbicides and reduces environmental contamination. Encapsulated herbicides release the active ingredient directly onto weeds, allowing for precise targeting and effective weed control. This method improves weed management efficiency and promotes higher agricultural productivity, especially in wet direct-seeded rice cultivation. Further studies are needed to understand the effect of encapsulated herbicides on microbial communities within the soil over an extended period and focus on the bioavailability of essential nutrients. Understanding these interactions will be the key to optimizing their use for sustainable crop production.

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Authors' contributions

SS: Carried out the experiment, statistical analysis and prepared manuscript, MH: Chairman for the research experiment and guided for preparation of article and finalized, MJ: Member for the research experiment and guided to prepare a manuscript revision and finalized.

Conflict of interest

The authors declare that there is no conflict of interest.

Ethical issues: None

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