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Assessment of herbicide efficacy, phytotoxicity and economics in soybean (*Glycine max* L. Merrill)

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Abstract
Weeds are the major menace which causes more reduction in the yield as it evaluating survival tactics necessitates assessment of bioefficacy and phytotoxicity of new herbicides. A study was conducted at the University of Agricultural Sciences, GKVK, Bengaluru, during the *Kharif* seasons of 2022 and 2023. The experiment consists of seven different treatments, each replicated thrice in Randomized Complete Block Design (RCBD). Among the various herbicidal treatments, the application of bentazone 48% SL @ 1200 g a.i. ha^{-1} recorded significantly reduced total weed dry weight (29.56 and 46.63 g m^{-2}), showed the highest weed control efficiency (76.68% and 73.07%) at 30 and 45 days after sowing (DAS), respectively. Furthermore, application of bentazone 48% SL @ 960 g a.i. ha^{-1} led to notable improvements in plant height (27.31 cm) and seed yield (2225 kg/ha) and which was on par to the traditional practice of hand weeding at 20 DAS and one intercultural operation at 30 DAS (27.76 cm and 2290 kg/ha, respectively). This treatment also exhibited a lower weed index (2.83%) and higher net returns (Rs. 55,669 ha^{-1}) with B:C ratio of 2.76 as compared to other treatments. However, it is important to note that the higher dosage of bentazone (1200 g a.i. ha^{-1}) induced some phytotoxic effects on soybean particularly five days after application. Encouragingly, the weed control measures did not adversely affect the germination, root length, shoot length and seedling vigour index of the subsequent black gram crop.

Keywords: Bentazone**,** weed control efficiency, yield, economics, bioassay studies

Introduction
Oilseed crops, particularly soybean (*Glycine max* L. Merrill) hold a crucial position in both the global and Indian agricultural sectors. Renowned for its exceptional nutritional value, soybean boasts high protein content (40-42%), vegetable oil content (18-20%) and essential nutrients. Its versatility and substantial yield potential have earned it the monikers "Wonder Crop" and "Golden Bean" making it an important crop against acute malnutrition.
Globally, soybean cultivation covers an area of 127.60 million hectares, producing 364.07 million tons annually, with an average yield of 2796 kg/ha. India ranks fourth in cultivation area, with 11.40 million hectares contributing to 13.78 million tons annually and an average yield of 921 kg/ha (Anonymous, 2021) [6]. However, despite its potential, soybean productivity in India and Karnataka lags behind global averages, primarily due to biotic stress, particularly weed infestations. Weeds can cause yield losses ranging from 58% to 85% if not managed effectively during the crop-weed competition phase.
Traditional weed control methods like manual weeding have proven effective but are becoming expensive, labor-intensive and time-consuming. Unpredictable weather patterns and labor shortages necessitate for alternative weed management strategies. Herbicidal weed control emerges as a practical solution, with various herbicidal formulations. However, the evolving survival strategies of weeds require continuous research and the development of new herbicidal formulations. Shifts in weed emergence patterns have led to the development of early post-emergent herbicides which play a pivotal role in modern agriculture, especially in managing weed populations that can impact crop yields (Manisankar *et al.*, 2022) [10]. Assessing the bioefficacy and phytotoxicity of these herbicides in soybean cultivation is vital for informed weed management decisions, ensuring effective weed control without compromising crop health

and yield potential.

Bentazone, a newly developed early-post emergent herbicide shows promising in control on broad- leaved weeds. However, comprehensive testing of its bioefficacy and phytotoxicity at different doses in comparison to existing herbicides like imazethapyr and quizalofop ethyl is essential. This research aims to advance weed control practices in soybean farming, bridging the productivity gap and assessing the impact of different weed management practices on the succeeding black gram crop.

Materials and Methods

A field experiment was conducted at ZARS, University of Agricultural Sciences, GKVK, Bengaluru during the *Kharif* seasons of 2022 and 2023. The experimental soil was a red sandy loam with a moderately acidic pH of 5.64 had an electrical conductivity of 0.17 dS m^{-1}, organic carbon content of 3.4 g/kg, available nitrogen level of 278.15 kg/ha, phosphorus content of 25.50 kg/ha and potassium content of 192.80 kg/ha. To ensure scientific rigor, the study utilized the soybean variety JS-335 and followed a randomized block design with seven distinct treatments were replicated thrice. These treatments included; bentazone 48% SL @ 720 g a.i. ha^{-1} (T_1), bentazone 48% SL @ 960 g a.i. ha^{-1} (T_2), bentazone 48% SL @ 1200 g a.i. ha^{-1} (T_3), imazethapyr 10% SL @ 100 g a.i. ha^{-1} (T_4), quizalofop ethyl 5% EC @ 60 g a.i. ha^{-1} (T_5) hand weeding at 20 DAS and one intercultural operation at 30 DAS (T_6) and weedy check (T_7). The soybean crop was sown on June 2nd and 9th in 2022 and 2023, respectively and harvested on September 10th and 23rd in the corresponding years. Herbicide treatments were applied at 20 DAS as an early post emergent (EPoE) using a knapsack sprayer with a WFN 78 nozzle and a spray volume of 500 liters ha^{-1}. To assess weed density, quadrates measuring 50 × 50 cm were randomly placed in two locations within each treatment plot. Within these quadrates, grassy, broad-leaved and sedge weeds were counted and individually collected. The collected weeds were then dried to eliminate moisture and oven-dried at 60 °C ± 5 °C. Weed dry weights were measured in grams per square meter (g/m2) and square root transformation of $\sqrt{(X+1)}$ was applied for statistical analysis.

Various weed indices were calculated using the formulas recommended by Barla and Upasani (2022) [7]:

Weed management index (WMI)

WMI = [(YT-YC)/YC] / [(WC-WT)/WC]

Where,

YT = Yield of treated plot.

YC = Yield of control (weedy check) plot.

WC = Weed dry weight in control (weedy check) plot. WT= Weed dry weight in treated plot.

Weed persistence index (WPI)

WPI = (WT/WC) × (WPC/WPT)

Where,
WT = Weed dry weight in treated plot.
WC = Weed dry weight in control (weedy check) plot.
WPC = Weed population in control (weedy check) plot.
WPT = Weed population in treated plot.

Bioassay studies were conducted to assess the impact of herbicidal residue on the subsequent black gram crop. Black gram was manually sown (Dibling method) in each treatment within dedicated net plot areas, received recommended fertilizer doses and was regularly irrigated. Germination percentage, shoot and root length measurements and vigour index calculations were taken at 10, 15 and 30 days after sowing (DAS), following the formulas used for calculation of germination (%) and seedling vigour index introduced by Abdul Baki and Anderson (1973) [2].

$$\text{Germination (\%)} = \frac{\text{Total number of seedling emergence}}{\text{Total number of seeds sown}} \times 100$$

Seedling vigour Index = Germination (%) × [Root length (cm) + Shoot length (cm)].

Resul and Discussion

Weed Dynamics

The major weed flora observed in the experimental field was *Cyperus rotundus* (among sedges), *Echinochloa colona, Eleusine indica, Cynadon dactylon, Dactyloctenium aegyptium, Digitaria marginata* (among grasses), *Ageratum conyzoides, Acalypha indica, Alternathera sessilis, Borreria hispida, Oldenlandia umbellata* (among broad-leaved weeds). Weed management practices significantly influenced on weed dynamics (Table 1 and 2). The application of bentazone 48% SL @ 1200 g a.i. ha^{-1} exhibited the highest weed control efficiency (WCE) at 30 and 45 DAS (76.68 and 73.07%, respectively). This was attributed to reduced weed density (23.53 and 27.48 No. m^{-2}) and dry weight (29.56 and 46.63 g m^{-2}) might be due to bentazone's mode of action, involving interaction with quinone B at the photosystem II reaction center leading to oxidative stress within weed cells and their subsequent demise (Czekus *et al.*, 2020) [8]. However, bentazone 48% SL at 960 g a.i. ha^{-1} showed the highest weed management index (WMI) at 30 and 45 DAS (2.02 and 2.10, respectively) and the lowest weed index (WI) of 2.83, likely due to higher seed yield compared to other herbicidal treatments. Quizalofop ethyl 5% EC @ 60 g a.i. ha^{-1} noticed reduced grassy weed density (8.37 and 10.66 No. m^{-2}) and dry weight (17.39 and 26.40 g m^{-2}) could be due to inhibiting acetyl coenzyme A carboxylase (ACCase), essential for fatty acid synthesis in grassy weed species (Barla and Upasani, 2022) [7]. Hand weeding at 20 DAS and one intercultural operation at 30 DAS recorded reduced weed density (8.04 and 14.47 No. m^{-2}) and weed dry weight (6.76 and 15.59 No. m^{-2}) due to manual removal of weed during the critical period of crop-weed competition. Conversely, the weedy check exhibited the highest weed density (84.54 and 89.82 No. m^{-2}) and greater weed dry weight (126.74 and 173.16 No. m^{-2}) at 30 and 45 DAS, respectively.

Table 1: Effect of weed control treatments on weed density and dry weight of weeds in soybean (mean of 2022 and 2023)

	Weed density (No. m^{-2})								Weed dry weight (g m^{-2})							
Treatment	**Sedges**		**Grasses**	**Broad leaved**			**Total**		**Sedges**			**Grasses**	**Broad leaved**		**Total**	
	30 DAS	**45 DAS**	**30 DAS**	**45 DAS**	**30 DAS**	**45 DAS**	**30 DAS**	**45 DAS**	**30 DAS**	**45 DAS**	**30 DAS**	**45 DAS**	**30 DAS**	**45 DAS**	**30 DAS**	**45 DAS**
T_1	4.48 (19.16)	4.77 (21.82)	4.96 (23.72)	5.02 (24.33)	4.64 (20.65)	4.61 (20.31)	8.02 (63.54)	8.20 (66.47)	3.95 (14.65)	4.74 (21.57)	5.67 (31.30)	6.41 (40.17)	4.69 (21.04)	5.42 (28.46)	8.19 (67.00)	9.51 (90.21)
T_2	3.07 (8.49)	3.47 (11.15)	3.82 (13.71)	4.23 (17.00)	3.35 (10.32)	3.05 (8.33)	5.77 (32.53)	6.11 (36.49)	2.77 (6.78)	3.73 (12.96)	5.03 (24.38)	5.87 (33.58)	2.94 (7.70)	3.45 (10.98)	6.15 (38.87)	7.52 (57.53)
T_3	2.60 (5.83)	3.07 (8.49)	3.41 (10.7)	3.73 (12.99)	2.81 (6.99)	2.64 (5.99)	4.93 (23.53)	5.32 (27.48)	2.36 (4.67)	3.40 (10.59)	4.58 (20.08)	5.46 (28.95)	2.39 (4.80)	2.83 (7.08)	5.32 (29.56)	6.74 (46.63)
T_4	3.48 (11.16)	3.84 (13.82)	4.16 (16.38)	4.53 (19.66)	3.64 (12.34)	3.46 (10.99)	6.38 (39.89)	6.73 (44.48)	3.13 (8.88)	4.09 (15.80)	5.29 (27.05)	6.15 (36.93)	3.58 (11.87)	4.03 (15.28)	6.87 (47.81)	8.21 (68.01)
T_5	4.17 (16.49)	4.48 (19.15)	3.05 (8.37)	3.40 (10.66)	4.42 (18.65)	4.20 (16.66)	6.65 (43.52)	6.88 (46.48)	3.69 (12.7)	4.46 (18.94)	4.28 (17.39)	5.23 (26.40)	4.41 (18.49)	5.07 (24.78)	7.02 (48.59)	8.42 (70.13)
T_6	1.00 (0.00)	2.18 (3.83)	2.29 (4.38)	2.75 (6.65)	2.12 (3.66)	2.22 (3.98)	2.96 (8.04)	3.91 (14.47)	1.00 (0.00)	1.77 (2.20)	2.35 (4.71)	3.20 (9.32)	1.71 (2.05)	2.24 (4.07)	2.64 (6.76)	3.96 (15.59)
T_7	4.84 (22.49)	5.30 (27.16)	5.22 (26.39)	5.62 (30.66)	6.05 (35.66)	5.74 (31.99)	9.18 (84.54)	9.51 (89.82)	5.63 (30.8)	7.54 (55.96)	7.26 (51.88)	8.10 (64.69)	6.7 (44.05)	7.30 (52.51)	11.26 (126.74)	13.19 (173.16)
S.Em (±)	0.07	0.07	0.07	0.08	0.05	0.05	0.27	0.13	0.05	0.06	0.05	0.06	0.06	0.09	0.56	0.58
LSD (P=0.05)	0.20	0.22	0.21	0.22	0.15	0.15	0.79	0.39	0.13	0.17	0.15	0.17	0.18	0.27	1.64	1.67

***Figures in parenthesis are original values; DAS:** Days after sowing'

Table 2: Weed indices as influenced by weed management treatments in soybean (mean of 2022 and 2023)

Treatment	WCE (%)		WPI		WMI		WI (%)
	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS	
T_1: Bentazone 48% SL @ 720 g a.i. ha^{-1} (EPoE)	47.13	47.90	0.70	0.70	0.91	0.90	42.16
T_2: Bentazone 48% SL @ 960 g a.i. ha^{-1} (EPoE)	69.33	66.78	0.80	0.82	2.02	2.10	2.83
T_3: Bentazone 48% SL @ 1200 g a.i. ha^{-1} (EPoE)	76.68	73.07	0.84	0.88	1.41	1.48	15.70
T_4: Imazethapyr 10% SL @ 100 g a.i. ha^{-1} (EPoE)	62.28	60.72	0.80	0.79	1.23	1.26	28.60
T_5: Quizalofop ethyl 5% EC @ 60 g a.i. ha^{-1} (EPoE)	61.66	59.50	0.74	0.78	1.23	1.27	28.90
T_6: Hand weeding at 20 DAS and one intercultural operation at 30 DAS	94.66	90.99	0.56	0.56	1.56	1.62	-
T_7: Weedy check (Untreated control)	-	-	-	-	-	-	59.56

DAS: Days after sowing; **EPoE:** Early post emergent; **WCE:** Weed control efficiency; **WI:** Weed index

Plant growth and development and enzymatic activity of soil

During the study plant growth and development and enzymatic activity in soil was deliberated to evaluate the impact of different weed management practices (Table 4). Among the herbicidal application, higher plant height was noticed in bentazone 48% SL at 960 g a.i. ha^{-1} at 30 and 45 DAS (17.01 and 27.31 cm, respectively) due to reduced crop weed competition by herbicidal mode of action on weeds led to increased nutrient availability, soil moisture and light which are typically seized by weeds (Akila and Babu, 2019) [4] and it was on par with hand weeding at 20 DAS and one intercultural operation at 30 DAS (17.42 and 27.76 cm, respectively). However, weedy check recorded lesser plant height (14.58 and 20.54 cm, respectively).

Similarly, at 45 DAS significantly higher number of leaves per plant and dry matter accumulation per plant was found in application of bentazone 48% SL at 960 g a.i. ha^{-1} (19.80 No. $plant^{-1}$ and 6.20 g $plant^{-1}$, respectively) due to the increased number of leaves might have facilitated to capture more solar energy for metabolic use, more CO2 fixation and produce greater photosynthates which may cause a positive effect on biomass production and increase the total dry matter production per plant. Results are in line with Ahirwar *et al*. (2018) [3].

At 30 and 45 DAS, maximum number of active nodules was found in hand weeding at 20 DAS and one intercultural operation at 30 DAS (24.66 and 47.25 No. $plant^{-1}$, respectively) followed by application of bentazone 48% SL at 960 g a.i. ha^{-1} (23.56 and 46.44 No. $plant^{-1}$, respectively) due weed free environment in the rhizosphere led to the formation of more roots and effective nodules (Abdallah *et al*., 2021). While, weedy check observed lower number of leaves (11.82 No. $plant^{-1}$), lesser dry matter accumulation per plant (3.24 g $plant^{-1}$) and recorded minimum number of active nodules per plant at 30 and 45 DAS (11.40 and 31.80 No. $plant^{-1}$, respectively).

Table 3: Effect of different weed management treatments on growth and development of soybean and soil enzyme activity (mean of 2022 and 2023)

Treatment	Plant height (cm)		No. of $leaves^{-1}$		Dry matter accumulation $plant^{-1}$ (g)		No. active $nodules^{-1}$		Dehydrogenase activity at 15 DAHS (µg TPF g^{-1} 24 h^{-1})
	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS	30 DAS	45 DAS	
T_1	14.87	22.13	5.68	14.20	2.81	4.02	13.70	36.21	1.93
T_2	17.01	27.31	6.26	19.80	3.06	6.20	23.56	46.44	2.31
T_3	16.49	23.95	6.04	17.26	2.99	5.52	19.05	42.60	1.83
T_4	16.12	23.84	5.85	16.80	2.97	5.06	16.58	37.52	2.10
T_5	15.56	22.83	5.76	15.36	2.85	4.40	16.27	36.77	1.99
T_6	17.42	27.76	6.54	20.42	3.13	6.69	24.66	47.25	2.72
T_7	14.58	20.54	5.56	11.82	2.78	3.24	11.40	31.80	2.57
S.Em (±)	0.20	0.42	0.37	0.43	0.22	0.21	0.47	1.62	0.06
LSD (P=0.05)	0.59	1.22	NS	1.24	NS	0.61	1.37	4.71	0.17

DAS: Days after sowing; **DAHS:** Days after herbicidal spraying

Significantly higher soil dehydrogenase activity was found in hand weeding at 20 DAS and one intercultural operation at 30 DAS (2.72 µg TPF g^{-1} 24 h^{-1}) followed by weedy check (2.57 µg TPF g^{-1} 24 h^{-1}). These treatments, devoid of herbicidal application, promoted increased enzyme production through microbial and plant interactions. Among the herbicidal treatments, higher dehydrogenase activity observed in bentazone 48% SL @ 960 g a.i. ha^{-1} (2.31 µg TPF g^{-1} 24 h^{-1}). Whereas, bentazone 48% SL @ 1200 g a.i. ha^{-1} recorded lower soil dehydrogenase activity (1.83 µg TPF g^{-1} 24 h^{-1}) might be due to competitive and toxic effects of herbicides in the soil (Pal *et al.*, 2013). Though, the application of bentazone 48% SL at 1200 g a.i. ha^{-1} observed higher control in weeds but exhibited slight discoloration and stunted symptoms with a visual phytotoxicity rating of 1 observed between 5 to 21 days after herbicide application (DAHS). The higher bentazone dosage led to phytotoxicity in soybean, disrupting chlorophyll synthesis, resulting in reduced plant growth, development and enzymatic activity compared to the lower dosage of bentazone (Ali *et al.*, 2021) [5].

Yield and yield attributes

All the weed management approaches had a significant impact on various yield-related parameters when compared to the weedy check (Table 5). The application of bentazone 48% SL @ 960 g a.i. ha^{-1} resulted remarkable increase in seed yield about 58.34% (2225 kg/ha) and haulm yield 47.03% (3157 kg/ha) due to significantly recording higher number of pods per plant (41.85), number of seeds per pod (2.88), hundred seed weight (10.31) this inturn results for obtaining maximum harvest index (0.413) and it was on par with in hand weeding at 20 DAS and one intercultural operation at 30 DAS (2290 and 3206 kg/ha, 42.92, 2.91, 0.36 and 0.416, respectively). However weedy check noticed lower yield and yield attributes. This positive outcome can be attributed to the precise dosage of bentazone herbicide which resulted in a reduced production of reactive oxygen species. This reduction, inturn decreased the reliance on soybean antioxidant enzyme activity, ultimately leading to higher yields (Justin *et al.*, 2023) [9].

Table 4: Yield attributes, yield and economics of soybean as influenced by different weed management treatments (mean of 2022 and 2023)

Treatment	Number of pods/plants	Number of seeds/pods	100 seeds weight (g)	Seed yield (kg/ha)	Haulm yield (kg/ha)	Harvest index	Gross returns (Rs./ha)	Net returns (Rs./ha)	B:C ratio
T_1	26.67	2.19	9.98	1325	2097	0.385	51802	20570	1.66
T_2	41.85	2.88	10.31	2225	3157	0.413	87379	55669	2.76
T_3	37.71	2.59	10.25	1931	2828	0.405	75739	43552	2.35
T_4	33.76	2.35	10.16	1635	2438	0.401	64066	32958	2.06
T_5	31.92	2.24	10.04	1628	2429	0.399	63801	32201	2.02
T_6	42.92	2.91	10.36	2290	3206	0.416	89956	50156	2.26
T_7	20.39	2.16	9.90	926	1672	0.352	36065	6265	1.21
S.Em (±)	0.94	0.08	0.52	101	137	0.009	-	-	-
LSD (P=0.05)	2.75	0.24	NS	293	399	0.026	-	-	-

Economics

Among the different treatments, the higher cost of cultivation recorded in hand weeding at 20 DAS and one intercultural operation at 30 DAS (Rs. 39,800 ha^{-1}) with higher gross returns (Rs. 89,956 ha^{-1}) and net returns (Rs. 50,156 ha^{-1}) but higher net returns (Rs. 55669 ha^{-1}) with higher B:C ratio of 2.76 was obtained in application of bentazone 48% SL @ 960 g a.i. ha^{-1} herbicide due to reduced labour cost with higher weed control efficiency and no phytotoxicity effect on the crop (Meseldzija *et al.*, 2020) [11]. While, lesser B:C ratio was obtained in weedy check treatment (1.41).

Bioassay studies

There was no significant difference in the length of the shoot and root of black gram at 15 and 30 DAS which was sown after the harvest of soybean (Table 6). This might be due to the lesser persistence capacity of herbicide in soil as it remains in the soil for about 7 to 21 days and later, they have completely degraded by the time of black gram crop was sown (Sudhakara *et al.*, 2014) [13], but at 30 DAS, significantly lower seedling vigour index was recorded in bentazone 48% SL @ 1200 g a.i. ha^{-1} (2111.75) as compared to other herbicidal treatments this might be due recording a lesser germination per cent recorded.

Table 5: Effect of different weed management treatments on succeeding crop black gram (mean of 2022 and 2023)

Treatment	Germination (%)		Shoot and root length of black gram			Seedling vigour index	
			15 DAS		30 DAS		
	Shoot		Root	Shoot	Root	15 DAS	30 DAS
T_1	84.64	8.01	3.21	18.01	7.78	953.85	2200.45
T_2	86.51	8.03	3.24	18.45	8.30	977.81	2319.44
T_3	83.31	7.99	3.19	17.73	7.56	934.14	2111.75
T_4	85.25	8.04	3.23	18.43	8.28	963.10	2282.21
T_5	85.21	8.01	3.21	18.08	8.24	956.69	2243.17
T_6	92.33	8.09	3.29	18.78	8.56	1050.74	2524.39
T_7	88.41	8.05	3.26	18.51	8.41	1000.06	2379.92
S.Em (±)	2.22	0.20	0.08	0.47	0.32	38.28	101.54
LSD (P=0.05)	6.44	NS	NS	NS	NS	NS	295.16

DAS: Days after sowing

Conclusion

Application of bentazone 48% SL @ 960 g a.i. ha^{-1} was found suitable for effective control of sedges and broad-leaved weeds and gave comparable yield with hand weeding at 20 DAS and one intercultural operation @ 30 DAS without any negative impact on crop growth and development and gave better WCE with higher B:C ratio (2.76) as compared to lower and higher dose of bentazone and other herbicidal application without hampering yield in soybean. Importantly, bentazone was not shown any observable phytotoxicity symptoms on the germination, root length, shoot length and seedling vigour index of the succeeding black gram crop.

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