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RESEARCH ARTICLE

Revolutionizing weed management through smart herbicide technology on boosting wet direct-seeded rice productivity

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Abstract

To investigate the impact of nanoencapsulation herbicides on weed control and yield of wet-seeded rice and control agroecotoxicity. Field experiments were conducted during the *kharif* season of 2022-23 and 2023-24 in a Randomized Block Design with eleven treatments and three replications. It was carried out with nanoencapsulated herbicides, *viz.*, pretilachlor and pyrazosulfuron ethyl loaded with zeolite, polycaprolactone and water-soluble polymers. These were compared with commercial formulations of pretilachlor, pyrazosulfuron ethyl and bispyribac sodium, which are weed-free and weedy check treatments. Pyrazosulfuron ethyl showed good compatibility with zeolite and was easier to encapsulate than other herbicides. On weed control measures, pyrazosulfuron ethyl loaded with zeolite @ 25 g a.i. ha^{-1} showed the lowest weed density, weed biomass and weed index and resulted in higher weed control efficiency, weed control index and herbicide efficiency index, led to recorded higher grain yield (5.3 and 5.1 t ha^{-1}) and straw yield (6.1 and 5.8 t ha^{-1}) of wet seeded rice during 2022 and 2023, respectively. It was on par with pyrazosulfuron ethyl encapsulated with polycaprolactone @ 25 g a.i. ha^{-1} recorded the weed density, weed biomass, weed index, weed control efficiency, weed control index, herbicide efficiency index, grain (5.2 and 5.0 t ha^{-1}) and straw yield (5.98 and 5.7 t ha^{-1}) during the respective years. Pyrazosulfuron ethyl loaded with zeolite was more efficient in controlling weeds and producing maximum grain and straw yield of wet direct-seeded rice due to the controlled release of the herbicide formulation targeting specific weed species, potentially reducing herbicide toxicity in the agroecosystem. Further research is essential to integrate the nanoencapsulated herbicide-releasing pattern with precision agriculture and ensure their effectiveness across diverse crops for sustainable crop production.

Keywords

agro-ecotoxicity; nano encapsulation; polycaprolactone; pyrazosulfuron ethyl; wet direct seeded rice; zeolite

Introduction

Rice (*Oryza sativa* L.) is considered a significant crop in India because it is a key component of the countrys' food and livelihood security. The worlds' population is predicted to grow at an alarming rate, reaching 8.8-9.1 billion in 2037, 9.5-10.5 billion in 2058 and 10.4-12.4 billion in 2100, i.e., by 2050, there will be more than 40 % increase in the worlds' rice consumption due to population growth (1). In India, rice is cultivated across 47.8 million hectares, yielding 135.7 Mt, with an average productivity of 2.84 t ha^{-1}. Similarly, in Tamil Nadu, the rice production is 42.63 lakh tonnes from an area of 18.43 lakh ha^{-1} with a productivity of 2.31 kg ha^{-1}(2). A large portion of the population relies on rice as a staple food and it is vital to the nations' agriculture and economy (3). As a result, it is anticipated that the agricultural sector will experience significant growth in the ever-growing global population to maintain food security (4).

Weeds pose a serious threat to the entire harvest in agroecosystems because they compete aggressively with rice crops for natural resources during their entire growth period. Weed infestation is a significant hindrance to wet-seeded rice. The season-long weed competition causes a 100 % yield drop in direct-seeded rice (5). In dry direct-seeded rice, uncontrolled weeds reduced the yield by 96 percent and in wet direct-seeded rice, by 61 percent. When rice is directly sown, weeds can reduce production by 40-100 percent (6). Manual weeding remains a feasible option, but it is becoming increasingly tedious as it is time-consuming, expensive and weather-dependent (7). Therefore, herbicides are widely used for controlling weeds. Significant problems with conventional herbicides are herbicide losses into the groundwater and water bodies and pollution of the environment, which causes environmental toxicity caused by conventional herbicides, posing a threat to human health, biodiversity and soil quality degradation that upsets the balance of the ecosystem (8). Modern technological developments and approaches with efficient solutions are needed to improve the value chain of the entire global agricultural production system (9).

Nanotechnology is a unique technology with several possible applications in the agriculture industry (10). Using nanotechnology in agriculture seems to be a potential strategy to transform traditional agricultural practices into advanced systems (11). The process of nano-encapsulation uses fats, starches, dextrins, alginates, protein and lipids as encapsulation materials to create a thin layer of protection against environmental deterioration while preserving the nutritional and functional properties of bioactive compounds in nanoscale-level capsules (12). Herbicides with Nano encapsulation are gaining popularity as a smart approach to developing agricultural methods by delivering the active component to the crops in a smart release manner. It has strong potential to increase herbicide use efficiency, minimize the environmental footprint and become essential for our agricultural food production systems to feed the worlds' growing population.

Slow-release herbicides are particularly beneficial for conserving agroecosystems. Polymers form the backbone of these systems by controlling the release of active ingredients. Polymeric materials are extensively used in herbicide encapsulation as carriers for the smart delivery system (13). Research indicates that encapsulated herbicides pose a lower risk to both humans and soil than conventional herbicides due to the controlled release formulation of herbicide to the desirable target species, reducing the toxicity to the non-target organisms (14, 15).

Given these advantages, nanoencapsulated herbicides are pivotal for effective weed control and sustainable agriculture practices while reducing soil ecotoxicity compared to conventional herbicides. Therefore, the present study aims to fabricate a new formulation of slow-release nano-encapsulated herbicide to enhance weed control and improve the productivity of wet direct-seeded rice.

Materials and Methods

Study site

Field experiments were carried out during the *kharif* seasons of 2022-2023 and 2023–2024 at the research farm of VOC Agricultural College and Research Institute (8°46' N latitude and 77°42' E longitude and at an altitude of 40 m above MSL) Tamil Nadu, Killikulam, is located in XI Agro-climatic zone of Indias' (East Coast Plains and Hills). The soil of the experimental plot was sandy clay loam, pH 7.8 and 7.6, EC 0.24 and 0.23 dsm^{-1}, OC 4.30 and 4.5 g kg^{-1}, low in available N (238 and 245 kg ha^{-1}), medium in available P (19 and 18 kg ha^{-1}) and high in available K (290 and 295 kg ha^{-1}) respectively. Weather parameters recorded during the experimental period were maximum temperature of 36.2^{0}C and 37.1^{0}C, minimum temperature of 21.7 ˚C and 21.1 ˚C and wind speed of 5.9 and 5.65 km $hr^{-1,}$ respectively.

Herbicide encapsulation and loading procedure

The standard method was followed with slight modification (16). The organic phase consisted of 100 mg polycaprolactone, 30 mL acetone, 200 mg triglycerides of capric acids, 40 mg sorbitan monostearate surfactant (Span 60) and 10 mg pretilachlor. The aqueous phase comprised the polysorbate surfactant 80 (60 mg) and Tween 80. Using a magnetic stirrer, the organic phase was gradually added to the aqueous phase and stirred for eight hours at room temperature. The resulting colloidal nanoparticles were concentrated to a final volume of 10-13 mL after removing the acetone, resulting in an herbicide concentration of 1 mg/mL). A four-percent starch solution was stirred continuously for one hour with a magnetic stirrer for water-soluble polymer-based preparation. This forms the aqueous phase. For the organic phase, 10 mg of the herbicides' active ingredient, 10 mL of water, 2 mL of polymer and 8 mL of acetone were stirred in the magnetic stirrer for 5 min. Drop-by-drop, the aqueous phase was added to the aqueous phase under stirring for about 8 hours to evaporate the solvent and the herbicide was collected for use as a liquid formulation. For encapsulation with the second polymer, the above-mentioned liquid formulation was taken and subjected to the same encapsulation procedure as the second polymer (17). When 100 g of zeolite and 1000 mL of 10 % herbicide were added, the solution was agitated for 15 minutes using a magnetic stirrer and left to dry overnight. The dried particles were obtained, which enabled the herbicide to adsorb on the zeolite (18).

Experimental details and data collection

The experiments were laid out in a Randomised Block Design with eleven treatments and three replications.

The treatment details are as;

T_1	Pretilachlor @ 0.75 kg a.i. ha^{-1}
T_2	Pretilachlor loaded with Zeolite @ 0.75 kg a.i. ha^{-1}
T_3	Pretilachlor encapsulated with Polycaprolactone (PCL) @ 0.75 kg a.i ha^{-1}
T_4	Pretilachlor encapsulated with Water soluble polymer (Poly allylamine hydrochloride) (PAH)+ Sodium Poly (styrene sulfonate) (PSS)) @ 0.75 kg a.i ha^{-1}
T_5	Pyrazosulfuron ethyl @ 25 g a.i ha^{-1}
T_6	Pyrazosulfuron ethyl loaded with Zeolite @ 25 g a.i ha^{-1}
T_7	Pyrazosulfuron ethyl encapsulated with Polycaprolactone (PCL) @ 25 g a.i ha^{-1}
T_8	Pyrazosulfuron ethyl encapsulated with Water soluble polymer (Poly allylamine hydrochloride) (PAH)+ Sodium Poly (styrene sulfonate) (PSS)) @ 25 g a.i ha^{-1}
T_9	PE Pretilachlor @ 0.75 kg a.i ha^{-1} fb EPoE Bispyribac sodium @ 25 g a.i ha^{-1} on 20 DAS
T_{10}	Weed free check
T_{11}	Weedy check

As per the treatment schedule, different herbicides were applied five days after sowing for ASD16 rice as pre-emergence in the experimental plots. The recommended cultural practices and plant protection measures were taken during the experiments.

Data analysis

The Shapiro-Wilk test (Proc Univariate) was used to determine whether the data residuals were normal. Before analysis, the square root transformation of weed density and biomass was performed. In the general linear model for weed density, biomass and rice yield, replication was considered a random variable, while herbicide treatments were the fixed effects. The weed density and biomass data were analyzed separately for 15, 30 and 45 days after sowing (DAS). With SAS software version 9.3 (SAS Institute Inc., Cary, NC, USA), the Proc-GLIMMIX technique was used to analyze variance (ANOVA) and proc-sort data was used to separate the means. Weed control efficiency was calculated based on weed density (19). The weed dry weight drove the weed control index and was expressed in percentage (20). The weed index was used the standard formula and expressed in percentages (21). The herbicide efficiency index (HEI) was determined using a formula that reflects herbicide efficacy and phytotoxicity (22). Linear correlation analyses were also performed to assess the relationships between weed parameters and yield using Pearsons' coefficient in Microsoft excel.

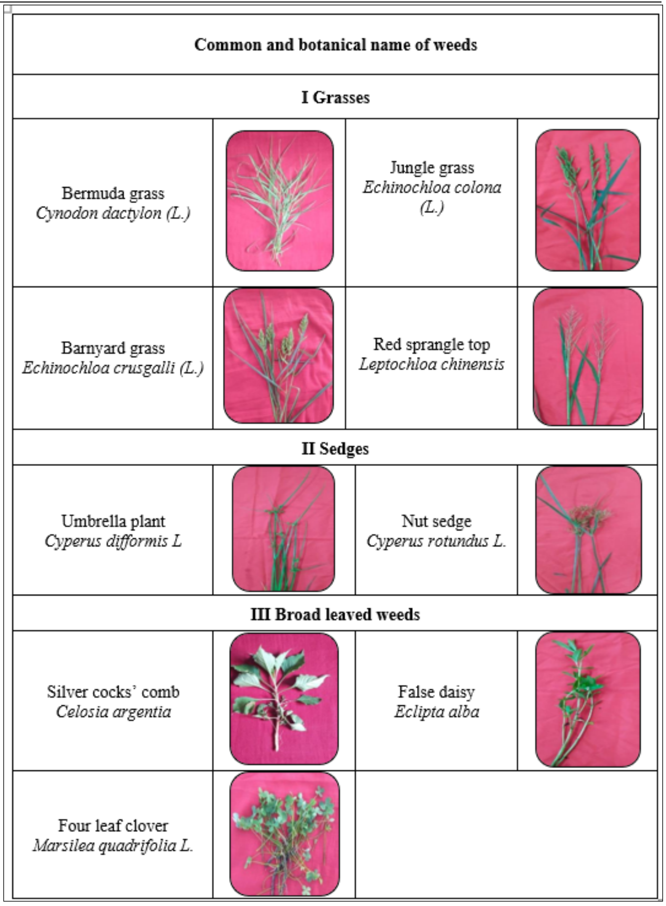

Fig. 1. Weed flora observed in the field experiment.

Results and Discussion

Weed flora

During the two years of experimental period, four species of grasses [Bermuda grass (*Cynodon dactylon),* barnyard grass *(Echinochloa crusgalli)*, jungle grass (*Echinochloa colona),* red sprangle top *(Leptochloa chinensis)*], two species of sedges [Umbrella plant (*Cyperus difformis)* and nut sedge (*Cyperus rotundus)*] and three species of broadleaved weeds [Silver cocks' comb (*Celosia argentia),* false daisy *(Eclipta alba),* four leaf clover *(Marsilea quadrifolia)*] were observed in the experimental field as shown in Fig. 1.

Weed density

Weed control treatments showed significant differences in weed density and biomass at 15, 30 and 45 DAS. The weed-free check registered significantly the lowest weed density and weed biomass at all stages of rice growth. Among the weed control treatments, the application of pyrazosulfuron ethyl loaded with zeolite at 25 g a.i. ha^{-1} recorded lower weed density of 2.52, 6.20, 23.93 m^{-2} at 15, 30, 45 DAS in 2022 and 4.97, 8.24, 26.27 m^{-2} at 15, 30 and 45 DAS in 2023, respectively. However, it was on par with pyrazosulfuron ethyl encapsulated with polycaprolactone at 25 g a.i. ha^{-1} recorded weed density of 2.65, 6.35, 24.19 m^{-2} at 15, 30, 45 DAS in 2022 and 5.21, 8.55, 26.56 m^{-2} at 15, 30, 45 DAS in 2023, respectively. The pyrazosulfuron ethyl loaded with zeolite shows (90.46 %, 70.12 %, 83.28 %) and (86.78 %, 82.85 %, 67.99 %) reduced weed density compared to control (weedy check) at the respective stages of 15, 30, 45 DAS during 2022 and 2023 (Table 1). It was on par with pyrazosulfuron ethyl encapsulated with polycaprolactone shows (89.97 %, 86.46 %, 69.80 %) and (82.02 %, 82.65 %, 67.63 %) percent reduced weed density at 15, 30, 45 DAS, respectively in 2022 and 2023 as compared to control. As pyrazosulfuron ethyl is a sulfonylurea group, a systemic and broad spectrum that inhibits the Acetolactate Synthase (ALS) (23). The modified delivery of pyrazosulfuron ethyl by zeolite improves herbicide efficacy, enhances the uptake of herbicides through leaf stomata and minimizes environmental impact (19). The PCL nanoparticles are low-toxicity polymers with a high loading capacity and minimize chemical degradation so that they can be used as nanocarriers for herbicides in agriculture (24). The highest weed density was recorded under a weedy check. Research indicates that nanoatrazine was more effective in controlling weed density than conventional herbicides at full dosage in *A. tenella* plants (25). It could be linked to the nanocapsules influenced release of atrazine, improved adherence to the leaves, or the uptake of the nanocapsules by the stomata on the leaves, all of which would improve the herbicides' delivery to the target organism and stop atrazine loss from entering the environment.

Weed biomass

Weed biomass is a valuable metric for assessing crop-weed competition as it reflects the growth-attributing factors utilized by weeds rather than just their weed count (26). Among the herbicide treatments, the application of pyrazosulfuron ethyl loaded with zeolite at 5 DAS reduced dry weight by 7.72, 9.12 and 3.11 times in 2022 and 5.59, 7.05 and 2.86 times in 2023 at 15, 30 and 45 DAS, respectively, when compared with the control. It was on par with pyrazosulfuron ethyl encapsulated with polycaprolactone recorded (7.45, 8.76 & 3.05) and (5.45, 6.65 and 2.79) times of lower weed dry weight at 15, 30 and 45 DAS in 2022 and 2023, respectively (Table 1). It could be because herbicides entrapped in zeolite have enhanced sorption and reduced herbicide dissipation in soil (18). This facilitates the herbicides' gradual release throughout the growing season, destroying the weed seeds' food sources and reducing weed regeneration and biomass. The controlled release of herbicide inhibits the weed both during the early and late emerging stages, resulting in a reduced weed dry weight. The higher weed dry weight of 39.76, 76.25 and 105.51 g m^{-2} during 2022 and 42.41, 78.96 and 110.31 g m^{-2} during 2023 at 15, 30 and 45 DAS, respectively, was recorded in weedy check. It might be due to the undisturbed weed growth during the entire crop growth period. Research indicates that slow-release herbicide formulations reduce the leaching loss of active chemicals, which impacts weed biomass and late-emerging weeds. The decomposition rate of microparticles was maintained by the microencapsulation of metazachlor with terpolymer, resulting in a prolonged release of herbicides and a reduction in excess leaching into the soil (28).

Weed control efficiency

Different weed control treatments highly influence weed control efficiency. Among the herbicide treatments, pre-emergence application of pyrazosulfuron ethyl loaded with zeolite recorded higher WCE (90.46, 86.77 and 70.12) and (82.82, 83.29 and 67.99) during the 2022 and 2023 experiments, respectively at 15, 30 and 45 DAS (Table 2). It might be due to the pyrazosulfuron ethyl having a broad weed control spectrum, such as grasses, sedges and broad-leaved weeds in wet direct, seeded rice. It results in symptoms like distortion, crinkling, stunting, chlorosis and ceasing meristematic growth. In the end, weeds lack branching or vital amino acids in their developing tips (29). Suppose a commercial formulation of pyrazosulfuron ethyl is applied in rice fields without nanoencapsulation. In that case, it shows minimal weed control efficiency because of the leaching down of herbicide molecules after application, posing a serious threat to soil and groundwater quality. Encapsulation ensures controlled release, preventing hydrolysis and microbial degradation, thereby increasing WCE in wet-seeded rice. Nanoencapsulated herbicides in

Table 1. Effect of weed management practices on total weed density and total dry weight of weeds in wet seeded rice

Treatment	Total weed density (No. m^{-2})						Total dry weight of weeds (g m^{-2})					
	2022-23			2023-24			2022-23			2023-24		
	15 DAS	30 DAS	45 DAS	15 DAS	30 DAS	45 DAS	15 DAS	30 DAS	45 DAS	15 DAS	30 DAS	45 DAS
T_1	4.4b (19.10)	5.2b (27.68)	7.4b (54.70)	4.7b (21.60)	5.5b (29.93)	7.6b (56.99)	4.4b (18.51)	5.4b (28.77)	8.5b (71.35)	4.6b (21.01)	5.7b (31.83)	8.8b (76.83)
T_2	3.3c (10.4)	4.5c (20.18)	6.6c (42.82)	3.7c (12.98)	4.8c (22.35)	6.7c (45.13)	3.8c (13.72)	4.6c (20.55)	7.9c (61.70)	4.0c (15.94)	4.9c (23.61)	8.2c (66.23)
T_3	3.3c (10.58)	4.6c (20.36)	6.6c (43.11)	3.7c (13.18)	4.8c (22.67)	6.8c (45.45)	3.8c (13.94)	4.6c (20.98)	7.9c (61.79)	4.1c (16.18)	5.0c (24.17)	8.2c (66.42)
T_4	4.4b (18.52)	5.3b (27.28)	7.4b (54.19)	4.6b (21.08)	5.5b (29.36)	7.5b (56.51)	4.3b (18.12)	5.3b (28.08)	8.4b (70.50)	4.6b (20.33)	5.6b (30.99)	8.7b (75.22)
T_5	3.4c (10.83)	4.6c (20.51)	6.6c (43.29)	3.7c (13.39)	4.8c (22.82)	6.8c (45.62)	3.8c (14.09)	4.7c (21.47)	7.9c (62.48)	4.1c (16.44)	5.0c (24.49)	8.2c (67.19)
T_6	1.7e (2.52)	2.6e (6.20)	4.9e (23.93)	2.3e (4.97)	3.0e (8.24)	5.2e (26.27)	2.4e (5.15)	3.0e (8.36)	5.9e (33.89)	2.8e (7.58)	3.4e (11.24)	6.2e (38.60)
T_7	1.8e (2.65)	2.6e (6.35)	5.0e (24.19)	2.4e (5.21)	3.0e (8.55)	5.2e (26.56)	2.4e (5.34)	3.0e (8.70)	5.9e (34.51)	2.9e (7.78)	3.5e (11.87)	6.3e (39.55)
T_8	2.6d (6.14)	3.4d (11.42)	5.9d (34.09)	3.0d (8.64)	3.8d (13.60)	6.1d (36.54)	3.0d (8.82)	4.0d (15.48)	6.8d (45.20)	3.4d (11.16)	4.4d (18.52)	7.1d (49.67)
T_9	4.4b (18.91)	3.4d (11.24)	5.9d (33.94)	4.7b (21.44)	3.7d (13.38)	6.1d (36.32)	4.3b (18.18)	3.9d (14.70)	6.7d (44.57)	4.6b (20.49)	4.3d (17.68)	7.0d (48.72)
T_{10}	0.7f (0.00)	0.7f (0.00)	0.7f (0.00)	0.7f (0.00)	0.7f (0.00)	0.7f (0.00)	0.7f (0.00)	0.7f (0.00)	0.7f (0.00)	0.7f (0.00)	0.7f (0.00)	0.7f (0.00)
T_{11}	5.2a (26.42)	6.9a (46.93)	9.0a (80.10)	5.4a (28.99)	7.1a (49.30)	9.1a (82.07)	6.3a (39.76)	8.8a (76.25)	10.3a (105.51)	6.5a (42.41)	8.9a (78.96)	10.5a (110.31)
p value	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

*Weed density and weed biomass data were subjected to square root transformation and original values of weed emergence are shown in parenthesis.

polymeric nanoparticles also have minimal leaching potential, reducing environmental risk. Similar research findings have been reported in various studies (30-32).

Weed control index

The weed control index was registered higher in pyrazosulfuron ethyl loaded with zeolite plots with index of 67.8 and 65.0 per cent in 2022 and 2023, respectively. It was followed by applying pyrazosulfuron ethyl encapsulated with polycaprolactone, recorded 67.29 and 64.13 percent during both years, respectively (Table 2). Pyrazosulfuron ethyl is a low-dose, new-generation herbicide that controls weeds effectively. Apart from that, encapsulation/ loading helps with long-term weed control, which reduces the herbicide dose by controlling the release of herbicides and prevents losses into the agroecosystem. Research indicates that the encapsulation of herbicides increases the stability of active substances and drastically lowers the use of sulfentrazone herbicide encapsulated in Ca-ALG microparticles by reducing the quantity and, in turn, released into the environment.

Weed index

The weed index is a measure of yield loss caused by varying degrees of weed competition compared to the relatively weed-free condition throughout the crop period, leading to higher productivity. The higher weed indexes of 53.72 and 55.76 in 2022 and 2023, respectively, were recorded in the weedy plot, indicating higher competition between the crop and weed for the resources. In this study, applying pyrazosulfuron ethyl loaded with zeolite was the best treatment, resulting in a lower weed index of 7.25 and 7.53 during both years. It was followed by pyrazosulfuron ethyl encapsulated with polycaprolactone, having a weed index of 9.58 and 9.35 per cent, respectively (Table 2). The lower weed index recorded in these treatments might be due to the application of encapsulated herbicides, reduced weed seed germination weed population, decreased crop weed competition and directly increased rice yield components and yield. The previous study also highlighted that atrazine encapsulated with polycaprolactone at 200 g ha^{-1}, its delivery system showed targeted weed control at 10 times lower doses with comparable efficacy than non-nano atrazine at 2000 g ha^{-1} in soybean (34).

Herbicide use efficiency

Among the herbicide treatment, pre-emergence application of pyrazosulfuron ethyl loaded with zeolite was also found to be the best treatment as it was registered higher herbicide use efficiency of 1.57 and 1.49 during both years and it was on par with pyrazosulfuron ethyl encapsulated with polycaprolactone with HUE of 1.50 and 1.43, respectively. The lower herbicide use efficiency (0.35 and 0.36) was registered in pretilachlor at 0.75 kg a.i. ha^{-1}. The result shows that a single application of encapsulated pyrazosulfuron ethyl performed better than two time-applied commercial herbicides, which can lessen the herbicide toxicity to the non-target organism and soil environment. Research indicates that PCL nanocapsules (200 g a.i. ha^{-1}) loaded with atrazine were ten times diluted and had the same inhibitory effect on weed development at the root and shoot stages as the conventional atrazine dose of 2,000 g a.i. ha^{-1}. Atrazine encapsulated with PCL decrease its mobility in the soil, which helps prevent leaching-related water table contamination (36). It also diminishes the herbicides' cytotoxic and genotoxic effects without sacrificing herbicidal efficacy.

Grain and straw yield

Similarly, different weed control treatments significantly influenced the grain and straw yield of wet direct-seeded rice during both years of the experiment (Fig. 2-3). In 2022, the grain yield varied from 2.7 to 5.6 t ha^{-1} and straw yield from 3.7 to 6.5 t ha^{-1}. Similarly, the grain and straw yields ranged from 2.5 to 5.5 t ha^{-1} and 3.4 to 6.2 t ha^{-1}, respectively, during 2023. The weed-free check treatment recorded significantly higher grain and straw yield than all other weed control treatments. Nevertheless, the herbicide-applied treatments, pre-emergence application of pyrazosulfuron ethyl loaded with zeolite recorded 5.3 & 5.1 t ha^{-1} and 6.1 & 5.9 t ha^{-1} grain and straw yield which were 100.41 & 109.01 and 65.95 & 71.99 % higher grain and straw yield when compared to weedy check treatment in 2022 and 2023 respectively. This could be because of less competition from weeds, which promotes a maximum weed-free environment where efficient use of all resources leads to increased crop growth and productivity. Research indicates a yield reduction of 70.7 per cent due to uncontrolled weed growth

Table 2. Effect of weed management practices on weed control efficiency, weed control index, weed index (%) and HEI in wet seeded rice

Treatment	Weed control efficiency (%)						Weed control index (%)						Weed index (%)		HEI	
	2022			2023			2022			2023			2022	2023	2022	2023
	15 DAS	30 DAS	45 DAS	15 DAS	30 DAS	45 DAS	15 DAS	30 DAS	45 DAS	15 DAS	30 DAS	45 DAS				
T_1	28.08	41.02	31.74	25.49	40.52	30.56	53.45	62.27	32.38	50.46	59.69	30.35	39.43	41.15	0.35	0.36
T_2	60.63	56.98	46.56	55.19	54.65	45.00	65.47	73.05	41.52	62.41	70.11	39.95	27.53	27.36	0.62	0.65
T_3	59.92	56.62	46.20	54.54	54.00	44.49	64.94	72.47	41.43	61.82	63.40	39.78	28.92	30.02	0.59	0.61
T_4	28.42	41.87	32.36	27.28	40.46	31.15	54.43	63.17	33.18	52.06	60.76	31.80	38.23	39.67	0.38	0.39
T_5	29.90	56.30	45.96	51.94	53.70	44.42	64.54	71.84	40.78	61.23	68.99	39.08	30.57	31.73	0.56	0.58
T_6	90.46	86.77	70.12	82.82	83.29	67.99	87.05	89.02	67.88	82.13	85.77	65.00	7.25	7.53	1.57	1.49
T_7	89.97	86.45	69.81	82.03	82.66	67.63	86.57	88.59	67.29	81.65	84.97	64.13	9.58	9.35	1.50	1.43
T_8	76.76	75.64	57.46	70.20	72.40	55.48	77.82	79.70	57.15	73.68	76.54	54.97	19.84	20.60	0.99	0.98
T_9	28.42	76.03	57.65	26.01	72.86	55.75	54.27	80.71	57.75	51.68	77.61	55.83	17.86	18.54	1.04	1.03
T_{10}	100	100	100	100	100	100	100	100	100	100	100	100	0	0	-	-
T_{11}	0	0	0	0	0	0	0	0	0	0	0	0	53.72	55.76	0	0

*Data not statistically analyzed

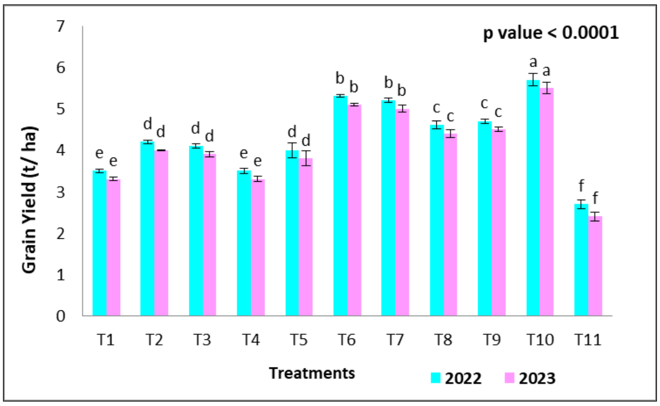

Fig. 2. Effect of weed management practices on grain yield of wet seeded rice in 2022-23. (Means followed by same letters are not significantly different).

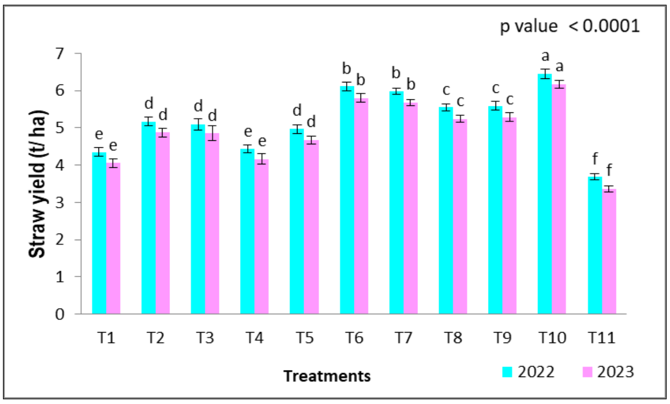

Fig. 3. Effect of weed management practices on straw yield of wet seeded rice in 2022-23. (Means followed by same letters are not significantly different).

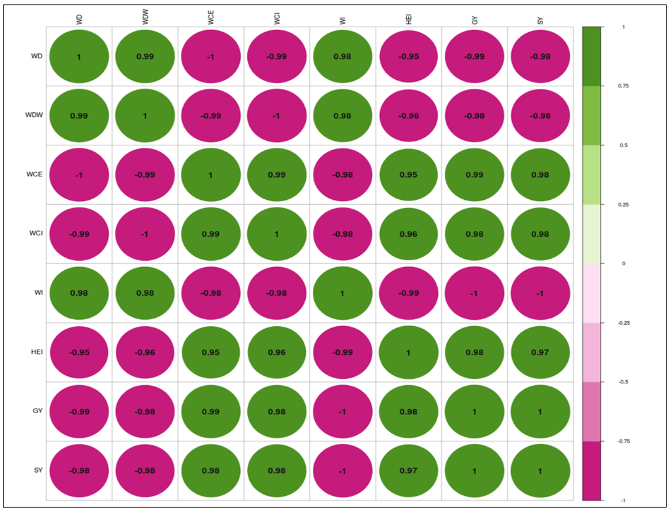

Fig. 4. Correlation between the weed parameter and yield of wet seeded rice in 2022-23.

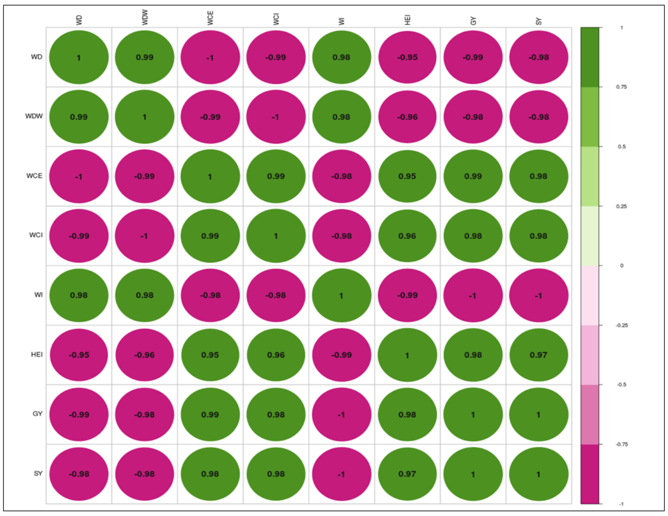

Fig. 5. Correlation between the weed parameter and yield of wet seeded rice in 2022-23. (Correlation is significant at 0.001 levels (two tailed). WD - Weed density, WDW - Weed dry weight, WCE - Weed control efficiency, WCI - Weed control index, WI - Weed index, HEI - Herbicide efficiency index, GY - Grain yield, SY - Straw yield).

in rice (37). Another research found the maximum grain yield of rice with oxadiargyl loaded with zeolite at 100 g ha^{-1} (18). This could result from longer-term, more effective weed control, which creates a favourable ecosystem for increased crop growth and yield. The least grain and straw yield was obtained from the weedy check (control). It might be due to severe weed competition throughout the crop growth period.

Correlation studies

The correlation studies between weed parameters and yield were assessed (Fig. 4-5). Grain and straw yield was negatively correlated with weed density, weed dry weight and weed index. Still, it was positively correlated with weed control efficiency, weed control index and herbicide efficiency index during both years. This suggests that minimum weed density and biomass recorded maximum grain and straw yield. They enhance the crops' ability to absorb essential nutrients and, as a result, strengthen the source-to-sink relationship. Weed exerts a negative effect on crop productivity. Research indicates that the growth and development of the crop were positively impacted by more efficient weed control with encapsulated herbicide, increasing plant height by 18 % and above-ground biomass by 22 % (39). Encapsulation of herbicides in copper polymers lessened the detrimental effects on–target organisms, groundwater, surface water contamination and the environment. Controlled release of encapsulated herbicide gave enhanced weed control at minimal environmental risk (39, 40). Weedy check has increased weed biomass, which negatively correlates with yield.

Conclusion

The weed-free check produces the highest grain yield, whereas the weedy check produces the lowest yield because of the increased pressure from weeds on biomass and density. Among the herbicide treatments, it can be interpreted that the application of nanoencapsulated pyrazosulfuron ethyl loaded with zeolite was found to be more efficient in the slow release of herbicide and controlling the weeds effectively with higher herbicide efficiency index, apart from the production of maximum yield of wet direct seeded rice under the constrained situation of manual weeding. It also reduced the excessive application of herbicides, mitigating agroecotoxicity and sustaining the global agricultural food production system sustainably. Future studies are required to integrate nanoencapsulated herbicides with precision agriculture techniques, encouraging further research for their applicability in different crops or farming systems and assessing the environmental fate, biosafety and regulatory and economic feasibility. Analyzing these relationships will be essential for improving their application in sustainable crop production.

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Authors' contributions

SS experimented with statistical analysis and prepared the manuscript. MH, the research experiments' chairman, guided the articles' preparation and finalization. MJ, a member of the research experiment, was guided to prepare a manuscript revision and finalize it. SJ, member for the research experiment. SSr, a member for the research experiment, AKP, member for the research experiment.

Compliance with ethical standards

Conflict of interest: The authors declare that there is no conflict of interest.

Ethical issues: None

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