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Effective weed control through post-emergence herbicides to enhance blackgram (*Vigna mungo* L.) productivity in South India

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Pulses are essential components of vegetarian diet and play a pivotal role in addressing malnutrition by providing a vital source of dietary protein. However, weed competition remains as a significant obstacle to blackgram (*Vigna mungo* L) production, resulting in 25 to 35% yield losses. A field experiment was carried out at the National Pulses Research Centre, Tamil Nadu Agricultural University, Vamban, Pudukkottai, India during *Kharif* seasons of 2020 and 2021, to assess the suitable post-emergence herbicides for appropriate weed control in blackgram grown under irrigated conditions. The experimental field was observed to contain notable grass weed flora, specifically *Dactyloctenium aegyptium* and *Chloris barbata*, as well as broadleaved weeds, such as *Flaveria australica*, *Cleome gynandra*, *Eclipta alba*, *Convolvulus arvensis*, *Digera arvensis*, *Vicia* spp., and *Celosia argentea*. The results demonstrated that among the chemical weed management methods, spraying of Fomesafen @ 220 g + Fluzifop p-butyl @ 220 g ha^{-1} at 20 days after sowing (DAS) as a post-emergence herbicide treatment exhibited superior weed control efficiency, recording 66.80% and 68.53% at 30 and 45 DAS, respectively and recorded higher seed yield of 1088 kg ha^{-1}. Additionally, this method generated 8.1% higher net income and 12.5% more benefit–cost ratio than hand weeding, making it an economically profitable strategy for maximizing blackgram yield and effective labour management.

Keywords Blackgram, Post-emergence herbicide, Herbicide mixture, Weed control, Productivity enhancement, Economic profitability

Pulses are regarded as 'poor man's protein source,' containing 20–25% of protein and play a significant role in worldwide vegetarian diet[1–3]. Furthermore, they contribute environmental preservation by enhancing soil health. From the late twentieth century to the first decade of the twenty-first century, global pulses production experienced a consistent annual growth rate of 1.3%[4,5]. In recent years, the demand for pulses has been on a consistent upward trajectory, resulting in a growing disparity between production and consumption. This gap is poised to expand further due to an escalating global population, leading to increased consumption rates. By 2050, India, the world's second most populous nation, will require approximately 39 million metric tons of pulses annually. Achieving this demand will necessitate an annual growth rate of 2.2%, as per the data from Statista in 2022[5]. To bridge the growing demand and raise the per capita availability of pulses, countries made efforts to increase production and explore trade opportunities to augment domestic supply.

Blackgram (*Vigna mungo* L.), a prized pulse known for its high phosphoric acid content (2.85 to 23.6 mg/grams), holds a significant position in global agriculture. India is the highest producer of blackgram, sharing 70% of the worldwide production, with Myanmar and Pakistan following closely[6]. This leguminous crop is a nutritional powerhouse, boasting a composition of 48.0 and 22. 3% carbohydrates and protein, respectively; 154 mg of calcium, 9.1 mg of iron, 1.4 g of fat, 0.37 g of riboflavin, and 0.42 mg of thiamine per 100 g of

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blackgram[7]. The significance of blackgram cultivation in India is underscored by the nation's extensive pulse cultivation, covering 28.78 million hectares, yielding 25.46 million tonnes, and averaging 885 kg ha^{-1} in productivity[8]. In Tamil Nadu, blackgram cultivation encompasses an area of 0.407 million hectares, with an annual production of approximately 0.269 million tonnes and productivity of 660 kg ha^{-19}.

Despite the prominence of blackgram cultivation in India, its average productivity remains suboptimal, attributed to various factors such as subpar management practices, limited adoption of improved varieties and recommended techniques, climatic challenges like temperature and soil moisture stress, and various factors, namely physiology, biochemistry, and inherent crop-related factors[10–12]. Among these impediments, weed infestation is a significant hurdle[13]. Weeds, thriving in the hot and humid weather of blackgram cultivation, outpace crop growth, engaging in fierce competition for essential inputs, namely light, moisture, fertilizers and crop geometry, ultimately causing substantial reductions in blackgram yields[14].

Weed growth often coincides with blackgram germination, leading to early-stage competition for resources. This competition can severely hinder blackgram development, as both the crop and weeds vie for essential nutrients, water, and light. The early-stage competition between blackgram and weeds is particularly concerning because it can significantly impact on crop yields.[15]. Unchecked weed proliferation in blackgram fields can result in substantial yield losses, which can range from 27% to a staggering 100%. Such losses can have a severe economic impact on farmers and food production, particularly in regions where blackgram is a staple crop[16,17]. In most cases hand weeding is practiced for weed control but it is tedious, expensive, time-consuming and labour-intensive. Unpredictability of wet field conditions during the rainy season and labour scarcity during weed removal stage are posing problems for effective weed management. Moreover, timely manual weeding is not possible because of the moist field conditions brought on by the rain.

To address these challenges, it is crucial to implement effective weed management strategies, especially during the critical period when the crop is in direct competition with weeds. In the case of *kharif* blackgram cultivation, crop weed competition phase typically occurs from 12 to 35 DAS[18,19]. During this period, it is essential to employ practices and techniques that can help control weed growth and minimize competition with the crop, such as the use of selective herbicides, mechanical weeding, or other integrated weed management approaches. By doing so, farmers can mitigate yield losses, reduce the environmental impact of herbicides, and prevent the development of herbicide-resistant weeds, ultimately ensuring the success of their blackgram crop[12]. Moreover, herbicide control could be an alternate method for managing the weeds and boosting the yield of blackgram[20]. Applying pre- and post-emergence herbicides sequentially or in conjunction with manual weeding may be more advantageous than applying a single herbicide, as this latter may not be sufficient to provide broad-spectrum weed control[21].

Application of post-emergence herbicides, like quizalofop and imazethapyr, are useful in suppressing weeds in pulse crops. Many weeds were controlled throughout the season without harming soybeans when imazethapyr was sprayed as a post-emergence treatment at 50 to 75 g ha^{-122}. In blackgram,[23] found that using imazethapyr at a rate of 25 g ha^{-1} post-emergence had no negative effects on rainfed blackgram growth characteristics and produced a grain yield that was statistically comparable to two hand weeding (20 and 40 DAS). Application of post-emergence herbicide has advantages like minimizing the human labour consumption and controlling the second flush of weeds in pulse crops[24].

Current literature on weed management in blackgram has examined various herbicide options; however, there is a significant research gap concerning herbicide mixture strategies specifically tailored for effective weed control in blackgram fields. Utilizing herbicides and their mixtures could offer a viable alternative for managing weeds. With this background and research gaps, the current study is framed with the multifold objectives viz., assessing the impact of post-emergence herbicide application on reducing weed dry weight and weed growth, measuring crop yield, and evaluating the economic viability of cultivating blackgram during the *kharif* season under irrigated conditions.

Materials and methods

Field experiment design and location

A field experiment was conducted during the *kharif* seasons of 2020 and 2021 at the National Pulses Research Centre (NPRC), Tamil Nadu Agricultural University, Vamban, Pudukkottai, India which is situated at 10° 36′ N latitude and 78° 90′ E longitude with an altitude of 93 m above mean sea level. Weather parameters recorded during the study period is depicted in Fig. 1. During the blackgram cropping period in NPRC, Vamban, the amount of rainfall received was 357.7 mm and 267.0 mm in 2020 and 2021 respectively. The mean relative humidity recorded was 89% (07.22 h) and 59.39% (14.22 h) in 2020 and 2021 respectively. The soil of the experimental field was sandy-loam in texture, neutral in reaction (pH 6.31) with 0.32% organic carbon content and with low available N (162 kg ha^{-1}), medium P (18.5 kg ha^{-1}) and K (123 kg ha^{-1}) contents. The field layout of the experimental site was a randomized block design, with each treatment replicated three times.

Treatment details

The experiment encompassed the following treatments and their combinations:

T_1: Unweeded control
T_2: Weed-free
T_3: Hand weeding at 20 and 40 DAS
T_4: Imazethapyr 10 % SL @ 55g ha^{-1} at 20 DAS as a post-emergence herbicide
T_5: Fluzifop p-butyl 13.4 % w/w @ 250 g ha^{-1} at 20 DAS as a post-emergence herbicide
T_6: Propaquizafop @ 33.3 g + Imazethapyr @ 50 g ha^{-1} at 20 DAS (ready mix) as a post-emergence herbicide

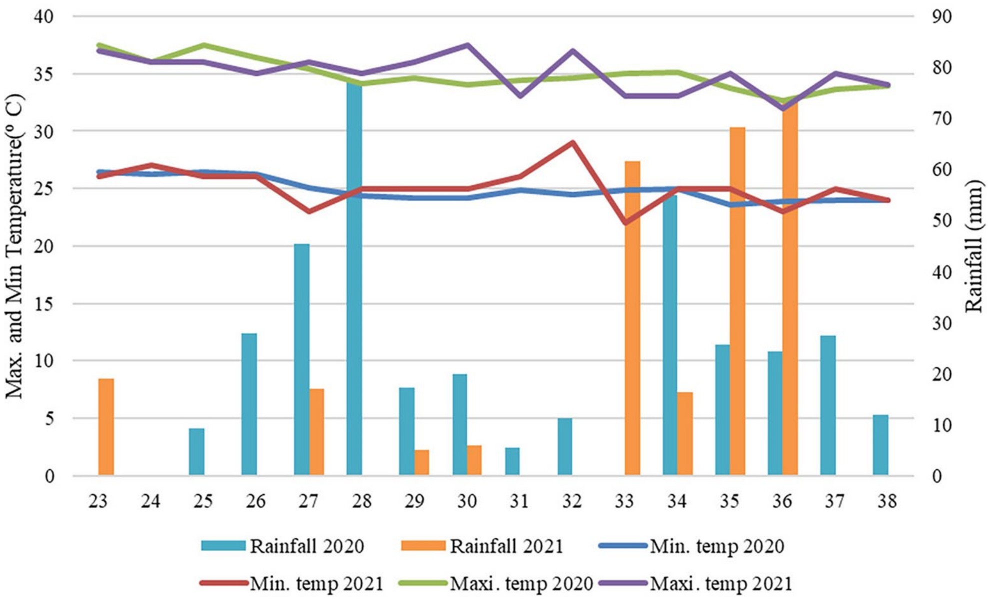

Fig. 1. Weather parameters observed during the experimental period.

T_7: Aciflourfen sodium @ 140 g + Clodinafoppropargyl @ 70 g ha^{-1} at 20 DAS (ready mix) as a post-emergence herbicide

T_8: Fomesafen @ 220 g + Fluzifop p-butyl @ 220 g ha^{-1} at 20 DAS as a post-emergence

Crop cultivation and management

Land preparation was done with one time disc ploughing followed by two times cultivator and finally one-time rotavator to make the soil to fine tilth. The field was divided into small plots with beds and channels. Gross plots of size 4.5 × 3.5 m were prepared and the net plot size was 4 × 3 m. A high-yielding blackgram variety VBN8 with special characters of Mungbean Yellow Mosaic Virus (MYMV) resistance and synchronized maturity was used for the study. Blackgram seeds at the rate of 20 kg ha^{-1} were treated with talc formulation of *Pseudomonas fluorescens* (*Pf1*) @ 200 g ha^{-1} of seed. Finally, seeds were treated with biofertilizers: *Rhizobium* (BMBS 47) @ 600 g ha^{-1} along with Phosphobacteria @ 600 g ha^{-1} using rice gruel as a binder. These seeds were dibbled in well-prepared field with a spacing of 30 × 10 cm between rows and plants respectively. Sowing was done on June 18, 2020 and June 16, 2021, with harvests on September 11, 2020, and September 5, 2021, respectively. To maintain soil fertility for better crop growth and yield, basal application of farmyard manure at a rate of 12.5 tonnes per hectare was applied before the last ploughing.

The blanket fertilizer doses of nitrogen (25 kg ha^{-1}), phosphorus (50 kg ha^{-1}), potassium (25 kg ha^{-1}), and sulfur (20 kg ha^{-1}) were applied basally. The treatments were applied as follows: T_1—No weed control was performed from sowing to harvest, T_2—Four manual weedings were carried out, keeping the field free of weeds throughout the cropping period, T_3—Hand weeding was done twice, at 20 and 40 DAS. The recommended dose specified post-emergence herbicides in the treatments T_4, T_5, T_6, T_7, and T_8 were applied at 20 DAS using a manually operated backpack sprayer fitted with a flat fan nozzle. From sowing to harvest, during 2020 and 2021 three and four irrigations were given respectively. This includes each one irrigation immediately after sowing, (life-saving) at 3 DAS, during flowering in 2020 and 2021, whereas in 2021 one additional irrigation was given during pod initiation stage. Rainfall received during 2020 and 2021 along with these irrigations were sufficient to meet out the crop water requirement. All the irrigations were given through the method of flooding with borewell water connected to 17.5 HP motors. The irrigation was withheld before Twelve days of harvesting. Foliar application of 2% DAP along with Naphthalene Acetic acid (NAA) at the rate of 40 mg/l once at 30 and 45 DAS was applied to increase flower production and prevents the flower dropping in blackgram. The spray solution of 2% DAP was prepared by soaking 10 kg in 25 L of water for 12 h to get 2% concentration. After 12 h, supernatant solution was collected and diluted with 475 L of water. The diluted spray solution was used for spraying one hectare by using Aspee backpack sprayer. When the crop reached a state of harvestable maturity, it was manually harvested according to treatment. Harvested product was placed in the threshing floor, exposed to sunlight for drying and then manually threshed and dried to a moisture content of 12%. The cleaned blackgram seeds were then weighed according to its treatment.

Data collection

In net plot area, five plants were selected randomly and tagged in all the three replications and used for biometric observations on growth and yield parameters namely number of pods per plant, number of seeds, number of seeds per pod and 100 seed weight. The grain yield from each net plot area was measured in kilograms, and the conversion factor based on the net plot size was then multiplied to convert the weight into kilograms per hectare.

Following weed observations were recorded using quadrant.

1. Weed density (number m^{-2})

   Weed density was recorded at 30 and 45 DAS using 0.25 m^2 quadrant. This data was then converted to a one-square meter area. For each plot, quadrants were placed randomly, and the number of weeds within each quadrant was recorded and expressed as the number per square meter.

2. Weed dry weight (g. m^{-2})

   Weed dry weight was recorded at 30 and 45 DAS. Weeds were collected, air dried and then oven dried at 75 ± 2 °C till constant weight was obtained by using an electronic balance and expressed in kg ha^{-1}.

3. Weed Control Efficiency (WEC): It was calculated for both 30 and 45 DAS using the following formula[25]:

$$\mathrm{WCE} = \frac{\mathrm{X(X-Y)}}{\mathrm{X}} \times 100$$

where: X = Number or dry weight of weeds in the unweeded plot Y = Number or dry weight of weeds in the treated plot.

Statistical analysis

Prior to statistical analysis, the weed dry weight and weed density data were transformed using the square root method (√x+0.5)[26]. The experimental data underwent statistical analysis following the methods proposed by[26]. Significance levels were assessed, and critical differences were determined at a probability level of $p \leq 0.05$ using Analysis of Variance (ANOVA) for the randomized block design. Treatment differences that were not statistically significant were indicated by "NS." The collected data of blackgram plant height and number of pods per plant were subjected to R studio statistical analysis for Boxplot diagram.

Economics

The total cost of blackgram cultivation under each treatment was determined by factoring in the labour for various operations and the costs of materials such as fertilizers, herbicide, irrigation, harvesting and threshing. The economic evaluation of each treatment considered all aspects of crop production along with current market prices for inputs expressed as US dollars (USD.) per hectare. Gross return was calculated by multiplying the crop yield per hectare by the prevailing minimum market rate, which was USD. 0.85 per kg of blackgram at the time of the study. Net return was determined by subtracting the cost of cultivation from the gross return for each treatment, using the formula: Net return = Gross return (USD.ha^{-1})—Cost of cultivation (USD.ha^{-1}). Finally, the Benefit-Cost (B:C) ratio was computed using the formula: B:C ratio = Gross return (USD.ha^{-1}) / Total cost of cultivation (USD.ha^{-1}).

Results

Weed flora and herbicide effects

The experimental field exhibited a diverse weed population, comprising grasses, sedges and broadleaved weeds. Predominant grassy weeds of *Dactyloctenium aegyptium* and *Chloris barbata*, *Cyperus rotundus* in the sedges category, and *Flaveria australica*, *Cleome gynandra*, *Eclipta alba*, *Convolvulus arvensis*, *Digera arvensis*, *Vicia* spp., and *Celosia argentea* among the broadleaved weeds were observed in the experimental field. No phytotoxicity symptoms were observed after the application of herbicides at 20, 25, and 30 days after herbicide spraying in blackgram.

Weed density, weed dry weight, and weed control efficiency

The results demonstrated that the weed-free plot (T_2) exhibited no weeds. The lower weed density and weed dry weight were recorded during 30 and 45 DAS in plots subjected to manual weeding twice by hand hoe at 20 and 45 DAS (T_3), with values of 5.13 and 6.46 numbers m^{-2}, and 3.33 and 4.92 g m^{-2}, respectively. Among the chemical herbicide treatments, spraying of Fomesafen @ 220 g + Fluzifop p-butyl at 220 g ha^{-1} at 20 DAS as a post-emergence herbicide treatment (T_8) recorded the lower weed density and weed dry weight at 30 and 45 DAS (8.12 and 8.88 numbers m^{-2}; 5.02 and 6.86 g m^{-2}, respectively). This performance was comparable to the application of Aciflourfen sodium @ 140 g + Clodinafop propargyl @ 70 g ha^{-1} at 20 DAS (ready mix) as post-emergence (T_7) observed at 30 DAS (Table 1). Additionally, Fluzifop P-butyl 13.4% w/w @ 250 g ha^{-1} at 20 DAS as post-emergence (T_5) recorded at 30 DAS showed similar weed control efficiency to Imazethapyr 10% SL @ 55 g ha^{-1} at 20 DAS as post-emergence (T_4).

Weed control efficiency (WCE) results are presented in Table 1. The WCE was higher in the weed-free plot (T_2) at both 30 and 45 DAS (100% and 100%, respectively), followed by plots subjected to manual weeding twice by hand hoe at 20 and 45 DAS (T_3) (79.04% and 77.12% at 30 and 45 DAS, respectively). Unweeded plot recorded higher weed population, which is indicated in Fig. 2. Among the various herbicides used, application of Fomesafen @ 220 g + Fluzifop p-butyl at 220 g ha^{-1} at 20 DAS as post-emergence (T_8) recorded greater WCE (66.80% and 68.53% at 30 and 45 DAS, respectively) (Table 1). The pictures of three different treatments are depicted in Fig. 2.

Treatments	Weed density (Nos.m^{-2})		Weed dry weight (g.m^{-2})		Weed control efficiency (%)	
	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS
T_1. Unweeded control	24.46	28.19	15.18	22.40	–	–
	(598.84)	(795.34)	(247.11)	(503.10)		
T_2. Weed free	0.00	0.00	0.00	0.00	100.00	100.00
	(0.00)	(0.00	(0.00)	(0.00)		
T_3. Hand weeding at 20 and 40 DAS	5.13	6.46	3.33	4.92	79.04	77.12
	(26.50)	(42.17)	(11.11)	(24.24)		
T_4.Imazethapyr 10%SL@55 g.ha^{-1} at 20DAS as post emergence	10.75	12.88	6.67	9.90	44.49	52.85
	(115.84)	(166.00)	(44.45)	(98.07)		
T_5.Fluzifop p- butyl 13.4%W/w @ 250 g/ha 20 DAS as post emergence	10.21	11.37	6.27	8.78	56.96	57.07
	(104.50)	(129.50)	(39.42)	(77.20)		
T_6.Propaquizafop @ 33.3 g + Imazethapyr @50 g.ha^{-1} at 20 DAS (ready mix) as post emergence	14.78	13.90	10.15	10.63	48.94	55.23
	(218.50)	(193.67)	(103.02)	(113.32)		
T_7. Aciflourfen sodium @ 140 g + Clodinafoppropargyl @ 70 g ha^{-1} at 20 DAS (ready mix) as post emergence	8.45	14.58	8.11	13.47	45.88	61.38
	(72.00)	(225.44)	(78.57)	(181.50)		
T_8. Fomesafen @ 220 g + Fluzifop p- butyl at 220 g ha^{-1} at 20 DAS as post emergence	8.12	8.88	5.02	6.86	66.80	68.53
	(65.67)	(79.17)	(25.26)	(45.90)		
SE	0.39	0.35	0.21	0.31	–	–
CD (P = 0.05)	1.38	1.17	0.76	1.08	–	–

Table 1. Effect of weed management practices on weed density, weed dry matter and weed control efficiency (%) of blackgram (Pooled mean of 2020 &2021). * Square root log transformed value & Figures in parenthesis indicate original values.

Field view T_1:Unweeded plot   T8: Fomesafen + Fluzifop p butyl sprayed plot

Fig. 2. Field photographs of blackgram crops under chemical weed management compared to an unweeded plot.

Growth Parameters

The results on growth parameters revealed that, in weed-free plot (T_2) the plants were significantly taller (44.9 cm) and had a maximum of 3.2 branches per plant. Among the chemical weed management practices, application of Fomesafen @ 220 g + Fluzifop p-butyl at 220 g ha^{-1} at 20 DAS as a post-emergence (T_8) treatment had the higher plant height (39.7 cm) and more number of branches per plant (3.0). This treatment was statistically comparable to Aciflourfen sodium @ 140 g + Clodinafop propargyl @ 70 g ha^{-1} at 20 DAS (ready mix) as a post-emergence treatment (T_7). Among the herbicide application the lower plant height and branches per plant was obtained in Propaquizafop @ 33.3 g + Imazethapyr @50 g.ha^{-1} at 20 DAS (ready mix) as post emergence (T_6) (Table 2 and Fig. 3). In the unweeded control (T_1), minimum plant height and number of branches per plant were recorded.

Yield parameters and yield

A significantly higher number of pods per plant (52.9) and seed yield of 1226 kg ha^{-1} was recorded in the weed-free treatment plot (T_2), followed by plots subjected to two manual weeding at 20 and 45 DAS (T_3). Among the chemical weed control practices, significantly higher number of pods per plant (43.33) and higher seed yield of 1088 kg ha^{-1} was achieved by applying Fomesafen @ 220 g + Fluzifop p-butyl at 220 g ha^{-1} at 20 DAS as a post-emergence treatment (T_8), which was on par with Aciflourfen sodium @ 140 g + Clodinafop propargyl @ 70 g ha^{-1} at 20 DAS (ready mix) as post-emergence (T_7). The minimum number of pods per plant and seed yield was observed in the unweeded control (T_1) as presented in Table 2 and Fig. 3. No significant differences

Treatments	Plant height (cm)	No. of branches/plant	No. of pods/Plant	No. of seeds/pod	100 seed wt (g)	Seed yield (kg/ha)	B: C ratio
T_1. Unweeded control	26.1	1.6	17.8	6.0	4.6	362	1.43
T_2. Weed free	44.9	3.2	52.9	6.4	5.0	1226	2.51
T_3. Hand weeding at 20 and 40 DAS	42.0	2.8	47.7	6.4	5.1	1096	2.44
T_4.Imazethapyr 10%SL@55 g.ha^{-1} at 20DAS as PoE	33.0	2.5	35.6	6.2	4.8	934	2.67
T_5.Fluzifop p- butyl 13.4%W/w @ 250 g.ha^{-1} 20 DAS as post emergence	34.5	2.5	37.9	6.2	4.8	959	2.67
T_6.Propaquizafop @ 33.3 g + Imazethapyr @50 g.ha^{-1} at 20 DAS (ready mix) as post emergence	32.1	2.4	33.0	6.2	5.0	910	2.48
T_7. Aciflourfen sodium @ 140 g + Clodinafoppropargyl @ 70 g.ha^{-1} at 20 DAS (ready mix) as post emergence	37.4	2.6	39.8	6.3	5.1	1037	2.76
T_8. Fomesafen @ 220 g + Fluzifop p-butyl at 220 g.ha^{-1} at 20 DAS as post emergence	39.7	3.0	43.3	6.4	4.9	1088	2.79
SE	1.63	0.03	1.43	0.11	0.07	35	–
CD (P = 0.05)	2.51	0.09	4.18	NS	0.20	104	–

Table 2. Effect different weed management practices on growth and yield attributes, seed yield and benefit–cost ratio of blackgram (Pooled mean of 2020 &2021).

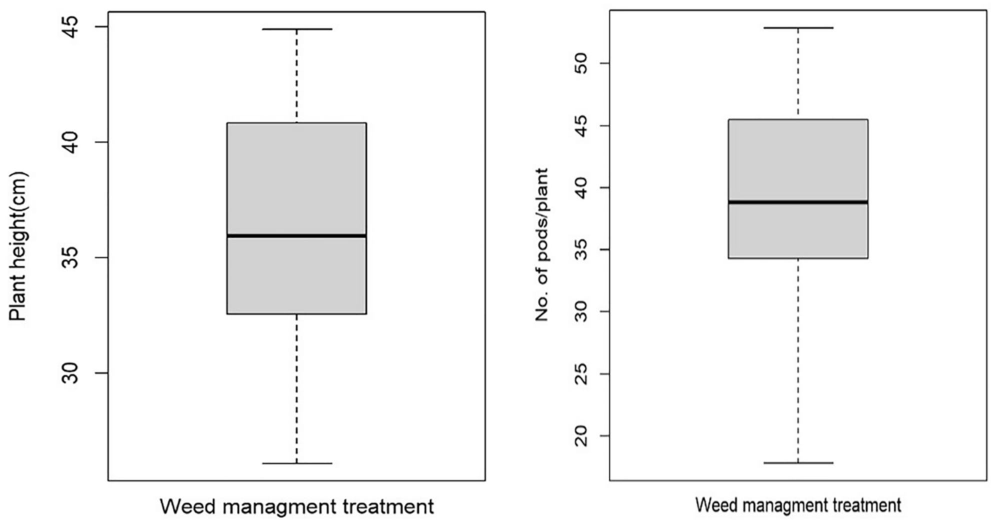

Fig. 3. Boxplot of plant height and number of pods per plant of blackgram due to weed management practices (Pooled mean of 2020 & 2021).

were observed in the number of seeds per pod and 100 seed weight among the treatments (Table 2). Among the several herbicide applications, application of Propaquizafop @ 33.3 g + Imazethapyr @ 50 g.ha^{-1} at 20 DAS (ready mix) as post-emergence herbicide (T_6) recorded the lower number of pods per plant and seed yield in blackgram.

Economics

The higher gross and net return of USD.1010 and 607 ha^{-1} respectively was recorded in the weed free treatment with a BCR of 2.51. Among the herbicide treatments, higher gross return (USD.896 ha^{-1}), net return (USD.575 ha^{-1}) and B:C ratio (2.79) was recorded by spraying of Fomesafen @ 220 g + Fluzifop p-butyl at 220 g ha^{-1} at 20 DAS as a post-emergence herbicide (T_8), followed by Aciflourfen sodium @ 140 g + Clodinafop propargyl @ 70 g ha^{-1} at 20 DAS (ready mix) as post-emergence (T_7) with a net return of USD.545 ha^{-1} and B:C ratio of 2.76. Despite achieving higher blackgram seed yield through two manual hand weeding at 20 and 40 DAS (T_3), spraying of Fomesafen @ 220 g + Fluzifop p-butyl at 220 g ha^{-1} at 20 DAS as post-emergence (T_8) resulted in 7.34% higher net income and 14.34% greater B:C ratio than manual hand weeding (Table 2 and Fig. 4). Among alternative herbicidal treatments, the better net return and B:C ratio were achieved with a ready mix of 33.3 g of propaquizafop and 50 g/ha of imazethapyr applied at 20 DAS. The lower gross and net return was observed in unweeded control (T_1).

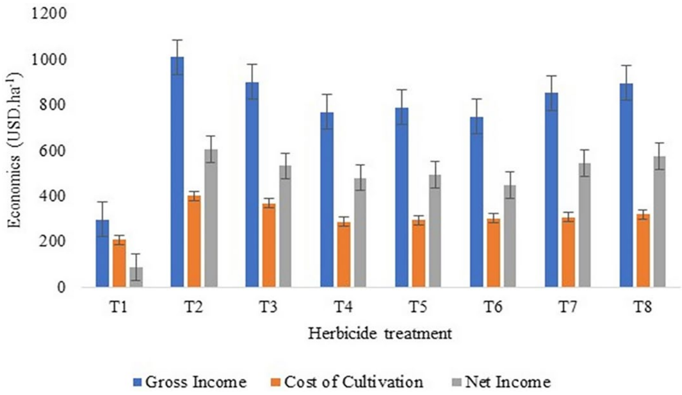

Fig. 4. Effect of different weed management practices on economics of blackgram (Pooled mean of 2020 & 2021).

Discussion

In the two years of study, significant variations were observed in weed density and weed dry weight. This variation can be attributed to the quantity of rainfall received during 2020 which is 25.35% higher than the average annual rainfall during the crop-growth period (Fig. 1). As the crop was raised under assured irrigation, rainfall is not considered as a main factor for significant crop loss. Blackgram is not a good competitor against weeds and hence weed will grow unrestricted[27]. The weed dry weight was significantly influenced by the chemical weed management practices employed. Notably, the higher weed dry weight was observed in the weedy check at both 30 and 45 DAS. This is attributed to the fact that, at later growth stages, many weeds cease active growth due to leaf senescence, resulting in reduced weed dry matter accumulation[28]. Similar findings of higher weed infestation under weedy control were reported[29,30]. The competitive advantage of weeds over crops, leading to increased weed dry weight, can be attributed to the higher weed density in the weedy check. In contrast, the lower weed density observed under hand weeding is likely due to the uprooting of weeds and their subsequent desiccation, resulting in decreased weed populations[13]. Among the chemical herbicides, the treatment involving Fomesafen @ 220 g + Fluzifop p-butyl @ 220 g ha^{-1} applied at 20 DAS as a post-emergence herbicide achieved the lower weed density and weed dry weight at 30 and 45 DAS. It might be more advantageous to utilize a combination of post-emergence herbicides rather than a single herbicide to provide broad spectrum weed control[31].

Reduced weed density and weed dry weight were observed in both the weed-free plot and manually weeded plot, resulting in higher WCE, increased plant height, and more branches in blackgram. While traditional methods of weed management, such as hoeing or hand weeding, are effective but they are labour-intensive, cost consuming, often insufficient, and can potentially damage the crop[32,33]. Appreciable growth and yield characteristics were observed under the conventional method of weed management, which can be attributed to the reduced competitiveness of weeds with the crop, creating a more favourable environment for crop growth and development. In contrast, the weedy check exhibited significantly lower values for growth and yield parameters, in line with research findings described for greengram[34,35]. The superior growth and greater yields of blackgram under weed-free conditions highlight the reduced physical suppression and competition in blackgram[36]. The effect of different weed management practices like manual weeding and herbicide application on weed growth was particularly successful, resulting in increased yields. This can be attributed to the better management of weeds in the early stages, which reduced weed growth, increased blackgram yield contributing characters, and ultimately resulted in higher yields[37,38]. This success can be attributed to the better control of both grassy and broadleaved weeds during the early growth period, with minimal adverse effects on the blackgram crop. The reduced seed yield in unweeded control can be primarily attributed to tremendous weed growth and intense crop-weed competition in soybean[39]. The lower yield is likely a consequence of the increased physical suppression and prolonged competition caused by weed infestation. These results are in accordance with those of others who reported similar findings in blackgram[40].

Application of Fomesafen @ 220 g + Fluzifop p-butyl @ 220 g ha^{-1} at 20 DAS as a post-emergence treatment for chemical weed management practices recorded higher gross and net returns and BCR of 16.41, 22.26.18, and 11.11%, respectively than ready mix of 33.3 g of propaquizafop and 50 g ha^{-1} of imazethapyr applied 20 DAS. Among alternative herbicidal treatments, the lowest net return and B:C ratio were achieved with a ready mix of 33.3 g of propaquizafop and 50 g.ha^{-1} of imazethapyr applied at 20 DAS. This may be the result of efficient weed control achieved by post-emergence application of Fomesafen @ 220 g + Fluzifop p-butyl @ 220 g ha^{-1}at 20 DAS.

Additionally, this strategy requires less labor and results in a 16.36% increase in yield, making it an economically viable method for optimizing blackgram seed production. Furthermore, the chemical cost is lower than the cost of manual weeding. These findings align with previous research results[41–43]. Even though the weed-free condition produced a higher gross return (USD.1010 ha^{-1}) and net income (USD.607 ha^{-1}), the B:C ratio was lower because four-hand weedings incurred more expenditure to maintain the wee free condition.

Based on the two-year study, the experimental data showed that, in terms of chemical weed management, the post-emergence spraying of Fomesafen @ 220 g + Fluzifop p-butyl @ 220 g ha^{-1} at 20 DAS recorded the lower weed density, weed dry weight, increased blackgram yield and B:C ratio. It was statistically comparable with

Aciflourfen sodium @ 140 g and Clodinafop propargyl @ 70 g ha^{-1} at 20 DAS (ready mix) as post-emergence[44–46]. The study also emphasizes the importance of applying herbicides at the right time, particularly on 20th DAS. Application of herbicides at critical crop growth stage can significantly impact the efficacy of weed management practices in blackgram and its yield.

Conclusion

Based on two years of rigorous experimentation, the research output indicated that within the spectrum of weed management strategies employed in blackgram cultivation, application of Fomesafen at 220 g + Fluzifop p-butyl at 220 g ha^{-1} on the 20th DAS recorded lower weed density of 8.12; 8.88 weed numbers m^{-2} and weed dry weight of 5.02; 6.86 g. m^{-2} at 30 and 45 DAS respectively and significantly higher seed yield of 1088 kg ha^{-1}, gross return of USD. 896 ha^{-1} and B:C ratio 2.79. This result was statistically on par with the yield obtained through the use of Aciflourfen sodium at 140 g + Clodinafop propargyl at 70 g ha^{-1} on 20 DAS as a ready-mix post-emergence application, primarily due to the reduction in overall cultivation expenses.

In summary, the application of Fomesafen at 220 g + Fluzifop p-butyl at 220 g ha^{-1} on the 20th DAS effectively curtailed weed density and dry matter, leading to a substantial boost in seed yield of blackgram. This study underscores the efficacy of this specific herbicide combination as a promising and viable weed management strategy for blackgram cultivation. This finding is also applicable to control the weeds in other pulses like greengram during the labour scarcity condition and hence this practice can be recommended to the pulse growing farmers.

Future research may be focussed to explore the extended critical period of weed competition to develop effective weed management strategies to minimize yield loss in irrigated blackgram. Additionally, examining the effect of herbicide application on soil microbial population, nodulation potential in pulses, nitrogen fixing potential of root nodules and seed quality assessment to monitor the residual potential of herbicides will answer several queries with regard to the environmental safety of herbicides. This research is important for maintaining soil fertility and productivity in an ecofriendly manner.

Data availability

All data generated or analysed during this study are included in this published article. The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Conceptualization, supervision, methodology and formal analysis—S.M.M. and M.G. Original draft preparation— S.M.M., R.P., K.S., A.D., and V.M.B. Data curation and analysis—S.M.M., R.P., K.S., M.G., V.M.B and S.M. Project administration, investigation- S.M.M. and M.G. Writing—review and editing- S.M.M., R.P., K.S., A.D.,V.M.B. and S.M. All authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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