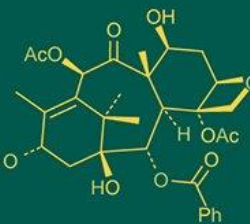
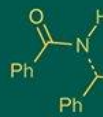


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(6): 1181-1191
www.biochemjournal.com
Received: 12-05-2026
Accepted: 15-06-2026

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Efficacy of certain new generation herbicides in blackgram (*Vigna mungo* L.)

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i6Sn.8794>

Abstract

The present investigation entitled “Efficacy of Certain New-Generation Herbicides in Blackgram (*Vigna mungo* L.)” was conducted during the kharif season of 2024-25 at the Research Farm, Department of Agronomy, Sardar Patel University, Balaghat (Madhya Pradesh). The experiment was laid out in a Randomized Block Design (RBD) with ten treatments and three replications. The treatments included both Pre-Emergence (PE) and Post-Emergence (POE) herbicides diclosulam, pendimethalin + imazethapyr, propaquizafop + imazethapyr, sodium acifluorfen + clodinafop propargyl, pendimethalin alone, imazethapyr alone and their combinations with Hand Weeding (HW), along with two manual weedings and an unweeded control.

The experimental soil was clayey in texture (Vertisols), slightly alkaline (pH 8.51), low in organic carbon (0.38%) and nitrogen (160.3 kg ha⁻¹), medium in phosphorus (35.9 kg ha⁻¹), and high in potassium (268.8 kg ha⁻¹). The climate of Balaghat was characterized as tropical wet and dry with mean annual temperature of 29.6 °C and high rainfall during July-September. Observations were recorded on weed flora composition, weed density, weed dry weight, Weed Control Efficiency (WCE), crop growth parameters, yield attributes, and economic returns.

The experimental field was infested with a complex weed flora comprising grasses (e.g., *Digitaria sanguinalis*, *Cynodon dactylon*, *Echinochloa colona*), sedges (*Cyperus rotundus*), and broad-leaved weeds (*Amaranthus viridis*, *Trianthema portulacastrum*, *Commelina benghalensis*, *Euphorbia hirta*, *Phyllanthus niruri*). Among all treatments, diclosulam (20 g ha⁻¹) applied as pre-emergence, either alone or in combination with one hand weeding at 30 DAS, proved most effective in suppressing the entire spectrum of weed flora throughout the crop growth period. It maintained zero weed density and dry weight up to 15 DAS and significantly lower values at later stages (up to harvest). The treatment pendimethalin + imazethapyr (1000 g ha⁻¹ PE) with HW at 30 DAS ranked next in effectiveness. Post-emergence herbicides such as propaquizafop + imazethapyr and sodium acifluorfen + clodinafop were moderately effective, mainly against existing grassy weeds, but less efficient in controlling late-emerging or perennial weeds.

In terms of crop performance, the highest plant height, number of branches per plant, pods per plant, seeds per pod, and 100-seed weight were recorded under diclosulam + HW at 30 DAS, followed by pendimethalin + imazethapyr + HW and two hand weedings. These treatments also resulted in significantly higher seed yield and haulm yield compared with the unweeded control, where yield losses reached up to 85-90% due to severe weed competition. The weed control efficiency exceeded 85% in diclosulam-based treatments throughout the crop growth stages, while post-emergence treatments recorded 45-65%. All herbicidal treatments were phytotoxin-free and safe to blackgram at recommended doses, as evidenced by normal germination, plant vigour, and absence of chlorosis or necrosis symptoms.

The study thus confirmed that early-season weed suppression through pre-emergence herbicides, particularly diclosulam, integrated with manual weeding ensures effective, economical, and sustainable weed management in blackgram under Balaghat conditions. The findings emphasize that integrated weed management (IWM) combining chemical and cultural approaches offers the most reliable strategy for maintaining a weed-free environment, optimizing resource use efficiency, and improving crop productivity in pulse-based systems.

Keywords: Blackgram, *Vigna mungo*, diclosulam, pendimethalin + imazethapyr, weed density, weed control efficiency, yield, economics, integrated weed management

Introduction

Pulses are among the most superior and important groups of crops to provide plant protein of the highest quality. Their proteins complement cereal proteins in the largely vegetarian

Indian diet. The pulses play an important role in nutritional security, especially in populations that are dependent upon vegetarian food sources. With respect to agriculture, pulses enrich the soil and thus help in eco-friendly farming (Saravanane *et al.* 2020) ^[1].

Among various pulse crops, blackgram (*Vigna mungo* L.), popularly called urdbean, uradbean, mashbean, minapappu, mungobean, or black mapte bean, has a place in prominence due to its wide adaptability, short growth duration, and high nutritional value (Nihal *et al.* 2025) ^[2]. It finds wide cultivation in all tropical and subtropical regions of the world, especially in India; obviously, for it grows under the various agro-ecological conditions. Blackgram may be cultivated as a pure crop, mixed crop, catch crop, or even as a sequential crop, especially under residual soil moisture after the harvesting of rice. The adaptability of blackgram has become an advantage for it to be grown in both *kharif* and *rabi* seasons, providing sustenance to small and marginal farmers. Nutritionally, blackgram is an excellent source of carbohydrates (48%), protein, iron (9.1 mg), fat (1.4 g), riboflavin (0.37 g), and thiamine (0.42 mg) per 100 g of seed (Asaduzzaman *et al.* 2010) ^[3]. It is unique among pulses due to its ability to form a mucilaginous, pasty texture upon soaking, which makes it an essential ingredient in many traditional Indian foods such as vada, idli, dosa, and halwa. Additionally, blackgram residues (bhusa) serve as valuable livestock feed, improving nitrogen, calcium, and phosphorus balance in animals. Weed infestation is a major biotic stress that adversely affects the growth and productivity of blackgram. The short-statured and compact varieties currently under cultivation, such as TBG 104 and PU-31, are high-yielding and disease-resistant, but they exhibit slow early growth, making them less competitive with weeds. Moreover, weeds act as alternate hosts for insect pests and viruses, including the Yellow Mosaic Virus, exacerbating crop damage (Dhayal *et al.* 2022) ^[4]. The critical period of crop-weed competition in blackgram occurs between 15 to 45 days after sowing (DAS). Yield losses due to weed competition can range from 50% to 87%, depending on the weed species composition and density. Traditional weed management methods such as hand weeding and intercultivation are increasingly uneconomical due to the rising cost and scarcity of agricultural labor. Additionally, continuous rainfall during the early crop stages often disrupts timely manual weeding operations. In recent years, the use of herbicides in pulse-based cropping systems has gained considerable importance as an effective and economical method for weed control. However, over reliance on selective post-emergence herbicides, particularly those targeting grassy weeds, has led to weed flora shifts toward broadleaf species. A notable example is the increasing prevalence of common vetch (*Vicia sativa* L.), which has become a problematic weed in blackgram relay cropping systems, especially in the north coastal zone of Andhra Pradesh (Malviya and Saini, 2023) ^[6]. While pre-emergence herbicides such as pendimethalin have been widely adopted, they are often ineffective against perennial sedges like *Cyperus rotundus* and certain broadleaf weeds such as *Commelina benghalensis* and *Trichodesma indicum*. Similarly, post-emergence application of imazethapyr alone fails to provide broad-spectrum weed control due to the diversity of weed flora in blackgram fields. Recent research suggests that new-generation herbicides and ready-mix formulations, such as combinations of imazethapyr with pendimethalin or propaquizafop, show promising results for

controlling both grassy and broadleaf weeds effectively. These formulations also offer extended residual activity, reduce labor dependency, and promote better crop establishment and yield performance.

Materials and Methods

The present experiment is laid out in the field of the Research Farm of Department of Agronomy, Sardar Patel University Balaghat-481331, M.P. during kharif season, 2024-25. The land topography of the experimental site was almost uniform with an adequate surface drainage. The internal drainage of the experimental site is medium. The field experiment was laid out in a Randomized Block Design (RBD) with three replications to statistically evaluate the treatment effects.

Design	RBD
Replications	3
Treatments	10
Gross Plot size	5.4 x 4.0 m
Net plot size	4.2 x 3.0 m
Variety	PU-31
Spacing	30 x 10 cm

Treatment Details

A total of ten treatment involving different source and combinations. The treatments were as follows:

W ₁ :	Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹
W ₂ :	PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹
W ₃ :	PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS
W ₄ :	PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS
W ₅ :	Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS
W ₆ :	Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS
W ₇ :	PE application of pendimethalin 1000 g ha ⁻¹
W ₈ :	Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS
W ₉ :	Two hand weedings at 15 and 30 DAS
W ₁₀ :	Unweeded check (Control)

Details of Herbicides Used in the Study

1. Diclosulam 2. Pendimethalin + imazethapyr 3. Propaquizafop + imazethapyr 4. Sodium acifluorfen + clodinafop propargyl 5. Pendimethalin 6. Imazethapyr.

Data collection and observations

Observations on weeds Weed parameters at different growth stages of blackgram crop viz., 15, 30, 45, 60 DAS and at harvest were recorded from selected quadrat (0.25 m²) in each plot. 1. Weed Flora, 2. Weed Density, 3. Weed Dry Weight, 4. Weed Control Efficiency (WCE), 5. Weed Index (WI).

Biometric observations on crop

1. Phytotoxicity, 2. Initial and Final Plant population, 3. Plant Height, 4. Leaf Area Index, 5. Number of Branches/Plant, 6. Dry Matter Production, 7. Number of Effective Rhizobium nodules/plant, 8. Number of Pods/Plant, 9. Test Weight, 10. Seed Yield, 11. Haulm Yield, 12. Harvest Index.

Result and discussion**Parameters influenced by different treatments in blackgram**

Treatments	Weed density m ⁻² (15 DAS)			
	Grasses	Sedges	BLWs	Total
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	0.00	0.00	0.00	0.00
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	2.19	3.67	1.67	7.53
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	0.00	0.00	0.00	0.00
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	2.16	3.69	1.61	7.46
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	19.59	12.37	6.30	38.26
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	19.62	12.38	6.31	38.31
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	3.24	5.09	2.67	11.00
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	19.60	12.39	6.32	38.31
W ₉ : Two hand weedings at 15 and 30 DAS	19.64	12.40	6.33	38.37
W ₁₀ : Unweeded check (Control)	19.67	12.41	6.33	38.41
SE±	0.38	0.19	0.17	
CD@5%	1.13	0.55	0.50	
CV (%)	6.21	4.32	7.80	

Treatments	Weed density m ⁻² (30 DAS)			
	Grasses	Sedges	BLWs	Total
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	6.81	5.03	1.03	12.87
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	6.52	7.76	4.89	19.17
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	6.83	5.06	1.06	12.95
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	6.44	7.8	4.91	19.15
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	8.86	8.42	6.91	24.19
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	20.53	8.59	11.04	40.16
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	15.41	9.31	9.37	34.09
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	23.12	10.11	15.41	48.64
W ₉ : Two hand weedings at 15 and 30 DAS	6.11	4.31	3.38	13.8
W ₁₀ : Unweeded check (Control)	27.03	14.38	15.93	57.34
SE±	0.46	0.29	0.26	
CD@5%	1.36	0.84	0.76	
CV (%)	6.29	6.16	6.22	

Treatments	Weed density m ⁻² (45 DAS)			
	Grasses	Sedges	BLWs	Total
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	17.03	8.03	4.37	29.43
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	18.38	11.37	8.03	37.78
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	5.66	3.63	0.6	9.89
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	4.78	6.06	2.55	13.39
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	19.34	12.48	10.37	42.19
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	25.06	21.03	13.03	59.12
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	19.97	18.37	9.37	47.71
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	27.16	24.03	19.03	70.22
W ₉ : Two hand weedings at 15 and 30 DAS	5.58	3.82	2.52	11.92
W ₁₀ : Unweeded check (Control)	31.03	35.37	21.37	87.77
SE±	0.38	0.44	0.23	
CD@5%	1.13	1.30	0.67	
CV (%)	3.78	5.29	4.34	

Treatments	Weed density m ⁻² (60 DAS)			
	Grasses	Sedges	BLWs	Total
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	23.37	11.37	10.03	44.77
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	18.03	17.03	13.03	48.09
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	16.37	8.37	5.16	29.9
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	15.03	12.03	7.03	34.09
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	23.37	17.37	14.03	54.77
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	31.03	26.39	20.37	77.79
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	24.37	34	21.03	79.4
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	37.03	39.03	25.69	101.75
W ₉ : Two hand weedings at 15 and 30 DAS	16.37	12.37	9.37	38.11
W ₁₀ : Unweeded check (Control)	44.37	43.03	28.37	115.77
SE±	0.52	0.79	0.37	
CD@5%	1.52	2.33	1.11	
CV (%)	3.57	6.13	4.23	

Treatments	Weed density m ⁻² (AT Harvest)			
	Grasses	Sedges	BLWs	Total
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	64.03	12.03	11.88	87.94
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	39.07	54.03	22.03	115.13
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	30.03	10.37	7.03	47.43
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	24.15	26.03	14.03	64.21
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	69.03	31.37	22.37	122.77
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	72.37	45.17	38.03	155.57
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	48.03	58.37	26.37	132.77
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	77.37	48.03	43.38	168.78
W ₉ : Two hand weedings at 15 and 30 DAS	24.83	24.9	11.89	61.62
W ₁₀ : Unweeded check (Control)	90.37	60.37	44.03	194.77
SE±	1.92	1.09	0.69	
CD@5%	5.65	3.21	2.04	
CV (%)	6.13	5.09	4.92	

Treatments	Weed dry weight m ⁻² (15 DAS)			
	Grasses	Sedges	BLWs	Total
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	0.00	0.00	0.00	0.00
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	0.09	0.08	0.09	0.26
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	0.00	0.00	0.00	0.00
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	0.09	0.09	0.08	0.26
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	0.73	0.60	0.73	2.06
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	0.74	0.61	0.74	2.09
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	0.13	0.41	0.12	0.66
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	0.73	0.60	0.74	2.07
W ₉ : Two hand weedings at 15 and 30 DAS	0.74	0.62	0.74	2.10
W ₁₀ : Unweeded check (Control)	0.75	0.62	0.75	2.12
SE±	0.01	0.01	0.01	
CD@5%	0.04	0.03	0.03	
CV (%)	6.55	4.83	4.86	

Treatments	Weed dry weight m ⁻² (30 DAS)			
	Grasses	Sedges	BLWs	Total
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	2.18	0.17	0.89	3.24
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	0.9	3.03	1.81	5.74
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	1.56	0.16	0.87	2.59
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	0.82	2.92	1.84	5.58
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	3.83	3.72	2.33	9.88
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	6.56	3.78	5.32	15.66
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	4.19	3.88	4.79	12.86
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	6.95	3.63	5.55	16.13
W ₉ : Two hand weedings at 15 and 30 DAS	0.8	0.12	1.56	2.48
W ₁₀ : Unweeded check (Control)	9.44	8.16	8.84	26.44
SE±	0.14	0.10	0.10	
CD@5%	0.41	0.29	0.31	
CV (%)	6.65	5.74	5.28	

Treatments	Weed dry weight m ⁻² (45 DAS)			
	Grasses	Sedges	BLWs	Total
W ₁ : PE application of diclosulam 20 g ha ⁻¹	5.33	1.72	3.1	10.15
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	7.02	5.32	3.89	16.23
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + HW at 30 DAS	1.88	0.42	1.13	3.43
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	1.73	0.92	1.39	4.04
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	8.37	6.43	4.73	19.53
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	10.98	8.71	7.36	27.05
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	10.16	8.22	5.63	24.01
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	12.89	9.32	9.08	31.29
W ₉ : Two hand weedings at 15 and 30 DAS	2.04	0.94	1.42	4.4
W ₁₀ : Unweeded check (Control)	16.36	14.31	13.46	44.13
SE±	0.21	0.17	0.17	
CD@5%	0.62	0.51	0.50	
CV (%)	4.73	5.33	5.65	

Treatments	Weed dry weight m ⁻² (60 DAS)			
	Grasses	Sedges	BLWs	Total
W ₁ : PE application of diclosulam 20 g ha ⁻¹	8.86	4.73	5.89	19.48
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	10.56	8.59	7.61	26.76
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + HW at 30 DAS	6.54	2.75	3.33	12.62
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	6.22	3.89	4.42	14.53
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	11.74	8.86	7.99	28.59
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	16.61	12.45	13.18	42.24
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	12.01	17.08	12.29	41.38
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	18.08	19.37	13.63	51.08
W ₉ : Two hand weedings at 15 and 30 DAS	6.51	3.91	4.17	14.59
W ₁₀ : Unweeded check (Control)	22.01	21.26	17.84	61.11
SE±	0.47	0.29	0.23	
CD@5%	1.40	0.85	0.68	
CV (%)	6.85	4.83	4.39	

Treatments	Weed dry weight m ⁻² (AT HARVEST)			
	Grasses	Sedges	BLWs	Total
W ₁ : PE application of diclosulam 20 g ha ⁻¹	23.94	9.15	9.9	42.99
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	21.7	22.84	14.07	58.61
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + HW at 30 DAS	14.88	7.36	8.63	30.87
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	12.76	10.42	8.76	31.94
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	26.95	20.14	15.55	62.64
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	30.19	21.44	19.38	71.01
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	21.53	30.03	18.11	69.67
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	34.01	26.6	23.01	83.62
W ₉ : Two hand weedings at 15 and 30 DAS	13.02	10.71	8.81	32.54
W ₁₀ : Unweeded check (Control)	40.03	31.12	25.82	96.97
SE±	0.64	0.60	0.64	
CD@5%	1.88	1.76	1.88	
CV (%)	4.60	5.50	7.26	

Treatments	Weed control efficiency (%)				
	15 DAS	30 DAS	45 DAS	60 DAS	At harvest
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	99	82.9	73.76	64.24	53.66
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	86.74	71.72	60.55	52.83	37.84
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	99	85.29	88.79	74.99	65.92
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	86.74	74.47	87.44	72	64.84
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	-	58.91	53.27	49.95	33.76
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	-	38.04	36.7	28.57	25.28
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	67.87	48.13	43.39	29.9	26.65
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	-	38.47	27.3	14.72	12.52
W ₉ : Two hand weedings at 15 and 30 DAS	-	85.65	86.65	71.9	64.23
W ₁₀ : Unweeded check (Control)	-	-	-	-	-
SE±	1.64	2.27	1.76	1.31	0.72
CD@5%	4.80	6.66	5.16	3.85	2.12
CV (%)	3.26	5.97	4.85	4.50	2.97

Treatments	Pre-emergence herbicides	Post-emergence herbicides
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	2	0
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	0	0
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	2	0
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	0	0
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	0	0
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	0	0
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	0	0
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	0	1
W ₉ : Two hand weedings at 15 and 30 DAS	0	0
W ₁₀ : Unweeded check (Control)	0	0
SE±	0.02	0.01
CD@5%	0.04	0.01
CV (%)	6.43	8.84

Treatments	Plant population (m ⁻²)	
	Initial	Final
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	26.59	25.14
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	31.4	31.27
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	27.02	25.41
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	31.53	31.23
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	31.49	31.17
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	31.03	30.55
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	31.22	31.06
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	31.62	30.84
W ₉ : Two hand weedings at 15 and 30 DAS	31.59	31.37
W ₁₀ : Unweeded check (Control)	31.79	31.6
SE±	0.81	0.59
CD@5%	2.39	1.76
CV (%)	4.62	3.42

Treatments	Plant height (cm)				
	15 DAS	30 DAS	45 DAS	60 DAS	At harvest
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	2.5	9.38	13.99	14.92	15.19
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	4.67	11.13	15.47	15.53	17.86
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	2.6	9.71	14.82	15.21	16.4
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	4.87	11.66	15.84	16.09	18.43
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	4.13	10.85	14.86	15.05	15.36
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	4	10.78	14.31	15.1	15.29
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	4.61	11	14.93	15.33	17.79
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	3.98	10.75	14.21	14.81	15.14
W ₉ : Two hand weedings at 15 and 30 DAS	3.87	11.09	15.79	16.07	18.15
W ₁₀ : Unweeded check (Control)	3.82	10.63	13.94	14.77	15.04
SE±	0.09	0.36	0.35	0.32	0.49
CD@5%	0.28	1.07	1.04	0.94	1.45
CV (%)	4.16	5.95	4.15	3.61	5.14

Treatments	Leaf Area Index				
	15 DAS	30 DAS	45 DAS	60 DAS	At harvest
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	0.31	0.67	1.53	1.92	1.47
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	0.38	0.71	1.62	1.96	1.54
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	0.31	0.69	1.64	2	1.57
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	0.39	0.72	1.69	2.02	1.61
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	0.36	0.68	1.51	1.79	1.45
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	0.36	0.67	1.48	1.69	1.36
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	0.38	0.69	1.58	1.72	1.42
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	0.36	0.64	1.45	1.66	1.32
W ₉ : Two hand weedings at 15 and 30 DAS	0.35	0.71	1.66	1.99	1.59
W ₁₀ : Unweeded check (Control)	0.35	0.62	1.33	1.55	1.18
SE±	0.01	0.02	0.04	0.04	0.05
CD@5%	0.03	0.06	0.12	0.11	0.13
CV (%)	4.60	4.78	4.38	3.51	5.42

Treatments	Number of branches plant ⁻¹			
	30 DAS	45 DAS	60 DAS	At harvest
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	3.22	5.02	6.19	6.79
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	5.61	6.23	6.72	7.05
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	3.42	5.92	6.36	7.08
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	5.69	6.68	6.86	7.36
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	4.44	5.24	6.29	6.34
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	4.24	5.18	6.22	6.22
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	5.58	6.12	6.24	6.88
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	4.19	4.94	5.68	5.99
W ₉ : Two hand weedings at 15 and 30 DAS	5.64	6.59	6.79	7.3
W ₁₀ : Unweeded check (Control)	4.1	4.28	5.06	5.45
SE±	0.17	0.15	0.12	0.19
CD@5%	0.49	0.43	0.34	0.57
CV (%)	6.25	4.40	3.22	5.04

Treatments	Dry matter production (kg ha ⁻¹)				
	15 DAS	30 DAS	45 DAS	60 DAS	At harvest
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	157	388	702	1118	1741
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	201	407	714	1180	1926
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	159	393	717	1217	2080
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	204	414	721	1304	2093
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	189	392	691	1088	1714
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	188	384	677	1041	1668
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	195	401	684	1129	1752
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	189	375	672	1009	1653
W ₉ : Two hand weedings at 15 and 30 DAS	187	412	721	1264	2084
W ₁₀ : Unweeded check (Control)	186	372	627	911	1180
SE±	5.90	12.24	21.82	28.77	45.50
CD@5%	17.40	36.12	64.37	84.89	134.23
CV (%)	5.38	5.40	5.49	4.46	4.37

Treatments	Number of effective rhizobium nodules plant ⁻¹			
	30 DAS	45 DAS	60 DAS	At harvest
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	17.43	31.3	28.77	27.03
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	20.79	35.63	30.03	28.37
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	18.49	34.3	30.03	28.66
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	21.69	37.9	31.43	29.9
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	19.23	31.09	28.23	26.99
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	19.16	30.77	26.83	26.57
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	19.73	33.63	27.46	27.18
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	19.1	30.73	26.43	25.37
W ₉ : Two hand weedings at 15 and 30 DAS	21.97	37.68	30.23	28.7
W ₁₀ : Unweeded check (Control)	18.69	28.23	25.97	21.97
SE±	0.57	0.92	1.01	0.61
CD@5%	1.68	2.71	2.98	1.81
CV (%)	4.97	4.84	6.13	3.87

Treatments	Number of pods plant ⁻¹	Number of seeds pod ⁻¹	Test weight (g)
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	15.3	4.1	37.8
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	16.2	4.3	40.1
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	15.7	4.7	40.3
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	16.4	5.3	40.6
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	14.8	4	37
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	14.5	3.9	36.9
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	15.1	4.1	37.2
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	14.4	3.6	35.8
W ₉ : Two hand weedings at 15 and 30 DAS	16.3	5.1	40.3
W ₁₀ : Unweeded check (Control)	11.7	2.9	33.3
SE±	0.36	0.09	0.99
CD@5%	1.05	0.25	2.92
CV (%)	4.04	3.52	4.45

Treatments	Seed yield (kg ha ⁻¹)	Haulm yield (kg ha ⁻¹)	Harvest index (%)	Weed index (%)
W ₁ : Pre-emergence (PE) application of diclosulam 20 g ha ⁻¹	621.5	996.5	26.1	19.9
W ₂ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹	702.5	1122.5	26.3	9.8
W ₃ : PE application of diclosulam 20 g ha ⁻¹ + Hand weeding (HW) at 30 DAS	717.5	1221.5	24.8	7.8
W ₄ : PE application of pendimethalin + imazethapyr 1000 g ha ⁻¹ + HW at 30 DAS	783.5	1240.5	26.5	-
W ₅ : Post-emergence application of propaquizafop + imazethapyr 127 g ha ⁻¹ at 15 DAS	605.5	987.5	25.8	21.9
W ₆ : Post-emergence application of sodium acifluorfen + clodinafop propargyl 180 g ha ⁻¹ at 15 DAS	573.5	976.5	24.7	25.9
W ₇ : PE application of pendimethalin 1000 g ha ⁻¹	615.5	1013.5	25.5	20.6
W ₈ : Post-emergence application of imazethapyr 75 g ha ⁻¹ at 15 DAS	569.5	966.5	24.8	26.5
W ₉ : Two hand weedings at 15 and 30 DAS	776.5	1232.5	26.3	0.5
W ₁₀ : Unweeded check (Control)	318.5	775.5	17.1	57.9
SE±	19.54	23.65	0.72	0.74
CD@5%	57.63	69.78	2.13	2.19
CV (%)	5.34	3.87	5.06	5.96

The experimental field was heavily infested with a diverse assemblage of weed species representing all major groups grasses, sedges, and broad-leaved weeds typical of the rainfed tropical ecosystem. The grassy weeds were dominated by *Digitaria sanguinalis* (large crabgrass), *Cynodon dactylon* (Bermuda grass), and *Echinochloa colona* (jungle rice), which are known for their rapid germination, profuse tillering, and strong competitive ability for soil nutrients, moisture, and sunlight. These species, particularly *Cynodon dactylon*, possess vigorous underground rhizomes that enable them to regenerate even after mechanical disturbance, making them among the most persistent perennial weeds in pulse-growing regions (Tripathi & Pandey, 2020) ^[7]. The sedge component was represented mainly by *Cyperus rotundus* (purple nut sedge), a notorious perennial weed with a prolific underground tuber system. Its ability to survive adverse conditions and multiply rapidly even under limited moisture makes it a constant menace in *kharif* pulses. The broad-leaved weed flora was dominated by *Amaranthus viridis*, *Trianthema portulacastrum*, and *Commelina benghalensis*, which germinate in successive flushes throughout the growing season (Tripathi & Pandey, 2020; Mohler & Johnson, 2020) ^[7, 8]. Their broad canopies and faster early growth suppress the relatively slow-growing blackgram seedlings by shading and depriving them of light, space, and nutrients during the critical establishment phase (Dash *et al.* 2024; Muduli *et al.* 2023; Nihal *et al.* 2025) ^[2, 9, 10].

The overall weed spectrum, therefore, comprised both annual and perennial species with overlapping growth periods, leading to continuous competition from sowing to harvest. This complex weed flora environment reflected the typical composition found in blackgram fields under tropical *kharif* conditions where intermittent rainfall and high soil moisture favour successive weed emergence. Blackgram, being a short-statured and initially slow-growing legume with limited early canopy development, could not compete effectively with such aggressive weeds during the first 30-40 days after sowing.

The period from germination to canopy closure thus represents the critical weed-free period, and failure to manage weeds during this interval results in substantial yield reduction (Dash *et al.* 2024; Muduli *et al.* 2023; Nihal *et al.* 2025) ^[2, 9, 10].

In this context, the use of herbicides with residual and broad-spectrum activity becomes essential to restrict early weed establishment. *Diclosulam*, when applied as a pre-emergence treatment, exhibited strong residual soil activity and effectively prevented the germination and establishment of both monocot and dicot weeds. Its mode of action involves inhibition of acetolactate synthase (ALS) enzyme, which is vital for the synthesis of branched-chain amino acids in weeds. The selectivity of diclosulam to blackgram ensured that the crop remained unaffected while the emerging weeds were completely suppressed. Pendimethalin + imazethapyr, another pre-emergence combination, offered broad-spectrum control by inhibiting both shoot and root growth in emerging weeds. However, its residual effect was relatively shorter than that of diclosulam, resulting in a mild re-emergence of weeds at later stages (Marimuthu *et al.* 2024; Singh *et al.* 2018) ^[8, 12].

The post-emergence herbicides, such as propaquizafop + imazethapyr and sodium acifluorfen + clodinafop, though effective in controlling existing weed populations, were

comparatively less efficient against later-emerging flushes and perennial species like *Cyperus rotundus* and *Cynodon dactylon*. These herbicides primarily act on actively growing foliage and lack soil residual activity, making them less suitable for prolonged weed suppression. Consequently, fields treated only with post-emergence herbicides experienced renewed weed growth during mid to late crop stages. The observations collectively underscore that early-season weed management through pre-emergence herbicides is indispensable for suppressing the initial and most damaging flush of weeds that competes vigorously with blackgram during its establishment phase. Integrated use of pre-emergence herbicides with timely cultural or manual operations thus provides the most effective strategy for maintaining a clean and healthy crop environment throughout the growing season (Singh *et al.* 2018; Patel & Patel, 2022) ^[5, 13, 16].

Weed density and dry matter are direct indicators of treatment efficacy. The data showed that all herbicidal treatments significantly reduced weed density compared with the unweeded control. Diclosulam completely suppressed weed emergence up to fifteen days after sowing, maintaining a weed-free condition during the most sensitive phase of the crop. Pendimethalin + imazethapyr also performed well but allowed a slight infestation of sedges and broad-leaved weeds. Post-emergence herbicides reduced existing weeds but were less effective in preventing later germination. As the crop advanced, weed density increased in all treatments, yet plots receiving a combination of herbicide and hand weeding at thirty days remained the cleanest. The unweeded control, on the other hand, maintained a consistently high population, confirming that continuous interference from weeds limits crop growth severely (Marimuthu *et al.* 2024; Singh *et al.* 2018) ^[8, 12].

Weed dry matter followed the same trend as density. The minimum weed biomass at all growth stages occurred in diclosulam + hand-weeding plots, followed closely by pendimethalin + imazethapyr + hand weeding and two hand-weeding treatments. The integrated use of chemical and manual control ensured both residual suppression and removal of late-emerging weeds, resulting in sustained low biomass even at harvest. Conversely, unchecked weed growth in the control plots produced heavy dry matter accumulation, which competed with the crop for nutrients, light, and moisture. The superiority of integrated methods over chemical-only options clearly demonstrated the advantage of combining persistence with mechanical removal to achieve season-long control (Marimuthu *et al.* 2024; Singh *et al.* 2018) ^[5, 12].

Weed control efficiency exhibited a clear inverse relationship with weed biomass accumulation, indicating that treatments capable of maintaining lower weed dry matter were also those with higher control efficiency. Among the various treatments tested, the maximum efficiency values were obtained in plots treated with diclosulam followed by hand weeding, pendimethalin + imazethapyr combined with hand weeding, and the treatment involving two manual weedings (Mishra & Yaduraju, 2017; Jadhav & Bhattacharya, 2019) ^[14, 15]. These treatments were successful in keeping the field nearly free from weed competition throughout the crop growth period, which was reflected in their consistently high WCE values exceeding 70 percent even at harvest. Diclosulam, when applied as a pre-emergence herbicide, provided almost

complete control during the early phase of the crop, maintaining near-total efficiency up to fifteen days after sowing. However, as its residual activity gradually declined with time and successive rainfall events, a small proportion of late-emerging weeds managed to establish, leading to a slight reduction in efficiency at later stages (Marimuthu *et al.* 2024; Singh *et al.* 2018)^[8, 12].

Incorporation of a single hand-weeding operation at thirty days after sowing effectively complemented the herbicide's residual action by physically removing surviving and newly emerged weeds. This integration not only revived the weed control efficiency but also sustained it at a higher level beyond sixty days, ensuring prolonged suppression until harvest. The combination of chemical and manual interventions thus demonstrated the advantage of sequential management, where herbicide application prevents early weed establishment while mechanical weeding eliminates later flushes that escape chemical control (Mishra & Yaduraju, 2017; Jadhav & Bhattacharya, 2019)^[14, 15].

On the other hand, post-emergence herbicides such as propaquizafop + imazethapyr and sodium acifluorfen + clodinafop recorded only moderate weed control efficiency. Their lower performance was mainly due to their foliar mode of action, which targets actively growing weeds present at the time of application but provides little or no residual effect on subsequently emerging species. Moreover, the presence of perennial weeds like *Cyperus rotundus* and *Cynodon dactylon*, which can regenerate from underground structures, further reduced the long-term effectiveness of post-emergence treatments. Consequently, weed biomass in these plots tended to increase at later growth stages, leading to a decline in overall efficiency (Singh *et al.* 2018; Patel & Patel, 2022)^[5, 13, 16].

The progressive reduction in WCE across all treatments with advancing crop age highlights the dynamic nature of weed emergence and the limitations of single-stage interventions. Continuous or staged weed management is essential to counter repeated germination waves under tropical kharif conditions where soil moisture fluctuations favour multiple weed flushes. Treatments that combined pre-emergence herbicides with a manual operation or mechanical weeding were able to maintain superior efficiency over time because they integrated both preventive and curative measures. Maintaining weed control efficiency above seventy percent until harvest proved critical for minimizing competition, conserving soil resources, and achieving higher yield. The results clearly demonstrate that an integrated approach, rather than reliance on any single herbicide, is necessary for sustaining long-term weed suppression and ensuring optimum productivity of blackgram (Mishra & Yaduraju, 2017; Jadhav & Bhattacharya, 2019)^[14, 15].

Observations on crop safety revealed that all the herbicides evaluated in the experiment were highly selective and safe for blackgram at the recommended rates of application. No major phytotoxic symptoms were observed in any treatment, indicating that the tested herbicides were compatible with the crop's physiological and biochemical systems. Diclosulam, when applied as a pre-emergence herbicide, caused only a mild and transient yellowing of cotyledons and the first true leaves during the initial few days after application. This temporary chlorosis was attributed to slight physiological stress induced by the herbicide's residual presence in the topsoil; however, the symptoms completely

disappeared within a week as the crop resumed normal growth. The rapid recovery of plants indicated that diclosulam, though biologically active in soil for a considerable period, remains selective to blackgram due to its limited uptake and efficient metabolic detoxification within plant tissues. Furthermore, no adverse effect on germination, plant stand, or seedling vigour was observed, confirming the crop's tolerance to its recommended dose (Marimuthu *et al.* 2024; Singh *et al.* 2018)^[5, 12].

The herbicide combinations involving pendimethalin + imazethapyr, propaquizafop + imazethapyr, and sodium acifluorfen + clodinafop exhibited excellent crop safety throughout the growing period. These mixtures did not produce any visible injury symptoms such as leaf chlorosis, necrosis, wilting, or growth retardation. The absence of phytotoxicity in these treatments can be ascribed to the high level of crop selectivity achieved through precise formulation and the crop's inherent ability to metabolize or compartmentalize the active ingredients before they reach toxic concentrations. Pendimethalin, for instance, primarily acts on germinating weed seedlings by inhibiting root and shoot elongation and has minimal effect on established crop seedlings. When combined with imazethapyr, which inhibits acetolactate synthase (ALS) in susceptible species, the mixture broadens the spectrum of weed control without compromising the safety of the legume crop.

A slight and temporary chlorosis was noticed in the plots treated with imazethapyr alone during the early post-emergence stage. This mild yellowing of younger leaves persisted for a few days and subsided as the crop advanced in age. The symptom was most likely due to transient inhibition of the ALS enzyme in the crop at higher initial absorption levels, but recovery occurred quickly through metabolic degradation of the herbicide within the plant. Importantly, this temporary response did not translate into any adverse effect on plant growth, nodulation, or final yield, signifying that the herbicide was physiologically selective to blackgram (Singh *et al.* 2018; Patel & Patel, 2022)^[5, 13, 16].

Overall, the absence of any significant or lasting phytotoxic effects across treatments confirmed the compatibility of all the tested herbicides with blackgram and demonstrated that the crop can safely tolerate their recommended doses under field conditions. The selectivity of these herbicides ensures that they can be effectively incorporated into integrated weed management programmes without the risk of crop injury or stand reduction. This aspect is particularly important for pulse crops like blackgram, which are generally sensitive to chemical stress during early growth stages. The results therefore validate the suitability of these herbicides for practical field use and reinforce the importance of dose accuracy and proper timing to maintain both crop safety and weed control efficacy (Mishra & Yaduraju, 2017; Jadhav & Bhattacharya, 2019)^[14, 15].

The uniformity of plant population across treatments showed that none of the herbicides interfered with germination or establishment. Differences in plant height, however, were pronounced. Plants in weed-free treatments were markedly taller than those in the unweeded plots, where competition for essential resources restricted elongation and canopy development. Pendimethalin + imazethapyr + hand-weeding produced the tallest plants throughout the growth period, followed closely by two

hand-weedings and diclosulam + hand-weeding (Marimuthu *et al.* 2024; Singh *et al.* 2018) ^[5, 12].

Leaf area index exhibited a similar pattern. Higher LAI in effectively weed-controlled plots indicated increased photosynthetic surface and enhanced light interception, while lower values in weedy plots resulted from shading by competing weeds. The number of branches per plant was also higher in weed-free conditions, reflecting improved physiological activity and nutrient availability. Under heavy weed pressure, the crop produced fewer branches due to suppressed growth and reduced assimilate supply (Marimuthu *et al.* 2024; Singh *et al.* 2018) ^[5, 12].

Dry matter accumulation in the crop canopy followed an increasing trend until harvest and was significantly influenced by weed control. The highest biomass was recorded in pendimethalin + imazethapyr + hand-weeding and diclosulam + hand-weeding treatments, which provided prolonged freedom from weed interference. Unweeded plots showed almost forty percent lower dry matter, highlighting the impact of weeds on resource capture. Effective weed control also promoted better root development and biological nitrogen fixation, as indicated by a greater number of active rhizobium nodules per plant. Enhanced nodulation under weed-free conditions can be attributed to better soil aeration and nutrient status, whereas heavy weed infestation restricted root activity and nodulation (Marimuthu *et al.* 2024; Singh *et al.* 2018) ^[5, 12].

Yield attributes such as number of pods per plant, seeds per pod, and test weight reflected the cumulative effect of weed management on crop growth. The maximum pods per plant were obtained in pendimethalin + imazethapyr + hand-weeding, closely followed by diclosulam + hand-weeding and two hand-weedings. The increase in pod number under these treatments resulted from improved branching, better flowering, and reduced abortion of reproductive structures due to absence of stress. Seeds per pod also increased under effective weed control because plants grown under weed-free conditions could allocate more assimilates for seed development (Marimuthu *et al.* 2024; Singh *et al.* 2018) ^[5, 12]. Similarly, test weight improved considerably when weeds were effectively managed, suggesting that nutrients and photosynthates were efficiently partitioned to the seeds (Sinha & Prakash, 2019; Patel & Patel, 2022) ^[13, 16].

The final seed and haulm yields mirrored the trends in yield attributes. Pendimethalin + imazethapyr + hand-weeding produced the highest seed yield, followed by two hand-weedings and diclosulam + hand-weeding. The yield advantage over the unweeded control exceeded sixty percent, confirming the severe yield loss caused by weed competition in blackgram. Higher haulm yield in these treatments indicated overall improvement in biomass production and better growth vigour. The harvest index was also greater in effectively weed-controlled plots, reflecting a higher proportion of economic yield to total biomass. In contrast, the unweeded control recorded a lower harvest index due to poor partitioning efficiency. The weed index, which denotes yield reduction relative to the best treatment, was lowest in the integrated treatments, further confirming their superiority in maintaining yield potential (Marimuthu *et al.* 2024; Singh *et al.* 2018) ^[5, 12].

Conclusion

The results of this investigation lead to the following major conclusions

1. The experimental field was infested with a complex weed flora comprising annual and perennial grasses, sedges, and broad-leaved weeds. Effective control of these species was essential during the early growth stages of blackgram to minimize yield loss.
2. Pre-emergence application of diclosulam 20 g ha⁻¹, followed by one hand-weeding at 30 DAS, proved to be the most efficient treatment in suppressing weeds, reducing their biomass, and maintaining high weed control efficiency throughout the crop growth period.
3. The treatment pendimethalin + imazethapyr @ 1000 g ha⁻¹ + hand-weeding was equally effective and statistically comparable to diclosulam + hand-weeding in most parameters.
4. Post-emergence herbicides such as propaquizafop + imazethapyr and sodium acifluorfen + clodinafop provided moderate control of existing weeds but were less effective in preventing later flushes due to lack of residual activity.
5. All herbicides were found safe and selective to blackgram, showing no adverse effect on crop stand, nodulation, or growth.
6. Effective weed control significantly improved all growth and yield attributes, leading to higher seed and haulm yields.
7. In terms of economic efficiency, diclosulam + hand-weeding at 30 DAS recorded the highest net returns and benefit-cost ratio, making it the most profitable option under the prevailing conditions.
8. Therefore, integrated weed management involving a pre-emergence application of diclosulam followed by one timely hand-weeding is recommended as the most suitable, cost-effective, and environmentally sustainable weed control strategy for blackgram cultivation in similar agro-climatic regions.

In conclusion, the study emphasizes that early-season integrated weed management is the key to achieving high productivity and profitability in blackgram. Adoption of such practices will not only enhance yield but also contribute to sustainable pulse production by reducing herbicide load, conserving soil health, and maintaining ecological balance in the farming system.

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