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RESEARCH ARTICLE

Comparative efficacy of herbicide-mixtures for efficient weed management and productivity enhancement of *pre-Kharif* greengram

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ABSTRACT

Early slow growing behaviour of short-duration greengram (*Vigna radiata* L. Wilczek) makes it a poor competitor against weeds and failure to take up timely weed control measures may lead to severe yield losses. Hence, the present study was taken up during the *pre-Kharif* seasons of 2022 and 2023 at Kalyani, West Bengal with an objective to assess different herbicide-mixes for their weed managing efficiency in greengram and improving productivity and profitability. Propaquizafop (2.5%) + imazethapyr (3.75%) w/w ME (propaquizafop + imazethapyr) 125 g/ha and quizalofop-ethyl (5% EC) + imazethapyr (10% SL) (quizalofop-ethyl + imazethapyr) 50+75g/ha at 15 days after sowing (DAS) were most effective against grasses. Clodinafop-propargyl (8%) + sodium-acifluorfen (16.5%) EC (clodinafop-propargyl + sodium-acifluorfen), irrespective of doses, significantly reduced growth of broad-leaved weeds. Imazamox (35%) + imazethapyr (35%) WG (imazamox + imazethapyr) 60 g/ha was most effective in controlling sedges. Clodinafop-propargyl + acifluorfen-sodium 245 g/ha, propaquizafop +imazethapyr 125 g/ha and quizalofop-ethyl+ imazethapyr (50+75 g/ha) showed similar efficacy in reducing overall weed growth recording higher weed control efficiency. Weed management with these treatments significantly increased greengram growth traits, greengram productivity and benefit cost ratio. The principal component analysis confirmed the superiority of those treatments. The identified effective herbicide-mixtures usage would help in successful inclusion of greengram in rice-wheat systems.

Keywords: Clodinafop-propargyl + acifluorfen-sodium, Imazamox + imazethapyr, Greengram, Propaquizafop + imazethapyr, Quizalofop-ethyl + imazethapyr, Weed management

INTRODUCTION

Greengram [*Vigna radiata* (L.) Wilczek] ranks third among the prominent pulse crops in India after chickpea and pigeon pea. Every 100 g of nutrient-dense greengram seeds is enriched with 23.9 g of protein, 16.3 g of total dietary fibre, 3.32 g of ash, and 62.6 g of carbohydrate (USDA 2019). Additionally, the highly nutritive biomass of greengram makes it preferred choice for livestock feed. They are also widely grown as green manure or cover crop. Greengram can add significant nitrogen in soil by fixing 58-109 kg N/ha through symbiotic association with *Rhizobium* (Mehandi *et al*. 2019). The enhancement of soil nutrient status in pulse-based systems, along with the partial transfer of these advantages to the following crop, contributes to a reduced dependence on chemical fertilisers and assists in reducing greenhouse gas emissions. Pulses are also considered excellent crops for carbon sequestration than cereals because of their higher root biomass. Borase *et al.* (2020) found that including greengram in rice-wheat system increased soil organic carbon and microbial biomass carbon by 17% and 27%, resulting in improved soil enzyme activity. Addition of carbon-rich residues and substrates to soil facilitates diversified microbial proliferation in a pulse-based system. Therefore, inclusion of greengram into high input intensive cereal-based systems is a potential approach to establish a sustainable agro-food system.

One of the primary challenges faced by greengram farmers is weed infestation, with the extent of yield losses primarily being influenced by the composition and severity of the infesting weed flora. The critical crop weed competition period in greengram spans from 20 to 30 days after seeding (DAS). The early slow growing behaviour also makes it a poor competitor against weeds and failure to take up timely weed control measures may lead to high yield losses, occasionally reaching 90% (Azam *et al.* 2018). In India, hand weeding has been the traditional weed control measure but with summer temperatures rising to 50°C, it is becoming impossible to manually weed summer crops. The use of selective eco-safe

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herbicide-mixes can be a viable alternative for effectively managing weeds, limiting the spread or appearance of new weed species, and combat herbicide resistance. Few emerging novel post-emergence herbicides such as clodinafop-propargyl + acifluorfen-sodium, imazethapyr + imazamox, propaquizafop + imazethapyr and quizalofop-ethyl + imazethapyr were reported to effectively control weeds with a weed control efficiency of more than 87-95% in soybean and groundnut (Lakshmidevi *et al.* 2022, Sandil *et al.* 2015, Tripathi and Singh 2022). However, information on bio-efficacy of these herbicides in greengram is relatively scanty. Hence, the present experiment was taken up to identify suitable effective and economical broad-spectrum herbicide-mix to manage weeds in greengram and improve greengram productivity economically.

MATERIALS AND METHOD

The field experiment took place at District Seed Farm (AB Block), Kalyani, under Bidhan Chandra Krishi Viswavidyalaya, West Bengal, during the pre-*Kharif* season of 2022 and 2023. The farm is located at approximately 22^{0}93'N latitude and 88^{0}53'E longitude, with an average elevation of 9.75 m above mean sea level (MSL). The soil had a clay loam texture and a pH of 7.2. The recorded amounts of nitrogen (N), phosphorus (P), and potassium (K) were 250.5 kg/ha, 33.8 kg/ha, and 178.0 kg/ha, respectively. The current study utilised a randomised complete block design. Nine different weed management treatments were evaluated in summer greengram (cv 'IPM 205-7') which include: pre-emergence application (PE) of imazethapyr 10% SL (imazethapyr) 75 g/ha; post-emergence application (PoE) of imazethapyr 75 g/ha; clodinafop-propargyl (8%) + sodium-acifluorfen (16.5%) EC (clodinafop-propargyl + sodium-acifluorfen) 183.5 g/ha PoE; clodinafop-propargyl (8%) + sodium-acifluorfen (16.5%) EC (clodinafop-propargyl + sodium-acifluorfen) 245 g/ha PoE; propaquizafop (2.5%) + imazethapyr (3.75%) w/w ME (propaquizafop + imazethapyr) 125 g/ha PoE; quizalofop-ethyl (5% EC) + imazethapyr (10% SL) (quizalofop-ethyl + imazethapyr) 50+75g/ha PoE; imazamox (35%) + imazethapyr (35%) WG (imazamox + imazethapyr) 60 g/ha PoE ; hand weeding twice; unweeded check. Imazethapyr 75 g/ha (pre) was applied within 24 h of sowing, whereas the rest of the treatments having herbicide sprays were applied at 15 DAS. Two hand weedings were taken up on 20 and 35 days after seeding (DAS). All herbicide-mixes were ready-mixes, except quizalofop-ethyl + imazethapyr, which was a tank-mix. All the treatments were replicated thrice. The recommended seed rate of 25 kg/ha, with a plant spacing of 10 cm and a row spacing of 30 cm was adopted. Nitrogen (N), phosphorus (P) and potassium (K) were added at sowing time at the rate of 20, 40, and 40 kg/ha, respectively. A knapsack sprayer with a capacity of 16 litres and flat fan nozzles was used to apply herbicide. The spray volume employed was 500 litres/hectare. Thinning was done at 15 DAS to ensure even crop stand. Data on various growth parameters of weeds and crops were collected at 30, 45, and 60 DAS. Weed control efficiency (WCE), weed control index (WCI) and weed index (WI) were calculated according to Singh *et al*. (2018). Additionally, yield and yield related characters were recorded during harvest. Crude protein was estimated by multiplying seed nitrogen concentration (Jackson 1973) with 6.25. The benefit-cost ratio (B:C) was calculated by dividing the gross income by the cost of cultivation. The statistical analysis was done on the pertinent experimental data using analysis of variance (ANOVA) for randomised complete block design (RCBD). An ANOVA was conducted specifically for the weed density and dry matter (biomass) data, following a square root transformation ($\sqrt{x+0.5}$). The ANOVA of the experimental data showed no statistically significant change (p=0.05) among the years, treatments, and interactions between years and treatments. Hence, the study presents the mean data from two consecutive years. The treatment means were compared at p=0.05 using the Least Significant Difference (LSD) method. SPSS version 25 software was utilised to calculate the necessary regression models. The principal component analysis was done using the PCA function of FactoMineR package in R software version 4.4.0.

RESULTS AND DISCUSSION

Weeds response

The most prominent grassy weeds during the experimental period were *Cynodon dactylon, Setaria glauca*, *Leptochloa chinensis*, *Eleusine indica*, *Imperata cylindrica*, and *Digitaria sanguinalis*. The broad-leaved weeds included *Phyllanthus niruri*, *Euphorbia hirta*, *Parthenium hysterophorus* and *Digera muricata*. The only sedge weed was *Cyperus rotundus*. Throughout the experimental period, grassy weeds ranked first in dominance followed by broad-leaved weeds and sedges (**Table 1**). The experimental crop was included in a rice-based system in a lowland situation, which likely led to a prevalence of grassy weeds. According to Walia and Singh (2006), grassy weeds dominated the widely practiced intensive cereal-based systems in India.

Hand weeding twice had significantly lowest density of grasses, broad-leaved and sedges (**Table 1**). Out of the various tested herbicides, propaquizafop + imazethapyr 125 g/ha PoE and quizalofop-ethyl + imazethapyr 50+75g/ha PoE were most efficient in suppressing grassy weeds. They reduced grass weed density by 84.2-85.5% and 82.3-84.7% compared to weedy check on 25 and 45 DAS, respectively. Clodinafop-propargyl + sodium-acifluorfen at 245 g/ha significantly lowered (79.6–84.5% compared to weedy check) broad-leaved weed density among the evaluated herbicides. No significant difference occurred in broad-leaved density between lower dose (183.5 g/ha) and higher dose (245 g/ha) of clodinafop-propargyl + sodium-acifluorfen on 25 DAS. However, on 45 DAS, application of higher dosage resulted in a significant decline in broad-leaved weed density by 22.2% as compared to its lower dose. Imazamox + imazethapyr at 60 g/ha, caused most significant reduction in sedge population compared to all other herbicide treatments. This ready-mix registered 50.0-54.7% lower sedge density than weedy check. Also, all the treatments comprising imazethapyr were statistically comparable in their ability to control sedge density.

Hand weeding twice had the lowest weed biomass of all weed types. Among the tested herbicides, propaquizafop + imazethapyr recorded the lowest grass biomass on 25 DAS, which was closely followed by quizalofop-ethyl + imazethapyr 50+75g/ha PoE and clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE (**Table 2**) which reduced grassy weed biomass by 83.2-85.4%, as compared to weedy check. Almost a similar trend was noted on 45 DAS as well. Clodinafop-propargyl + sodium-acifluorfen at 245 g/ha recorded the highest efficacy against broad-leaved weeds, as evident from their significantly lower biomass. Increasing the dosage of clodinafop-propargyl + sodium-acifluorfen from 183.5 g/ha to 245 g/ha reduced the broad-leaved weeds biomass by 22.9-33.9%. Herbicides containing imidazolinone significantly reduced sedge biomass on 25 DAS, with no significant difference between them. However, on 45 DAS, imazamox-imazethapyr was most effective in suppressing sedge biomass.

Hand weeding twice registered the highest weed control efficiency (WCE) and weed control index (WCI) of 95.1-95.2 and 97.1-97.4% during the crop growing period (**Table 1** and **2**). Among the various tested herbicides, propaquizafop + imazethapyr and quizalofop-ethyl + imazethapyr had considerably higher WCE of 77.0-77.6% on 25 DAS and 71.7-73.5% on 45 DAS. The next best was clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE, which also consistently recorded a comparatively higher WCE of 70.5-74.1% during the crop life cycle. Following almost a similar trend, WCI in these three herbicide-mixes ranged from 79.2-80.1% and 75.2-78.1% on 25 and 45 DAS, respectively. They also recorded substantially lower weed index (WI) of 10.1-14.1%. Herbicides having higher WCI and WCE but lower WI exhibit greater efficiency in limiting weed growth.

Table 1. Weed density (no./m^2) under different weed control treatments in greengram (mean of two years)

Treatment	30 DAS				45 DAS				WCE (%)	
	Grasses	Broad-leaved	Sedges	Total	Grasses	Broad-leaved	Sedges	Total	25 DAS	45 DAS
Imazethapyr 75 g/ha PE	5.89 (34.2)	4.34 (18.4)	2.77 (7.2)	7.76 (59.8)	6.64 (43.6)	5.54 (30.2)	3.75 (13.6)	9.37 (87.4)	65.8	60.3
Imazethapyr 75 g/ha PoE	5.64 (31.4)	4.16 (16.8)	2.91 (8.0)	7.53 (56.2)	6.92 (47.4)	5.48 (29.6)	3.80 (14.0)	9.56 (91.0)	67.8	58.6
Clodinafop-propargyl + sodium-acifluorfen 183.5 g/ha	5.09 (25.4)	3.56 (12.2)	3.56 (12.2)	7.09 (49.8)	6.09 (36.6)	4.70 (21.6)	4.18 (17.0)	8.70 (75.2)	71.5	65.8
Clodinafop-propargyl + sodium-acifluorfen 245 g/ha	4.66 (21.2)	3.30 (10.4)	3.75 (13.6)	6.76 (45.2)	5.59 (30.8)	4.16 (16.8)	4.20 (17.2)	8.08 (64.8)	74.1	70.5
Propaquizafop + imazethapyr 125 g/ha	3.78 (13.8)	4.18 (17.0)	2.98 (8.4)	6.30 (39.2)	4.64 (21.0)	5.37 (28.4)	3.64 (12.8)	7.92 (62.2)	77.6	71.7
Quizalofop-ethyl + imazethapyr (50+75g/ha)	3.94 (15.0)	4.25 (17.6)	2.84 (7.6)	6.38 (40.2)	4.32 (18.2)	5.24 (27.0)	3.67 (13.0)	7.66 (58.2)	77.0	73.5
Imazamox + imazethapyr 60 g/ha	5.30 (27.6)	3.79 (13.8)	2.51 (5.8)	6.91 (47.3)	6.27 (38.8)	4.97 (24.2)	3.15 (9.4)	8.53 (72.4)	73.0	67.1
Hand weeding twice	2.21 (4.4)	1.87 (3.0)	1.22 (1.0)	2.98 (8.4)	2.39 (5.2)	2.02 (3.6)	1.58 (2.0)	3.36 (10.8)	95.2	95.1
Unweeded check	9.77 (95.0)	8.21 (67.0)	3.64 (12.8)	13.24 (174.8)	10.92 (118.8)	9.10 (82.4)	4.39 (18.8)	14.85 (220.0)	-	-
LSD (p=0.05)	0.3	0.27	0.23	0.46	0.36	0.36	0.27	0.56		

*Data square root transformed. Values in parentheses indicate the original weed count; WCE: Weed control efficiency; PE = pre-emergence application; PoE = post-emergence application; DAS = days after seeding

In the current study, herbicide mix comprising imazethapyr and propaquizafop /quizalofop-ethyl were found to effectively check grassy weed population and density. The ready-mix clodinafop-propargyl + acifluorfen-sodium also demonstrated significant efficacy against grasses. The "fops" herbicides present in these herbicide-mixes, *viz*. propaquizafop, quizalofop-ethyl, and clodinafop-propargyl, are aryloxy-phenoxypropionate herbicides. They are commonly employed for broad-spectrum management of a variety of annual and perennial grassy weeds. These herbicides specifically inhibit the functioning of the eukaryotic-type Acetyl-CoA-carboxylase enzyme in the chloroplasts of susceptible grasses (Takano *et al.* 2020). The ready-mix clodinafop-propargyl + acifluorfen-sodium at a higher dose showed maximum efficacy against broad-leaved weeds. The constituent acifluorfen-sodium of this ready-mix is a diphenyl-ether herbicide, which is reported to restrict the proliferation of broad-leaved weeds (Tang *et al.* 2020). It obstructs the function of protoporphyrinogen oxidase in susceptible plants, ultimately resulting in cell membrane rupture (Lewis *et al.* 2016). The ready-mix imazamox + imazethapyr effectively suppressed sedges. Plots treated with imazethapyr also showed a significant decline in sedge growth compared to the weedy check. Both imazethapyr and imazamox are classified as imidazolinone herbicides and are reported to control wide spectrum of weeds, especially grasses and broad-leaved weeds. They control weed growth by hindering the function of acetohydroxy acid synthase, which is a critical enzyme for production of branched-chain amino acids (Auria *et al.* 2022). However, it has been documented that both imazethapyr (Grichar 2002) and imazamox (USDA 2010) effectively manage sedges, as observed in this study. Since grasses were the pre-dominant weed type in the current experiment followed by broad-leaved weeds, herbicide-mixes targeted to control both these plant types were observed to be superior in managing overall weed growth.

Greengram response

Hand weeding twice recorded the tallest crop with highest leaf area index (LAI) throughout the crop growing period. The greengram plant height, and LAI with propaquizafop + imazethapyr and quizalofop-ethyl + imazethapyr were considerably higher than other herbicide treatments and no significant difference was found between them. However, they were statistically at par with clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE in terms of crop height on 50 DAS (**Table 3**). These two treatments recorded higher LAI values on the other two dates of observation as well, but were statistically at par with clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE and imazamox + imazethapyr on 30 DAS and clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE on 50 DAS.

Among the tested weed management interventions, hand weeding twice significantly augmented dry matter accumulation on 30 and 40 DAS (**Table 3**). On 50 DAS also, hand weeding twice recorded the highest biomass accumulation (327.2 g/m^2), but it was statistically equivalent with

Table 2. Weed biomass (g/m^2) under different weed control treatments in greengram (mean of two years)

Treatment	30 DAS				45 DAS				WCI (%)	
	Grasses	Broad-leaved	Sedges	Total	Grasses	Broad-leaved	Sedges	Total	25 DAS	45 DAS
Imazethapyr 75 g/ha PE	5.85 (33.8)	3.83 (14.2)	2.50 (5.8)	7.36 (53.7)	6.30 (39.2)	4.99 (24.5)	3.41 (11.2)	8.68 (74.9)	69.1	65.3
Imazethapyr 75 g/ha PoE	5.99 (35.4)	3.69 (13.1)	2.67 (6.6)	7.46 (55.1)	6.60 (43.1)	4.81 (22.7)	3.48 (11.6)	8.82 (77.5)	68.3	64.0
Clodinafop-propargyl + sodium-acifluorfen 183.5 g/ha	4.91 (23.6)	3.42 (11.2)	3.46 (11.5)	6.84 (46.3)	5.70 (32.0)	4.14 (16.6)	4.10 (16.3)	8.09 (65.0)	73.4	69.8
Clodinafop-propargyl + sodium-acifluorfen 245 g/ha	4.10 (16.3)	2.81 (7.4)	3.52 (11.9)	6.01 (35.6)	4.92 (23.7)	3.65 (12.8)	4.17 (16.9)	7.34 (53.4)	79.5	75.2
Propaquizafop + imazethapyr 125 g/ha	3.83 (14.2)	3.75 (13.6)	2.68 (6.7)	5.91 (34.5)	4.08 (16.2)	4.88 (23.3)	3.30 (10.4)	7.09 (49.9)	80.1	76.9
Quizalofop-ethyl + imazethapyr (50+75g/ha)	4.00 (15.5)	3.87 (14.5)	2.59 (6.2)	6.06 (36.2)	3.86 (14.4)	4.76 (22.1)	3.34 (10.7)	6.90 (47.2)	79.2	78.1
Imazamox + imazethapyr 60 g/ha	4.81 (22.7)	3.63 (12.7)	2.53 (5.9)	6.46 (41.3)	5.60 (30.9)	4.69 (21.5)	2.88 (7.8)	7.79 (60.2)	76.2	72.0
Hand weeding twice	1.61 (2.1)	1.55 (1.9)	1.02 (0.5)	2.24 (4.5)	1.76 (2.6)	1.70 (2.4)	1.30 (1.2)	2.59 (6.2)	97.4	97.1
Unweeded check	9.88 (97.3)	8.13 (65.7)	3.36 (10.8)	13.19 (173.8)	10.96 (119.7)	8.98 (80.3)	3.99 (15.4)	14.69 (215.4)	-	-
LSD (p=0.05)	0.38	0.29	0.19	0.51	0.34	0.33	0.23	0.51		

*Data square root transformed. Values in parentheses indicate the original weed dry matter; WCI: Weed control index; PE = pre-emergence application; PoE = post-emergence application; DAS = days after seeding clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE, propaquizafop + imazethapyr and quizalofop-ethyl + imazethapyr. Although the biomass with these three treatments on 30 and 40 DAS were significantly lower than the hand weeding, the values were significantly higher than the other tested herbicides.

Reduced crop-weed competition with application of clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE, propaquizafop + imazethapyr and quizalofop-ethyl + imazethapyr, as also evident from their substantially higher WCE and WCI in this study, might have improved resource utilization by the crop, which eventually led to crop height, biomass accumulation and leaf area development. Maji *et al*. (2020) also observed a significant decrease in leaf area index and crop growth traits as weed density increased. Intense weed pressure can adversely affect leaf traits such as leaf water potential, turgor pressure, stomatal conductance, and photosynthesis (Singh *et al.* 2022).

Nodulation

Hand weeding twice recorded the highest nodule number (36.4 nos./plant), which was closely followed by propaquizafop + imazethapyr and (35.6 nos./plant), clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE (35.0 nos./plant), and quizalofop-ethyl + imazethapyr (34.8 nos./plant) (**Table 3**). No significant difference was noted between these treatments. The nodule weights in these treatments were also statistically equivalent and varied between 33.9-36.3 mg/plant. Weed suppression in these treatments might have reduced weed-microbe competition for soil resources (Kato-Noguchi 2022), which likely led to improved nodulation. By limiting the growth of weeds, it is also possible to promote root growth through the efficient utilisation of soil nutrients. This, in turn, can offer sufficient infection sites for *Rhizobium* mediated nodulation. The unweeded check recorded significantly lower nodulation traits compared to all the other treatments. Allelochemicals exuded by the roots of weeds hinder nodulation (Chaniago *et al.* 2012). This might have led to poor nodulation characteristics in the weedy check treatment of the current study.

Greengram yield attributes, yield, and protein content

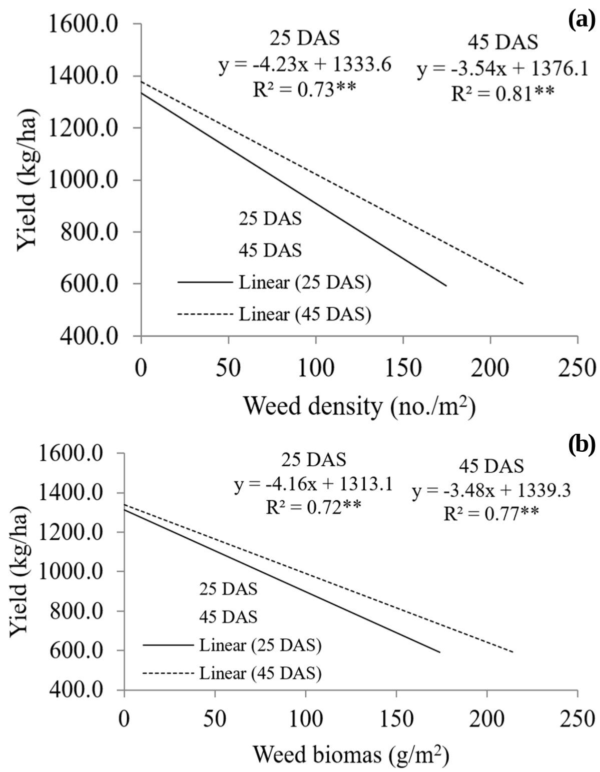
Hand weeding twice produced considerably higher number of pods/plant and seeds/pod (**Table 4**). Among the herbicidal measurements, quizalofop-ethyl + imazethapyr recorded highest pods closely followed by propaquizafop + imazethapyr and clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE. The pod-bearing capacities of these three treatments were noted to be statistically equivalent. Clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE recorded the highest number of seeds/pod among the herbicidal treatments, and it was statistically comparable to clodinafop-propargyl + sodium-acifluorfen) 183.5 g/ha PoE. No significant difference in seeds/pod was noted among the imazethapyr-constituting treatments. The herbicide treatments containing imazethapyr had significantly higher seed index in comparison to rest of the treatments. Interestingly, all the imidazolinone treated plots (22.5%-22.8%) had significantly lower protein content than hand weeding (24.4%). It has been reported that imazethapyr, by inhibiting acetohydroxy acid synthase, leads to a higher starch to protein ratio in seeds, resulting in larger seed size (Scarponi *et al.* 1997). This highlights the crucial need to determine the appropriate dosage of imidazolinone herbicides for each specific crop.

Hand weeding twice produced highest biological yield, with clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE, propaquizafop +

Table 3. Greengram growth parameters under different weed control treatments (mean of two years)

Treatment	Crop height (cm)			Leaf area index			Total dry matter (g/m^2)			Nodule no. /plant	Nodule weight (mg)
	30 DAS	40 DAS	50 DAS	30 DAS	40 DAS	50 DAS	30 DAS	40 DAS	50 DAS	40 DAS	
Imazethapyr 75 g/ha PE	14.9	26.4	34.5	1.05	1.96	2.50	121.2	188.6	244.4	29.6	22.0
Imazethapyr 75 g/ha PoE	15.6	27.7	34.8	1.02	2.04	2.58	123.1	184.8	245.3	30.0	23.1
Clodinafop-propargyl + sodium-acifluorfen 183.5 g/ha	17.4	32.0	39.2	1.10	2.31	2.93	136.7	216.0	293.1	31.8	28.5
Clodinafop-propargyl + sodium-acifluorfen 245 g/ha	18.4	35.1	46.9	1.17	2.29	3.29	155.5	231.2	309.6	35.0	33.9
Propaquizafop + imazethapyr 125 g/ha	21.9	37.6	47.6	1.21	2.62	3.56	147.6	226.7	304.8	35.6	36.3
Quizalofop-ethyl + imazethapyr (50+75g/ha)	21.5	38.2	49.3	1.24	2.70	3.41	159.0	230.9	302.5	34.8	34.8
Imazamox + imazethapyr 60 g/ha	19.0	32.3	41.4	1.15	2.37	3.05	137.8	211.4	280.7	33.0	30.1
Hand weeding twice	23.1	41.5	53.7	1.26	2.84	3.87	184.4	257.2	327.2	36.4	35.6
Unweeded check	12.8	22.8	30.0	0.89	1.68	2.14	106.9	159.1	208.9	20.2	18.7
LSD (p=0.05)	1.6	3.0	3.8	0.10	0.21	0.28	12.7	22.0	33.1	2.7	2.4

PE = pre-emergence application; PoE = post-emergence application; DAS = days after seeding



** Regression equation significant at $p \leq 0.01$.

Figure 1. Relationship between weed density and biomass and seed yield

imazethapyr, and quizalofop-ethyl + imazethapyr following closely behind (**Table 4**). These treatments exhibited statistically equivalent biological yields. Among the herbicidal treatments, application of quizalofop-ethyl + imazethapyr produced highest seed yield, which was statistically equivalent to propaquizafop + imazethapyr and clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE. A comparatively lower weed pressure and reduced competition for available resources in the herbicide-treated plots might have improved productivity. An inverse relationship between weed growth and yield is also apparent from regression analysis, which showed that weed density and weed biomass accounted for 73.0-81.0% and 72.0-77.0% variation in seed yield respectively (**Figure 1**). The hand weeding twice recorded the highest harvest index (HI) of 0.35. The HI in all the weed control measures *i.e.,* hand weeding twice and herbicidal treatments was statistically equivalent. This indicated that arresting weed growth offered favourable environment for resource utilization, which facilitated assimilation and redistribution of photosynthates from vegetative biomass to seeds.

Principal component analysis

A principal component analysis was performed on the different growth characters, yield attributing characters and yield of greengram along with WCE and WCI resulting from the different herbicide mixes (**Figure 2**). The first two principal components (PC 1 and PC 2) together accounted for 93.9% of the variability in the data with their individual contribution being 87.3% and 6.6% respectively. The contribution to PC 1 was the highest for yield, number of nodules per plant, total plant dry matter at 50 DAS and WCE at 45 DAS (9.5, 9.2, 9.0 and 8.8%). However, nodule dry weight per plant, plant height at 50 DAS, WCE and WCI at 25 DAS contributed the most to PC 2 (14.8, 14.2, 14.2 and 13.9%). The PCA in the present context helped to better visualise the difference between the treatments and the relatively more important characters contributing towards this difference were identified. The herbicide-mixes clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE, propaquizafop + imazethapyr, quizalofop-ethyl + imazethapyr (**Figure 2**) are in close proximity along the PC1 axis, having the highest positive values after hand weeding twice. Thus, apart from hand weeding

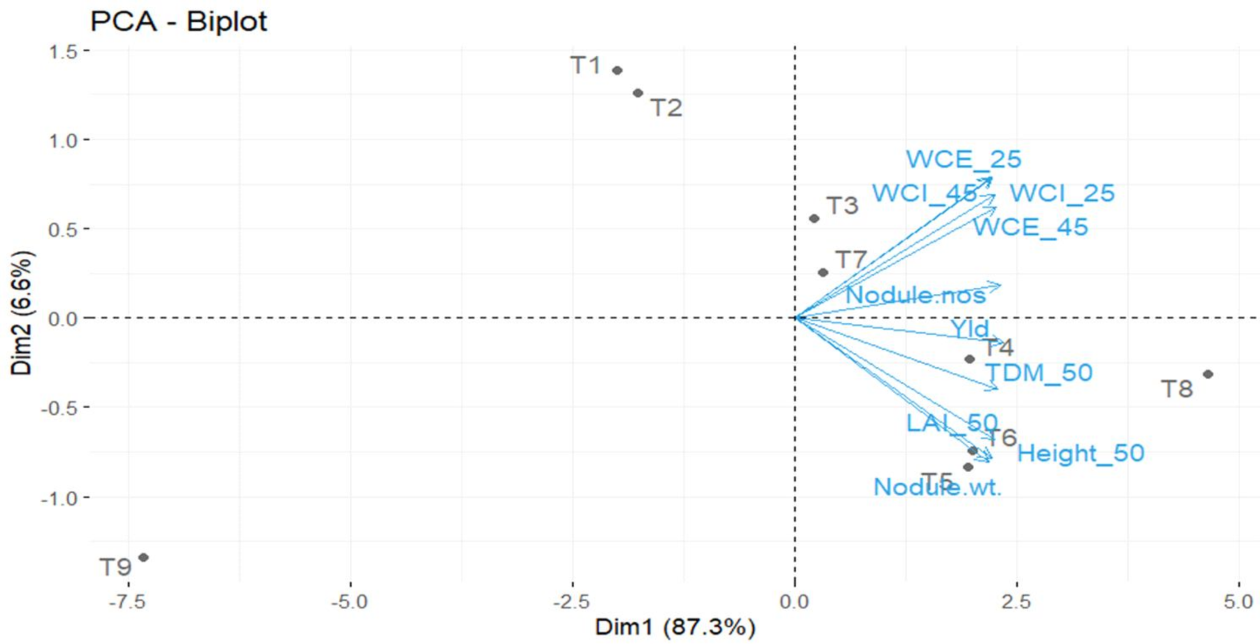
Table 4. Greengram yield traits, yield, crude protein and weed index under different weed control treatments (mean of two years)

Treatment	Pods/ plant	Seeds/ pod	Hundred seed weight (g)	Seed yield (kg/ha)			Biological yield (kg/ha)			Harvest index	Crude protein (%)	Weed index (%)
				2022	2023	Pooled	2022	2023	Pooled			
Imazethapyr 75 g/ha PE	7.8	7.4	3.30	836	942	889	2777	3009	2893	0.31	22.80	36.4
Imazethapyr 75 g/ha PoE	8.0	7.8	3.26	869	941	905	2719	2945	2832	0.32	22.60	35.1
Clodinafop-propargyl + sodium-acifluorfen 183.5 g/ha	9.4	9.2	2.89	1022	1064	1043	3407	3547	3477	0.30	23.80	25.2
Clodinafop-propargyl + sodium-acifluorfen 245 g/ha	10.4	9.8	2.97	1160	1232	1196	3626	3850	3738	0.32	23.90	14.2
Propaquizafop + imazethapyr 125 g/ha	10.8	7.2	3.32	1173	1271	1222	3553	3849	3701	0.33	22.70	12.4
Quizalofop-ethyl + imazethapyr (50+75g/ha)	11.5	7.6	3.31	1279	1229	1254	3763	3615	3689	0.34	22.80	10.1
Imazamox + imazethapyr 60 g/ha	9.6	7.8	3.33	1017	1125	1071	3178	3512	3345	0.32	22.50	23.2
Hand weeding twice	14.2	10.2	3.08	1437	1353	1395	4106	3866	3986	0.35	24.40	-
Unweeded check	6.0	6.6	2.60	549	467	508	2437	2209	2323	0.22	21.60	63.6
LSD (p=0.05)	1.29	0.9	0.24	179.3	189.2	125.35	442.2	467.5	446.96	0.05	1.44	

PE = pre-emergence application; PoE = post-emergence application

Table 5. Economic analysis under different weed control treatments in greengram (mean of two years)

Treatment	Gross returns (Rs. /ha)	Net returns (Rs./ha)	B:C ratio
Imazethapyr 75 g/ha PE	58301	20233	1.53
Imazethapyr 75 g /ha PoE	59350	21282	1.56
Clodinafop-propargyl + sodium-acifluorfen 183.5 g/ha	68400	30004	1.78
Clodinafop-propargyl + sodium-acifluorfen 245 g/ha	78434	39605	2.02
Propaquizafop + imazethapyr 125 g/ha/ha	80139	39645	1.98
Quizalofop-ethyl + Imazethapyr (50+75) g/ha	82237	42320	2.06
Imazamox + Imazethapyr 60 g/ha	70236	30992	1.79
Hand weeding twice	91484	46395	2.03
Unweeded check	33315	-2700	0.93



T1: imazethapyr 75 g/ha (PE), T2: imazethapyr 75 g/ha (PoE), T3: clodinafop-propargyl + sodium-acifluorfen 183.5 g/ha, T4: clodinafop-propargyl + sodium-acifluorfen 245 g/ha, T5: propaquizafop + imazethapyr 125 g/ha, T6: quizalofop-ethyl + imazethapyr (50+75 g/ha), T7: imazamox + imazethapyr 60 g/ha, T8: hand weeding twice, T9: unweeded check

Figure 2. PCA biplot of principal components (PC 1 and PC 2) for WCE, WCI, growth and yield characters in greengram (graph showing the top 10 variables based on contributions to PCs)

twice, these treatments had better performance especially in terms of those characters which contributed more to PC1, *viz*. yield, no. of nodules, WCE at 45 DAS, etc. and were on the same side (positive) of the PC 1. The herbicide treatments are clustered in 3 groups indicating similarity in performance of treatments within each group. Unweeded check remained on the far negative side on both axes due to poor performance than others.

Economics

Among all weed control treatments applied in the experiment, the highest net return was obtained with hand weeding twice (Rs. 46,395 /ha) followed by herbicidal treatment quizalofop-ethyl + imazethapyr (Rs. 42,320 /ha) (**Table 5**). A loss in crop production (Rs. -2700 /ha) recorded in unweeded check indicates that failure to manage weeds could result in significant economic losses. The maximum benefit-cost ratio was noted in treatment quizalofop-ethyl + imazethapyr (2.06), closely followed by hand weeding twice (2.03) and clodinafop-propargyl + sodium-acifluorfen 245 g/ha PoE (2.02). Intensive labour investment in the hand-weeded plots likely lowered the B:C ratio despite the edge earned in yields and net returns over other treatments.

Conclusion

The present study highlights the importance of timely weed treatment in greengram to improve crop growth and productivity by reducing weed-induced stress in the field. Successful adoption of greengram in grass-dominated cereal-based systems can be encouraged by using any of the following post-emergence broad-spectrum herbicide-mixtures, *viz*. clodinafop-propargyl + sodium-acifluorfen (245 g/ha), propaquizafop + imazethapyr (125 g/ha), and quizalofop-ethyl + imazethapyr (50+75 g/ha), as they are particularly effective against grassy weeds.

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