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RESEARCH ARTICLE

Combined effect of new generation herbicides on weed population, soil microbial population and yield in direct seeded rice (*Oryza sativa* L.)

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Abstract

Weeds are considered the biggest threat to direct seeded rice (DSR) which must be managed effectively to augment yield and economics in DSR. Hence, field experiments were conducted at Periyanarkunam, Bhuvanagiri taluk, Tamil Nadu. The studies comprised one preliminary field experiment conducted during *Navarai* 2021 to identify a suitable direct-seeded rice establishment method. The trial was laid in a split plot design with three main treatments (dry seeded, drum seeded and manual wet seeded rice) and nine sub treatments consisting of different weed management methods. In addition, two main field experiments during *Kuruvai* 2021 and 2022 to evaluate the impact of new generation herbicidal combinations on weed population, soil microbial population and yield in direct-seeded rice. These experiments followed a randomized block design with six weed management practices and four replications. The result showed that among the establishment methods drum seeded rice recorded the highest yield, which was comparable with manual wet seeded rice (M_3). However, in term of economics drum seeded rice documented the highest benefit-cost ratio (2.22) compared to manual wet seeded rice (1.95). Regarding weed management practices, application of new generation herbicides at a low dose did not show any detrimental effect on soil microbial population. Among the treatments tested, bensulfuron methyl 0.6 % + pretilachlor 6 % granules at 10 kg ha^{-1} application on 8 DAS (days after sowing) as pre-emergence (PE) followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % at 20 g ha^{-1} application on 25 DAS as post-emergence (PoE) and followed by hand weeding at 45 DAS, recorded the lowest weed population, the highest weed control efficiency and superior yield across all experiments. Hence, this practice is both efficient weed management and economically feasible for effective control of weeds in direct seeded rice.

Keywords: direct seeded rice; microbial population; new generation herbicides; weed management; yield

Introduction

Rice (*Oryza sativa* L.) is the main food crop accounting major share in the total food grains production (44 %) and plays a significant role in food security and Indian economy. In India, rice occupies 47.82 million hectares with a production of 137.82 million tonnes (1). Transplanting is the traditional method of rice cultivation, which is laborious, high water demanding, time intensive and led to higher cost on raising nursery, pulling out seedlings and transplanting(2). Due to shortage of labours during peak transplanting period, unstable supply of monsoon rains, decline in underground water and rising production costs need an alternative to the traditional transplanted rice (3). Direct seeded rice (DSR) has evolved as a promising alternative to transplanted rice. The growing popularity of DSR is attributed to its benefits, including improved water use efficiency, reduced methane emissions, lower labour costs, increased net profits and better maintenance of soil physical properties (4). Drum seeding of rice offer benefits such as, light in weight, easy to transport, gender-neutral, solves labour scarcity problem, sowing more area in short period, reduced production cost and increased the returnsrupee^{-1} invested (2).

Weed control in rice is a challenging task for the effective crop production due to their presence leads to significant reductions in crop yield and quality, which in turn reduces productivity and profitability. In DSR, weeds emerge along with rice and increasing the cost of production and reducing the yields up to 90 % by competing with the main crop for moisture, nutrients, light and space (5). Thus, among different agronomic management options, effective control of weeds is an essential condition for better growth and productivity of rice in all establishment methods. Though, manual weeding is the most common and an efficient method the scarcity, high wages of labour especially during the peak period of agricultural operations, make this method uneconomic and difficulty in differentiating grass weeds that mimic rice crop during early growth is an obstacle in the successful adoption of hand weeding (6). Mechanical method of weed management is also time consuming, laborious and reduces the benefit cost ratio.

Biological control of weeds can only be used for irrigated lowland rice, which is less effective due to low adaptability and less multiplication of biological control agents, narrow weed control and lack of knowledge among farmers (7).

Herbicidal weed management using judicious selection of herbicides at the right time, right dose with right method helps to manage weeds effectively besides increase crop yield. New generation herbicidal mix reduces such as, the rate of use, herbicide injury to crops, cost of application and problem of residual build up. The subsequent application of pre and post emergence herbicides integrated with one hand weeding which have higher bio efficacy against diverse weeds thus results in better crop growth and yield in DSR (8). However, applied herbicide not to harm the microbial population in the soil as microbial population is very much essential for soil health, plant growth, decomposition of organic matter, nutrient recycling and maintaining soil structure. Given the above, the experiment was undertaken to study the effect of combined new generation herbicides on weed population, microbial population in soil and yield in direct seeded rice.

Materials and Methods

Field experiments were conducted at Periyanarkunam village, Bhuvanagiri taluk, Tamil Nadu. The experiment comprises of one preliminary field experiment during *Navarai* 2021 (January) to evolve the suitable direct seeded rice establishment method and two main field experiments during *Kuruvai* (June) 2021 and 2022 to evolve the suitable combination of new generation herbicides on weed population, soil microbial population and yield in drum seeded rice. The experimental fields soil was clay loam, the initial nutrient status was low, medium and high in available nitrogen, phosphorus and potassium, respectively. The short duration rice cultivar ASD 16 was readily available in the local market in Sethiathoppu and purchased, used as test variety for the experiments.

Herbicides used

The new generation herbicides like bensulfuron methyl 0.6 % + pretilachlor 6 % GR (ready mix) at 10 kg ha^{-1} (Londax Power) in pre-emergence group, triafamone 20 % + ethoxysulfuron 10 % WG (ready mix) at 200 g ha^{-1} (COUNCIL active) in early post emergence group and metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP (ready mix) at 20 g ha^{-1} (PIMIX) and bispyribac sodium 10 % SC at 250 mL ha^{-1} (Nominee Gold) in post emergence category were selected for experimentation. Calculated quantity of herbicides was mixed with water at 500 L ha^{-1}, sprayed through knapsack sprayer fitted by flood jet nozzle. Dry sand at 50 kg ha^{-1} was mixed with granular herbicide. Water was maintained in thin film, at the time of herbicides application.

Experimental design and treatment details

The preliminary experiment was carried out in a split plot design (SPD) by three replications consisted of three direct seeded rice establishment methods in main plot and nine weed management practices in sub plots. The main field experiments were conducted in a randomized block design with four replications consist of six weed management practices in drum seeded rice. The treatment details were given in Table 1.

Weed population analysis

Weeds from four quadrants (0.25 m^2 area) placed randomly in each net plot were collected, expressed in no. m^{-2}. The roots were removed and then dried in hot air oven 80 °C ± 5 °C for 48 hr and weed dry matter production was computed, expressed in g m^{-2}. Weed control efficiency (WCE %) was calculated based on weed population recorded in each treatment using the formula (9):

$$\text{WCE (\%)} = \frac{\text{Weed population in control plot - Weed population in treated plot}}{\text{Weed population in control plot}} \times 100 \quad \text{(Eqn. 1)}$$

Table 1. Treatment details of the experiments.

Treatments	Treatment details
Preliminary field experiment during *Navarai* 2021	
	Main treatments
M_1	Dry seeded rice
M_2	Drum seeded rice
M_3	Manual wet seeded rice
	Sub treatments
S_1	Unweeded control
S_2	Twice hand weeding on 25 and 45 DAS
S_3	PE on 8 DAS, followed by HW at 45 DAS
S_4	EPoE on 12 DAS followed by HW at 45 DAS
S_5	PoE on 25 DAS followed by HW at 45 DAS
S_6	PE on 8 DAS followed by PoE on 25 DAS
S_7	EPoE on 12 DAS followed by PoE on 25 DAS
S_8	PE on 8 DAS followed by PoE on 25 DAS and HW at 45 DAS
S_9	EPoE on 12 DAS followed by PoE on 25 DAS and HW at 45 DAS
	Main field Experiments during *Kuruvai* 2021 and 2022
T_1	Unweeded control
T_2	Twice hand weeding on 25 and 45 DAS
T_3	Bispyribac sodium 10 % SC at 250 mL ha^{-1} on 20 DAS followed by HW on 45 DAS
T_4	PE on 8 DAS followed by PoE on 25 DAS
T_5	PE on 8 DAS followed by PoE on 25 DAS and HW at 45 DAS
T_6	EPoE on 12 DAS followed by PoE on 25 DAS and HW at 45 DAS

DAS -days after sowing, **HW**-hand weeding, **PE**-bensulfuron methyl 0.6 % + pretilachlor 6 % GR at 10 kg ha^{-1} on 8 DAS, **EPoE**- triafamone 20 % + ethoxysulfuron 10 % WG at 200 g ha^{-1} on 12 DAS, **PoE**- metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1} on 25 DAS.

Using the formula herbicide efficiency index (HEI) was calculated (10):

$$HEI = ((Y_T - Y_C)/ Y_C) \div (WDM_T/ WDM_C) \quad \text{(Eqn. 2)}$$

Where, Y_T, Y_C - yield in treated plot, control plot respectively and WDM_T and WDM_C - weed dry matter in treated plot and control plot respectively in g m^{-2}. Crop resistance index (CRI) was calculated using the formula (11):

$$CRI = (CDM_T \div CDM_C) \times (WDM_C \div WDM_T) \quad \text{(Eqn. 3)}$$

Where, CDM_T -crop dry matter in treated and CDM_C -crop dry matter in control plot (g m^{-2}). WDM_T, WDM_C weed dry matter in treated and control plots, respectively. Weed persistence index (WPI) was computed using the given formula (8):

$$WPI = \frac{DMT}{DMC} \times \frac{WPC}{WPT} \quad \text{(Eqn. 4)}$$

Where, DMT - dry matter production of weeds in treated plot. DMC - dry matter production of weeds in control plot, WPC - weed population in control plot and WPT - weed population in treated plot.

Weed index (WI) was computed using the formula (12):

$$WI\ (\%) = \frac{X-Y}{X} \times 100 \quad \text{(Eqn. 5)}$$

Where, X = yield from plot with minimum weeds, Y = yield of treated plot aimed at which WI is to be worked out.

Crop management

Dry seeded rice

The field was ploughed to fine tilth and levelled for sowing of seed dressed dry paddy seeds at the rate of 40 kg ha^{-1}. Seeds were manually line sown at 3 seeds $hole^{-1}$ in a spacing of 20 cm between the intra rows, 10 cm within inter rows. Optimum sowing depth of 2-3 cm was followed and the seeds were covered by thin soil layer for appropriate germination and to avoid bird's damage.

Drum seeded rice and manual wet seeded rice

The field was ploughed to fine tilth and made to puddled condition. A total of 40 kg paddy seeds ha^{-1} were soaked in water for 24 hr and stored in gunny bags for 24 hr. The seeding drums were filled with the pre-germinated seeds up to three-fourths of its capacity and sown in the field with a spacing of 20 cm between the rows and 10 cm between the plants of rows. For manual wet seeded rice, field preparation is same as that of drum seeded rice and sprouted seeds were manually sown at 3 seeds $hole^{-1}$ with a spacing of 20 × 10 cm.

Fertilization

A fertilizer schedule of 120 : 40 : 40 NPK (nitrogen, phosphorus, potassium) kg ha^{-1} respectively was applied in the experiments of rice crop. Half of the N, full dose of P and half portion of K was applied as basal. Another 50 % each of N was top dressed in two equal splits at active tillering (AT) and panicle initiation (PI) stages. The balance 50 % of K was top dressed at PI stage. The fertilizers used were urea, single super phosphate (SSP) and muriate of potash (MOP) to supply N, P and K, respectively.

Yield

The grain from net plot was cleaned, sun dried, weighed at 14 % moisture content and the yield was computed. After separation of grains, remaining straw from the net plot were sun dried and weighed, calculated and expressed in kg ha^{-1}.

Microbial population analysis

Soil samples were taken from the individual plots at pre-sowing, 60 DAS and at post-harvest. The samples were dried, powdered and the soil water extract (SW extract) of respective treatments were cultured to assess the soil microbial populations. The SW extract at 10^{-5} and 10^{-6} concentration was inoculated in glucose agar medium, observed at 3rd day for bacterial counts. For the fungal population, extract was inoculated (at a concentration 10^{-3} and 10^{-4}) in Rose Bengal agar medium and counts were taken at 4th day. The SW extract was inoculated in Ken Knight's agar medium at a concentration of 10^{-4} and 10^{-5} and count were taken on 11th day for actinomycetes. The population of microorganisms were expressed in ten thousand CFU g^{-1} of soil. Fungi and actinomycetes were identified based on morphology. Bacteria were identified through Hewlett Packard microbial identification system. The count of microorganisms (bacteria, fungi and actinomycetes) was carried out by using serial dilution pour plate method (13).

Statistical analysis

Weed population and dry matter production data shown higher variation therefore subjected to square root transformation $\sqrt{(x+0.5)}$ and analysed. Where, statistical significance was observed the critical difference at 0.05 level of probability was computed for comparison and the non-significant comparison - indicated as 'NS'. Agres software was used for statistical analysis.

Results and Discussion

All the methods of DSR establishment and weed management practices significantly influenced weed population during *Navarai* 2021. Among the main treatments evaluated, drum seeded rice (M_2) registered the lowest individual weed population (50.24, 32.77 and 26.87 no. m^{-2} of grasses, sedges and broad-leaved weeds, respectively), total weed population (109.88 no. m^{-2}) and weed dry matter production (64.14 g m^{-2}) (Table 2). This might be due to the disturbance of weed seed bank in the puddled field, which restricts weed seed germination compared to aerobic conditions. A similar trend was also observed earlier (14). Drum seeded rice (M_2) was on par with manual wet seeded rice (M_3).

In contrast, the highest individual weed population (79.07, 51.92 and 42.53 no. m^{-2} of grasses, sedges and broad-leaved weeds, respectively), total weed population (173.52 no. m^{-2}) and weed dry matter production (102.20 g m^{-2}) were recorded under dry seeded rice (M_1). The dominance of grasses compared to sedges and broadleaved weeds in dry DSR were earlier reported (15). Favourable environment conditions for weeds due to dry tillage and aerobic conditions as flooding was absent, results in maximum share of weeds to the total biomass (16).

Regarding weed management methods, bensulfuron methyl 0.6 % + pretilachlor 6 % granules at 10 kg ha^{-1} PE on 8 DAS application, followed by metsulfuron methyl + chlorimuron ethyl 20 % WP at 20 g ha^{-1} PoE at 25 DAS and hand weeding at 45 DAS (S_8) recorded the lowest individual weed population (26.09, 16.90 and 14.01 no. m^{-2} of grasses, sedges and broad-leaved weeds, respectively), total weed population (56.99 no. m^{-2}) and weed dry matter production (32.70 g m^{-2}). This might be the fact that

Table 2. Combined effect of new generation herbicides on weed population at 60 DAS in direct seeded rice (*O. sativa* L.) during *Navarai* 2021.

Treatments	Grass weed population (no. m^{-2})	Sedge weed population (no. m^{-2})	Broad-leaved weed population (no. m^{-2})	Total weed population (no. m^{-2})	Total weed dry matter production (g m^{-2})
M_1	8.92 (79.07)	7.24 (51.92)	6.56 (42.53)	13.19 (173.52)	10.13 (102.20)
M_2	7.12 (50.24)	5.77 (32.77)	5.23 (26.87)	10.51 (109.88)	8.04 (64.14)
M_3	7.13 (50.39)	5.78 (32.86)	5.24 (26.95)	10.52 (110.19)	8.05 (64.32)
SEd	0.08	0.07	0.06	0.12	0.09
CD (p = 0.05)	0.23	0.19	0.17	0.34	0.26
S_1	11.86 (140.17)	9.44 (88.59)	8.54 (72.40)	17.37 (301.17)	13.33 (177.19)
S_2	6.38 (40.25)	5.10 (25.46)	4.61 (20.78)	9.33 (86.50)	7.10 (49.97)
S_3	8.07 (64.62)	6.65 (43.76)	6.02 (35.71)	12.02 (144.08)	9.25 (85.01)
S_4	8.13 (65.67)	6.71 (44.56)	6.06 (36.28)	12.13 (146.52)	9.32 (86.45)
S_5	8.17 (66.22)	6.74 (44.90)	6.09 (36.57)	12.17 (147.69)	9.36 (87.14)
S_6	6.95 (47.77)	5.61 (30.92)	5.12 (25 69)	10.24 (104.38)	7.84 (60.89)
S_7	7.55 (56.51)	6.10 (36.69)	5.57 (30.49)	11.14 (123.69)	8.54 (72.41)
S_8	5.16 (26.09)	4.17 (16.90)	3.81 (14.01)	7.58 (56.99)	5.76 (32.70)
S_9	5.68 (31.81)	4.62 (20.86)	4.19 (17.09)	8.38 (69.76)	6.38 (40.25)
SEd	0.17	0.14	0.12	0.25	0.19
CD (p = 0.05)	0.34	0.28	0.25	0.50	0.38

Figures in the parentheses are original values, DAS-days after sowing.

bensulfuron methyl is a sulfonylurea group of herbicides that controls the mixed weed flora at initial stages also pretilachlor control the weeds by cell division inhibition and protein synthesis inhibition and the post emergence herbicide application was effective against broad-leaved weeds, the weeds emerged at later stages was removed by hand weeding (17). It was followed by application of triafamone 20 % + ethoxysulfuron 10 % WG at 200 g ha^{-1} EPoE on 12 DAS followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1} PoE at 25 DAS and one hand weeding on 45 DAS (S_9). Twice hand weeding on 25 and 45 DAS (S_2) was next in order. The highest individual weed population (140.17, 88.59 and 72.40 no. m^{-2} of grasses, sedges and broad-leaved weeds, respectively), total weed population (301.17 no. m^{-2}) and weed dry matter production (177.19 g m^{-2}) were recorded under unweeded control (S_1). Weeds compete with the crop more because they are spontaneous, highly persistent, prolific seed producers and have wider adaptability to the adverse conditions and thus produced the higher numbers of individuals and the highest total weed dry matter production in unweeded control plots.

Weed indices

Among the main treatments evaluated, drum seeded rice (M_2) recorded the highest WCE (61.63 %), HEI (1.22) and CRI (4.30) with the lowest WPI (0.98) and WI (19.17) (Table 3). These indices were numerically almost similar to manual wet seeded rice. The lower weed population might be the reason for lower weed dry matter production thus higher WCE was achieved. HEI shows the weed killing capability of particular treatment and its phytotoxicity on crops. CRI implies the relationship between proportionate increase in crop dry matter and a proportionate reduction in weed dry matter in the treated plots. The lowest WPI in drum seeded rice compared to conventional transplanting was also observed earlier (18). The lowest WCE (47.48 %), HEI (1.11), CRI (3.24) with the highest WPI (0.99) and WI (19.71) were recorded under dry seeded rice (M_1).

Regarding weed management methods, bensulfuron methyl 0.6 % + pretilachlor 6 % at 10 kg ha^{-1} PE on 8 DAS application, followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1} PoE at 25 DAS and hand weeding at 45 DAS (S_8) recorded the highest WCE (81.19 %), HEI (3.92) and CRI (8.24) with the lowest WPI (0.97) and WI. Similar findings of WCE were earlier emphasized by some reports (19). Same trend in HEI was also mentioned earlier (20). This CRI in drum seeded rice results were associated with the previous findings (21). Weed persistence index determines the resistance of escaped weeds against the specific weed control measure, reflected variability. The minimal value of WPI shows the less resistance in weeds against the tested treatments thus confirms the efficacy of the selected herbicides(22). Application of triafamone 20 % + ethoxysulfuron 10 % WG and 200 g ha^{-1} EPoE on 12 DAS, followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1} PoE at 25 DAS and hand weeding at 45 DAS (S_9) was next in order.

Table 3. Combined effect of new generation herbicides on weed indices in direct seeded rice (*O. sativa* L.) during *Navarai* 2021.

Treatments	Weed control efficiency (%)	Herbicide efficiency index (HEI)	Crop resistance index (CRI)	Weed persistence index (WPI)	Weed index (WI)
			Main treatments		
M_1	47.48	1.11	3.24	0.99	19.71
M_2	61.63	1.22	4.30	0.98	19.17
M_3	61.57	1.20	4.27	0.98	19.35
			Sub treatments		
S_1	--	--	1.00	1.00	41.73
S_2	71.62	--	5.02	0.98	9.69
S_3	52.95	0.61	2.55	1.00	25.55
S_4	52.14	0.55	2.48	1.00	26.77
S_5	51.75	0.50	2.43	1.00	28.07
S_6	65.82	1.32	4.01	0.99	16.17
S_7	59.55	0.89	3.23	0.99	21.50
S_8	81.19	3.92	8.24	0.97	--
S_9	77.04	2.81	6.46	0.98	5.20

Data not analyzed statistically and DAS - days after sowing.

Soil microbial population

The microbial population dynamics such as, bacteria, fungi and actinomycetes of soil samples at before sowing, 60 DAS and at post -harvest was assessed (Table 4). There is no statistical difference between the establishment methods on microbial populations.

Among the weed management practices in sub treatments, the microbial populations like bacteria, fungi and actinomycetes were not affected at post-harvest of rice. There is no statistical difference between the weed management practices on soil microbial populations. Though at 60 DAS, the microbial population decreased after herbicide application, it got increased at the time of post-harvest which is even higher than initial population. These are in line with the earlier findings (22). Thus, application of herbicides at the low dose did not show any detrimental effect on soil microbial populations.

Yield

Among the main treatments evaluated, drum seeded rice (M_2) registered the highest grain yield (4824 kg ha^{-1}), (which was on par with manual wet seeded rice (M_3) (Fig. 1). Higher yield under drum seeding was due to ample supply of resources that contributed towards higher accumulation of dry matter and enhanced portioning of photosynthate resulting in greater yield traits and ultimately the yield (23). The lowest grain yield (4087 kg ha^{-1}) was recorded under dry seeded rice (M_1). This could be due to severe weed infestation and increased plant-weed competition for resources that produced lesser number of panicles and grains $panicle^{-1}$ that finally reduced grain yield. Similar trend in dry seeded rice was also observed (24, 25).

Among the weed management practices, bensulfuron methyl 0.6 % + pretilachlor 6 % at 10 kg ha^{-1} PE application at 8 DAS, followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % at 20 g/ha PoE at 25 DAS and hand weeding at 45 DAS (S_8) recorded the highest grain yield (5639 kg ha^{-1}). Judicious selection of herbicides at the right time, right quantity with the right method helped to effectively control weeds and increases the crop yield (26). Application of triafamone 20 % + ethoxysulfuron 10 % WG at 200 g ha^{-1} EPoE on 12 DAS, followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1} PoE on 25 DAS and hand weeding on 45 DAS (S_9) was next in order. Twice hand weeding on 25 and 45 DAS (S_2) was next in order. Unweeded control (S_1) resulted in the lowest grain yield (3293 kg ha^{-1}). Severe competition exerted by weeds on the crop might be the reason in lower yield obtained in unweeded plot (7). Reduction in grain yield under weedy check was mainly due to severe infestation of weeds in the crop field. The weeds grown freely reached a vigor enough to compete with crop plants for nutrients, moisture and sunlight throughout the cropping season hence, restricted the crop plants resulted in reduced crop yield to more extent (27, 28).

Table 4. Combined effect of new generation herbicides on soil microbial population in direct seeded rice (*O. sativa* L.) during *Navarai* 2021.

Treatments	Bacteria (x 10^{-6} CFU g^{-1})			Fungi (x 10^{-4} CFU g^{-1})			Actinomycetes (x 10^{-5} CFU g^{-1})		
	Before sowing	60 DAS	Post-harvest	Before sowing	60 DAS	Post-harvest	Before sowing	60 DAS	Post-harvest
M_1	9.10	8.66	9.48	5.42	5.22	5.66	3.79	3.69	3.94
M_2	9.02	8.60	9.42	5.38	5.17	5.60	3.76	3.63	3.89
M_3	8.98	8.57	9.37	5.35	5.14	5.56	3.75	3.60	3.84
SEd	0.08	0.08	0.09	0.05	0.05	0.05	0.03	0.03	0.04
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS
S_1	9.05	9.07	9.57	5.44	5.49	5.85	3.95	4.01	4.07
S_2	9.03	9.04	9.51	5.42	5.44	5.80	3.81	3.97	4.04
S_3	9.03	8.53	9.48	5.38	5.24	5.68	3.79	3.62	3.95
S_4	9.04	8.51	9.43	5.41	5.21	5.65	3.82	3.61	3.91
S_5	8.98	8.49	9.41	5.35	5.16	5.60	3.70	3.58	3.87
S_6	9.01	8.47	9.39	5.37	5.09	5.54	3.81	3.54	3.84
S_7	9.08	8.43	9.37	5.38	5.04	5.50	3.64	3.51	3.81
S_8	9.06	8.39	9.33	5.36	4.99	5.44	3.73	3.48	3.78
S_9	9.01	8.35	9.30	5.33	4.95	5.39	3.66	3.42	3.76
SEd	0.19	0.18	0.20	0.12	0.05	0.12	0.08	0.08	0.08
C.D. ($p = 0.05$)	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS-non-significant, **CFU**-colony forming unit, **DAS**-days after sowing.

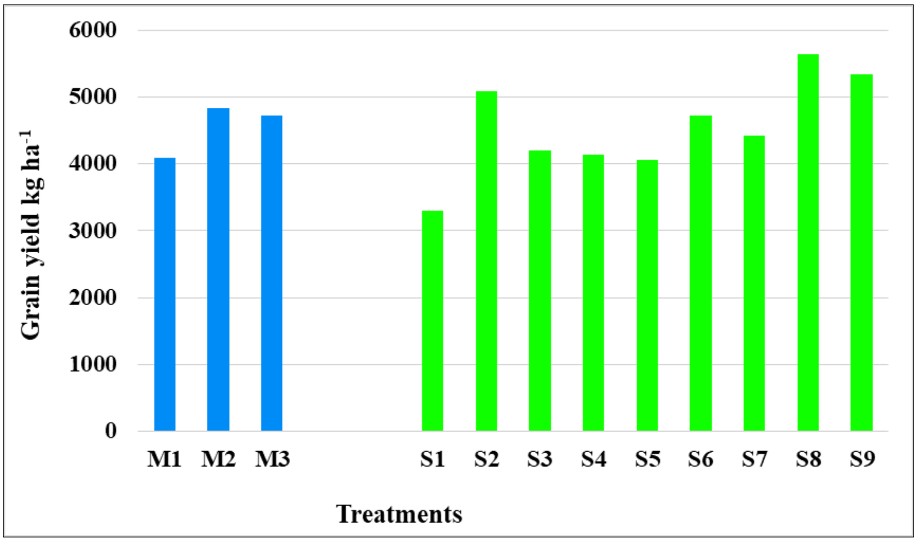

Fig. 1. Combined effect of new generation herbicides on grain yield in direct seeded rice (*O. sativa* L.) during *Navarai* 2021.

Benefit cost ratio (BCR)

Among the establishment methods drum seeded rice registered the lowest weed population and the highest yield which was on par with manual wet seeded rice. However, regarding economics drum seeded rice registered the highest BCR (2.22) (Fig. 2). Whereas manual wet seeded rice was uneconomical (BCR of 1.95) due to higher cost of cultivation compared to drum seeded rice. Therefore, drum seeded rice is a quintessential direct seeded establishment method in terms of economic feasibility compared to others.

With regards to weed management practices, bensulfuron methyl 0.6 % + pretilachlor 6 % granules at 10 kg ha^{-1} PE application at 8 DAS, followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1} PoE application at 25 DAS and hand weeding at 45 DAS (S_8) recorded the highest BCR of 2.39 (Fig. 2). The increased BCR in this treatment was chiefly due to highest grain and straw yield, lowest cost on weed control and better control of weeds during the cropping period. Higher BCR in herbicide-based weed management in wet seeded rice was earlier also reported (29). Application of triafamone 20 % + ethoxysulfuron 10 % WG at 200 g ha^{-1} EPoE on 12 DAS, followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1} PoE at 25 DAS and hand weeding at 45 DAS (S_9) was next in order. The lowest BCR (1.59) was observed under unweeded control (S_1) due to lower grain yield as the result of severe crop-weed competition. This result was accordance with the findings of earlier reports (30).

Hence, the superior weed management practices from this preliminary experiment were screened out and further field experiments were conducted as confirmatory experiments during *Kuruvai* 2021 and *Kuruvai* 2022 to evolve the suitable weed management practice for drum seeded rice.

Experiment II (*Kuruvai* 2021 and 2022)

Weed population

Among the treatments, bensulfuron methyl 0.6 % + pretilachlor 6 % application at 10 kg ha^{-1} PE at 8 DAS, followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1} PoE at 25 DAS and hand weeding at 45 DAS (T_5) recorded the lowest individual weed population, total weed population (47.49 and 58.05 no. m^{-2} during 2021 and 2022, respectively) and weed dry matter production (23.81 and 28.90 g m^{-1} during 2021 and 2022, respectively) (Table 5). This might be due to pre-emergence application of herbicides will maintain weed free condition up to 15 DAS, post-emergence herbicides may maintain weed free condition up to 35 DAS and the weeds emerged at the later stage was removed by hand weeding at 45 DAS(17). It was followed by application of bispyribac sodium 10 % SC at 250 mL ha^{-1} PoE on 20 DAS,followed by hand weeding on 45 DAS (T_3), which was on par with application of triafamone 20 % + ethoxysulfuron 10 % WG at 200 g ha^{-1} EPoE on 12 DAS, metsulfuron methyl 20 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1}PoE at 25 DAS and hand weeding at 45 DAS (T_6). The highest total weed population (211.50 and 225.22 no. m^{-2} during 2021 and 2022, respectively)

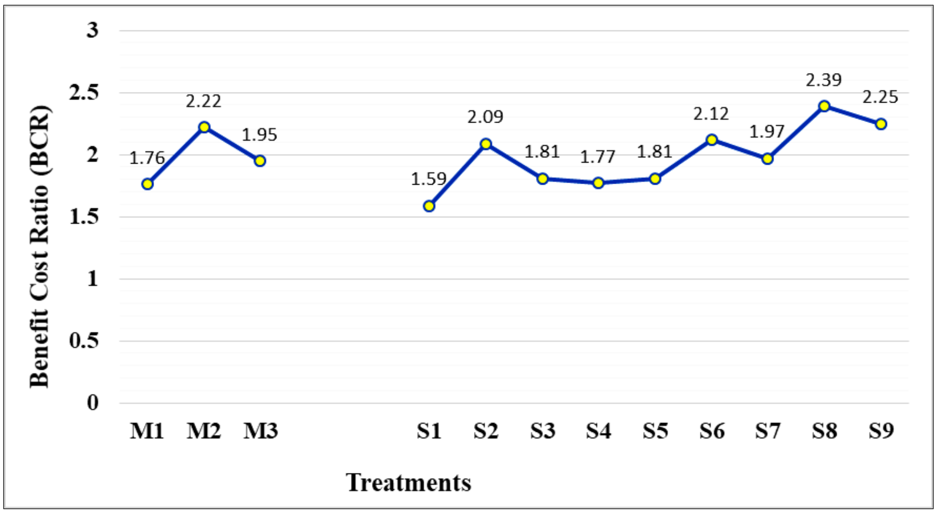

Fig. 2. Combined effect of new generation herbicides on benefit cost ratio in direct seeded rice (*O. sativa* L.) during *Navarai* 2021.

Table 5. Combined effect of new generation herbicides on weed population at 60 DAS in drum seeded rice (*O. sativa* L.) during *Kuruvai* 2021 and 2022.

Treatments	Total grass weed population (no. m^{-2})		Total sedge population (no. m^{-2})		Total broad-leaved weed population (no. m^{-2})		Total weed population (no. m^{-2})		Total weed dry matter production (g m^{-2})	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
T_1	(98.38) 9.94	(106.01) 10.32	(66.30) 8.17	(70.28) 8.41	(46.82) 6.88	(48.93) 7.03	(211.50) 14.56	(225.22) 15.02	(138.90) 11.81	(146.39)12.12
T_2	(28.20) 5.36	(35.52) 6.00	(21.09) 4.65	(26.57) 5.20	(13.57) 3.75	(17.10) 4.19	(62.86)7.96	(79.19)8.93	(33.92)5.87	(42.47)6.56
T_3	(24.90) 5.04	(31.29) 5.64	(18.13) 4.32	(23.28) 4.88	(11.43) 3.45	(13.73) 3.77	(54.46)7.41	(68.30)8.29	(28.27)5.36	(35.30)5.98
T_4	(31.80) 5.68	(41.06) 6.45	(23.62) 4.91	(30.49) 5.57	(15.57) 4.01	(20.10) 4.54	(70.99)8.46	(91.65)9.60	(39.72)6.34	(52.24)7.26
T_5	(21.78) 4.72	(27.12) 5.26	(15.98) 4.06	(19.16) 4.43	(9.73) 3.20	(11.77) 3.50	(47.49)6.93	(58.05)7.65	(23.81)4.93	(28.90)5.42
T_6	(25.10) 5.06	(31.80) 5.68	(18.47) 4.36	(23.40) 4.89	(11.59) 3.48	(14.68) 3.90	(55.16)7.46	(69.89)8.39	(28.67)5.40	(36.33)6.07
SEm±	0.13	0.15	0.11	0.13	0.09	0.11	0.20	0.21	0.15	0.17
CD(p = 0.05)	0.28	0.31	0.24	0.28	0.20	0.23	0.42	0.45	0.32	0.35

Figures in parenthesis are original values, **DAS**- days after sowing.

and total weed dry matter production (138.90 and 146.39 g m^{-1} during 2021 and 2022, respectively) were recorded under unweeded control (T_1). Weeds aggressively compete with crop because of its high growth rate, higher potential to acclimatize the fluctuating environment and efficient production of seeds are the reason for highest weed population (31).

Weed indices

Among the treatments, bensulfuron methyl 0.6 % + pretilachlor 6 % application at 10 kg ha^{-1} PE at 8 DAS, followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1} PoE at 25 DAS and hand weeding at 45 DAS (T_5) recorded the highest weed control efficiency (77.55 and 74.23 % during 2021 and 2022, respectively), herbicide efficiency index (3.77 and 3.27 during 2021 and 2022, respectively) and crop resistance index (10.00 and 8.73 during 2021 and 2022, respectively), with the lowest weed persistence index and weed index (Table 6). Herbicides applied in combination followed by hand weeding recorded the lowest weed population thus obtained the maximum weed control efficiency. The highest value of CRI indicates increased vigour of crop plant due to weed control measures (32). The lowest value of WPI might be due to the lowest persistence of escaped weeds indicating its broad-spectrum effect in controlling the weeds (33). Herbicide application enhanced the WCE and reduced WI due to restricted weed growth. Application of bispyribac sodium 10 % SC at 250 mL ha^{-1} PoE on 20 DAS, followed by hand weeding on 45 DAS (T_3) was next in order.

Soil microbial population

There was no significant difference between the different weed management practices on microbial populations like bacteria, fungi and actinomycetes in the herbicide treated plots and were not affected at post-harvest though it was slightly decreased at 60 DAS thus indicating that application of herbicides at the low dose have no detrimental effect on soil health (Table 7, 8). The similar findings were earlier also recorded (34).

Yield

Among the treatments, bensulfuron methyl 0.6 % + pretilachlor 6 % granular application at 10 kg ha^{-1} PE on 8 DAS, followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1} PoE on 25 DAS and hand weeding at 45 DAS (T_5) recorded the highest grain yield (6194 and 6112 kg ha^{-1} during *Kuruvai* 2021 and 2022, respectively) (Fig. 3). The highest grain yield with bensulfuron methyl is primarily due to reduced weed competition, minimum nutrient removal by weeds that might have improved the nutrient uptake capacity and improved the source and sink sizes, which in turn increased the yield attributes like productive tiller numbers, panicle length and filled grains (35). More photosynthates production from a greater number of effective tillers m^{-2} and dry matter partitioning (source to sink)

Table 6. Combined effect of new generation herbicides on weed indices in direct seeded rice (*O. sativa* L.) during *Kuruvai* 2021 and 2022.

Treatments	Weed control efficiency (WCE) %		Herbicide efficiency index (HEI)		Crop resistance index (CRI)		Weed persistence index (WPI)		Weed index (WI)	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
T_1	--	--	--	--	1.00	1.00	1.00	1.00	39.26	39.25
T_2	70.28	64.84	--	--	5.84	4.91	0.82	0.83	14.30	14.32
T_3	74.25	69.67	2.75	2.24	7.76	6.61	0.79	0.80	5.28	6.45
T_4	66.43	59.31	1.13	0.87	4.70	3.74	0.85	0.88	19.68	20.34
T_5	77.55	74.23	3.77	3.27	10.00	8.73	0.76	0.77	--	--
T_6	73.92	68.97	2.35	1.94	7.31	6.16	0.79	0.80	9.75	9.95

Data not analyzed statistically, **PE**-pre-emergence, **EPoE**-early post emergence, **PoE**-post emergence and **DAS**-days after sowing.

Table 7. Combined effect of new generation herbicides on soil microbial population in direct seeded rice (*O. sativa* L.) during *Kuruvai* 2021.

Treatments	Before sowing			At 60 DAS			At post-harvest		
	Bacteria (x 10^{-6} CFU g^{-1})	Fungi (x 10^{-4} CFU g^{-1})	Actinomycetes (x 10^{-5} CFU g^{-1})	Bacteria (x 10^{-6} CFU g^{-1})	Fungi (x 10^{-4} CFU g^{-1})	Actinomycetes (x 10^{-5} CFU g^{-1})	Bacteria (x 10^{-6} CFU g^{-1})	Fungi (x 10^{-4} CFU g^{-1})	Actinomycetes (x 10^{-5} CFU g^{-1})
T_1	8.80	5.72	3.84	8.84	5.75	3.88	8.92	5.80	3.93
T_2	8.76	5.64	3.80	8.80	5.70	3.85	8.86	5.78	3.89
T_3	8.73	5.70	3.74	8.68	5.66	3.71	8.80	5.75	3.82
T_4	8.70	5.64	3.70	8.63	5.59	3.69	8.78	5.70	3.77
T_5	8.64	5.56	3.71	8.57	5.52	3.66	8.73	5.68	3.74
T_6	8.66	5.59	3.64	8.51	5.46	3.60	8.69	5.66	3.69
SEd	0.20	0.12	0.08	0.19	0.12	0.08	0.21	0.13	0.09
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS

CFU-colony forming unit, **NS**-non-significant, **PE**-pre-emergence, **EPoE**-early post emergence, **PoE**-post emergence and **DAS**: days after sowing.

Table 8. Combined effect of new generation herbicides on soil microbial population in direct seeded rice (*O. sativa* L.) during *Kuruvai* 2022.

Treatments	Before sowing			At 60 DAS			At post-harvest		
	Bacteria (x 10^{-6} CFU g^{-1})	Fungi (x 10^{-4} CFU g^{-1})	Actinomycetes (x 10^{-5} CFU g^{-1})	Bacteria (x 10^{-6} CFU g^{-1})	Fungi (x 10^{-4} CFU g^{-1})	Actinomycetes (x 10^{-5} CFU g^{-1})	Bacteria (x 10^{-6} CFU g^{-1})	Fungi (x 10^{-4} CFU g^{-1})	Actinomycetes (x 10^{-5} CFU g^{-1})
T_1	8.61	5.77	3.75	8.65	5.81	3.82	8.75	5.85	3.87
T_2	8.57	5.72	3.71	8.63	5.78	3.79	8.70	5.83	3.84
T_3	8.53	5.74	3.70	8.50	5.69	3.65	8.64	5.82	3.80
T_4	8.49	5.71	3.68	8.47	5.63	3.63	8.60	5.79	3.74
T_5	8.46	5.68	3.59	8.40	5.56	3.52	8.57	5.74	3.72
T_6	8.41	5.66	3.60	8.36	5.49	3.49	8.51	5.69	3.66
SEd	0.20	0.12	0.08	0.19	0.11	0.07	0.21	0.13	0.09
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS

CFU-colony forming unit, **NS**-non-significant, **PE**-pre-emergence, **EPoE**-early post emergence, **PoE**-post emergence and **DAS**: days after sowing.

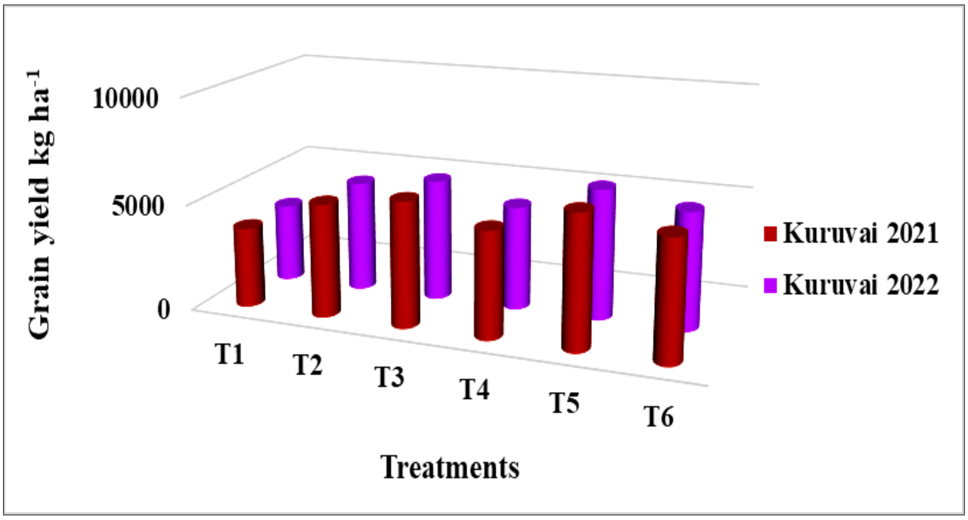

Fig. 3. Combined effect of new generation herbicides on grain yield in direct seeded rice (*O. sativa* L.) during *Kuruvai* 2021 and 2022.

might be the reason for higher grain yield (36). It was followed by application of bispyribac sodium 10 % SC at 250 mL ha^{-1} PoE on 20 DAS, followed by hand weeding on 45 DAS (T_3), which was on par with application of triafamone 20 % + ethoxysulfuron 10 % WG at 200 g ha^{-1} EPoE on 12 DAS, followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1} PoE at 25 DAS and hand weeding at 45 DAS (T_6). The lowest grain yield was recorded under unweeded control (T_1) (3762 and 3713 kg ha^{-1} during *Kuruvai* 2021 and 2022, respectively). Same trend was earlier also reported (37). Season long weed competition in wet seeded rice caused yield reduction in unweeded control (38, 39).

Benefit cost ratio (BCR)

Among the various weed management practices, bensulfuron methyl 0.6 % + pretilachlor 6 % granule application at 10 kg ha^{-1} PE at 8 DAS, followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1} PoE at 25 DAS and hand weeding at 45 DAS (T_5) recorded the highest BCR (2.78 and 2.49 during *Kuruvai* 2021 and 2022, respectively). (Fig. 4). The results showed that single herbicide use did not show any noteworthy results hence the combination of either pre and post emergence herbicides or pre and early post emergence herbicides coupled with one hand weeding was found to be an ideal and cost-effective method for effective weed management in direct seeded condition (13). Direct seeding using drum seeder significantly reduces labour dependency, thereby making it cost effective through timely intercultural operation (40). It was followed by application of bispyribac sodium 10 % SC at 250 mL ha^{-1} PoE on 20 DAS, followed by hand weeding on 45 DAS (T_3). The lowest BCR were recorded under unweeded control (1.93 and 1.73 during *Kuruvai* 2021 and 2022, respectively). The similar findings of low BCR in unweeded control were also observed (41, 42).

Conclusion

Bensulfuron methyl 0.6 % + pretilachlor 6 % granular application at 10 kg ha^{-1} PE on 8 DAS, followed by metsulfuron methyl 10 % + chlorimuron ethyl 10 % WP at 20 g ha^{-1} PoE at 25 DAS and hand weeding at 45 DAS in drum seeded rice had registered the lowest values of total weed population, total weed dry matter production, weed control efficiency, herbicide efficiency index, crop resistance index and the lowest values of weed persistence index and weed index. The highest grain yield and maximum BCR were also obtained during both the years of experiment. The treatment did not show any detrimental effect on soil microbial population Hence, this method of weed management can be recommended to achieve an environmentally safe, sustainable rice crop productivity and monetary returns in drum seeded rice.

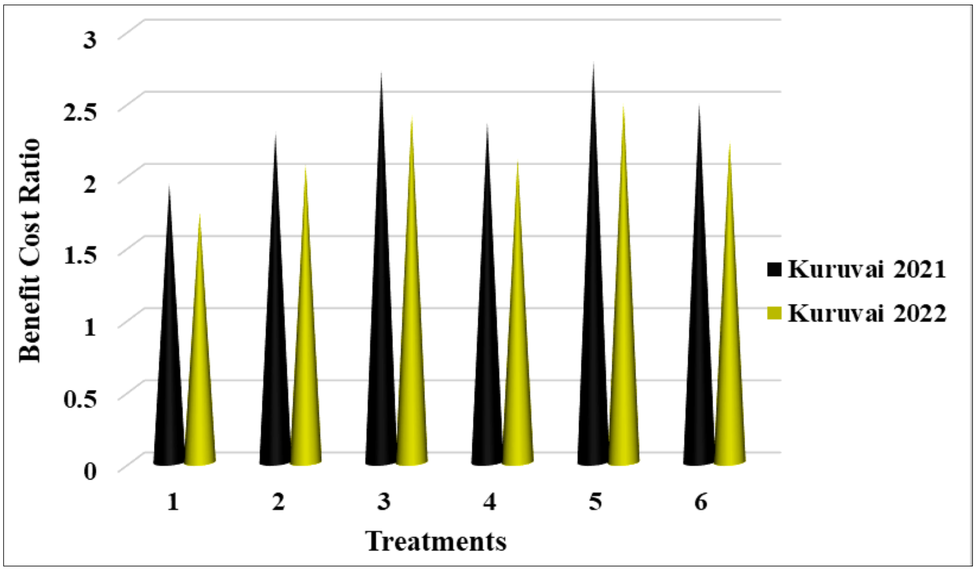

Fig. 4. Combined effect of new generation herbicides on grain yield in direct seeded rice (*O. sativa* L.) during *Kuruvai* 2021 and 2022.

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Authors' contributions

SR did the field experimentations, wrote the paper and did the analysis. SDJ edited the paper and participated in composing the original draft. SKSM and BG reviewed the manuscript and did the corrections. All the authors have read and approved the final version of the manuscript.

Compliance with ethical standards

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation, the authors used Quillbot and Grammarly to paraphrase/correct grammatical mistakes. After using this, the authors reviewed and/or edited the contents as needed and take full responsibility for the content of the published article.

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