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RESEARCH ARTICLE

Efficacy of adjuvant augmented glyphosate against purple nutsedge (*Cyperus* spp.) and its regrowth

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ABSTRACT

A field study was conducted in the *Vertisols* of South Gujarat to evaluate the efficacy of glyphosate-adjuvant combinations against a complex weed flora dominated by perennial sedges. The uniform pretreatment weed flora in the experimental area includes: *Cyperus rotundus*, *Echinochloa crus-galli* and *Trianthema portulacastrum*. Assessment revealed significant variation in mortality and regrowth of *Cyperus* spp. at 40 days after application (DAA). Glyphosate + ammonium sulphate (1.5 kg/ha + 2%) recorded complete mortality (100.0%) of *Cyperus* spp., and was statistically at par with glyphosate + 2,4-D (99.52%) and glyphosate + sugar (99.14%). Mechanical inter-culturing was ineffective as rhizome fragmentation triggered dormant bud release and caused a regrowth surge, while glyphosate + ammonium sulphate recorded minimum regrowth of *Cyperus* spp. Economic analysis at 40 DAA indicated glyphosate + ammonium sulphate and glyphosate + 2,4-D as the most viable strategies achieving the highest *Cyperus* control efficiency (>72%) with the lowest cost per percent control. The growth and yield parameters of the successively grown blackgram confirmed the lack of any significant residual effect from the applied herbicides. Thus, for the sustainable management of tuberous perennials, the adjuvant augmented glyphosate was found significantly more effective than traditional mechanical methods.

Keywords: Adjuvants, *Cyperus* spp., Glyphosate, Glyphosate + ammonium sulphate, Weed management

INTRODUCTION

Interference by weeds often results in substantial yield and economic losses (Rao 2022). Effective assessment of weed-induced losses is therefore essential for developing appropriate management strategies. Among perennial weeds, nutsedge (*Cyperus* spp.), particularly purple nutsedge (*Cyperus rotundus* L.) is recognized as one of the most problematic species worldwide (Benvenuti 2025). In India, it is widely distributed across cultivated lands up to 2000 m above mean sea level (Dev 2023.). Nutsedge infests numerous field and vegetable crops including rice, maize, cotton, sugarcane, onion, okra, cabbage, carrot and cucumber across tropical and subtropical regions (Dor and Hershenhorn 2013). The persistence and aggressiveness of *Cyperus* spp. are primarily attributed to vegetative reproduction through tubers and rhizomes, rather than seed propagation (Sharma and Gupta 2007; Lati *et al.* 2011). Purple nutsedge exhibits an exceptionally high multiplication rate with a single tuber capable of producing extensive daughter tubers within a short period leading to dense infestations (Dor and Hershenhorn 2013). Its C„ photosynthetic pathway and positive response to nitrogen further enhance its competitive advantage in cropping systems (Lati *et al.* 2011).

Crop yield reductions due to nutsedge interference have been widely reported, reaching severe levels in several vegetable crops (Roozkhosh *et al.* 2025). Although cultural and mechanical practices such as tillage, solarization and shading can suppress nutsedge growth and their effectiveness are often limited by rapid vegetative regrowth (Benvenuti 2025). Consequently, chemical weed control has become an integral component of nutsedge management (Varanasi *et al.* 2025).

Glyphosate [*N*-(phosphonomethyl) glycine] is a non-selective, systemic, post-emergence herbicide extensively used for broad-spectrum weed control (Baylis 2000). It inhibits the shikimate pathway leading to disruption of aromatic amino acid biosynthesis and plant growth inhibition (Duke and Powles 2008). However, its performance against perennial weeds such as *Cyperus* spp. is influenced by environmental conditions, formulation type, spray solution characteristics and plant growth stage (McMullan 2000). Recent studies emphasize that the use of herbicide mixtures and suitable adjuvants can enhance glyphosate absorption, translocation, and

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overall efficacy, while allowing reduction in application rates (Miller *et al.* 2013; Mahajan and Chauhan 2015). Combinations involving herbicides with different modes of action such as glyphosate with 2,4-D or oxyfluorfen may provide synergistic effects, improved control of perennial sedges and economic advantages over single or sequential applications.

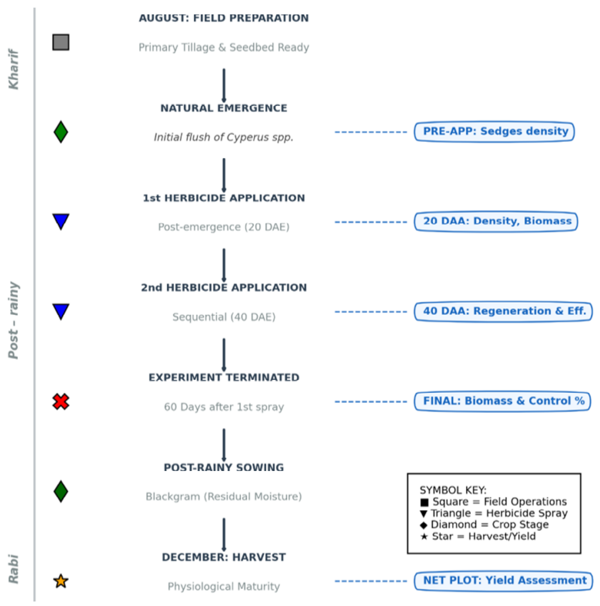
In view of the persistent nature of nutsedge and the need for cost-effective and efficient weed control strategies, the present study was undertaken to evaluate the synergistic potential of glyphosate- based herbicide combinations and additives for the management of nutsedge (*Cyperus* spp.) without any residual effect on crops grown in succession.

MATERIAL AND METHODS

Field trials were conducted during 2021–22 at Plot No. 11-A, College Farm, NAU, Bharuch (21.70° N, 72.99° E; 16.5 m AMSL) in the South Gujarat Agro-climatic Zone II. The study was carried out during the *Kharif* season to evaluate the efficacy of herbicides on *Cyperus* spp., and assess residual phytotoxicity of herbicides tested on blackgram sown in the rabi season as a bioassay. The experiment was conducted on fallow-cultivated land naturally, uniformly and heavily infested with *Cyperus* spp. for identifying cost effective and efficient control option. The tropical monsoon climate featuring a high thermal regime (max. 35.3°C) and morning relative humidity (94.1%) with 41 rainy days maintained a substantial vapor pressure deficit (evaporation 2.7–9.3 mm/day) that facilitated rapid subterranean tuber differentiation and shoot emergence. The edaphic situation was a clayey *Vertisol* characterized by high shrink-swell potential and moisture retention. Pre-experimental analysis (0–30 cm) revealed a sub-alkaline pH (7.8), non-saline EC (0.26 dS/m) and 0.45% OC. The fertility status was low in available N (242 kg/ha), medium in P, O… (36.1 kg/ha) and high in K, O (318 kg/ha) representing conditions highly conducive to the competitive vigour of the weed-crop association. The experimental field had been under a dill/soybean/sorghum cultivation during the previous three years followed by fallow periods. The predominantly nutsedge (*Cyperus* spp.) was associated with major weeds like *Digera arvensis*, *Commelina benghalensis*, *Echinochloa* spp. and *Trianthema portulacastrum*, in the experimental field.

The experiment was laid out in a randomized block design with three replications. Nine treatments were evaluated including: W_1: weedy check, W_2: inter culturing twice 20 and 40 days after seeding (DAS), W_3: glyphosate 41% SL (glyphosate) 2.0 kg/ha, W_4: glyphosate + ammonium sulphate 1.5 kg/ha + 2%, W_5: glyphosate + sugar 1.5 kg/ha + 2%, W_6: glyphosate + urea 1.5 kg/ha + 2%, W_7: glyphosate + kaolin 1.5 kg/ha + 1.5 kg/ha, W_8: glyphosate + 2,4-D amine 1.0 kg/ha + 1.0 kg/ha, W_9: glyphosate + oxyfluorfen 2.0 kg/ha. To ensure complete solubility and homogeneity, all adjuvants were dissolved separately in small aliquots of water prior to incorporation into the final spray mixture. The herbicidal were applied using a battery-operated knapsack sprayer fitted with a flat-fan nozzle. The equipment was calibrated to an operating pressure of 1.5–2.0 kg/cm² to deliver a constant spray volume of 375 L/ha, ensuring uniform droplet distribution and coverage on the target foliage. Required quantities of commercial formulations were calculated based on active ingredient (*a.i.*) concentration and gross plot area (12 m²).

Weed flora observations were recorded pre-spraying and at 20 and 40 days after herbicide application (DAA). Sedge density (no./m²) was determined using a 1.0 m² quadrat. Weed mortality (%) was computed based on the population of surviving plants relative to the initial stand. Regrowth count (no./plot) was monitored at 20 and 40 DAA to evaluate the longevity of suppression. *Cyperus* control efficiency (CCE, %) was calculated according to the formula suggested by Kondap and Upadhyay (1985).



Flowchart 1. Experimental timeline illustrating field preparation, herbicide applications against *Cyperus* spp. during the *Kharif* season and subsequent evaluation of residual effects on green gram grown in the *rabi* season

Experimental data were analysed using ANOVA for RBD (Panse and Sukhatme 1967). Weed density and regrowth counts were normalized using square root ($\sqrt{x+0.5}$) transformation and mortality percentages were arcsine ($\sin^{-1}\sqrt{x/100}$) transformed prior to analysis (Steel and Torrie 1960). Treatment means were compared using the F-test (P=0.05), with Least Significant Difference (LSD)and Duncan's Multiple Range Test (DMRT) utilized to separate significant means.

RESULTS AND DISCUSSION

Weed flora

A comprehensive floristic survey revealed a heterogeneous weed population comprising 15 species. Taxonomic distribution showed a dominance of *Amaranthaceae* and *Poaceae* among broad-leaved weeds and grasses, respectively. Among monocots, *Echinochloa crus-galli* and *Commelina benghalensis* were the major species, the latter possessing a dual seeding survival mechanism. The broad-leaved weeds were dominated by *Trianthema portulacastrum* and *Digera arvensis,* both exhibiting high ecological amplitude and succulent growth habits. The sedge complex was uniquely diverse featuring the perennial *Cyperus rotundus* alongside annual species like *C. iria*. The persistence of *C. rotundus* linked to its underground tuber/rhizome chain, which serves as a primary perennating organ (Rathod *et al.* 2025). The existence of fast growing C_4 grasses prostrate succulents and tuberous perennials created a high intensity competitive situation characterized by rapid occupation and significant resource depletion potential (Grime 2001).

Prior to treatment, sedges (*Cyperus* spp.) dominated the weed flora with a relative density of 41.87% followed by BLWs (35.87%) and grasses (22.26%). This hierarchy in the heavy *Vertisols* of South Gujarat reflects the adaptive plasticity of the *Cyperaceae* complex as edaphic factors favour sedges over annual grasses (Mishra *et al.* 2021). The initial weed density recorded prior to the application of treatments at 20 days showed a uniform distribution across the experimental site with no significant differences observed among the various plots (W_1 to W_9). The resilience of *Cyperus* spp. stems from a "basal bulb-rhizome-tuber" network acting as a carbohydrate sink for rapid colonization (Peerzada *et al.* 2017) alongside a C_4 pathway that optimizes resource acquisition (Biruk *et al.* 2025). Lower grass abundance suggests competitive exclusion by these prostrate dicots and perennial sedges (Vila *et al.* 2011). Well managing this population requires translocation intensive herbicides like glyphosate with adjuvants to disrupt tuber apical dominance (Chauhan *et al.* 2017, Singh *et al.* 2025).

Pre-treatment weed density did not differ significantly confirming uniform weed pressure and ensuring that observed differences in weed control and performance were due to treatment effects rather than field variability (Das and Gupta 2021). Such lack of statistical significance indicates a uniform weed seed bank, a phenomenon typically observed in high density field evaluations. The stability of the weed community structure suggests that the soil seed bank was well distributed, and initial flushes were unaffected by short term management variables (Shamina *et al.* 2022). Consequently, this uniformity provides a robust baseline for evaluating the direct effects of treatments on crop-weed competitive interactions and long-term weed flora shifts (Cordeau *et al.* 2022).

Impact of treatments on *Cyperus* density

The effect of herbicides and adjuvants on *Cyperus* density showed significant changes among treatments at 20 and 40 days after application, while initial *Cyperus* counts were uniform and not significant **(Figure 1)** indicating uniform invasion across plots and providing a reliable baseline for evaluating treatments. At 20 days after application, the weedy check had the highest *Cyperus* density significantly higher than all other treatments. Inter-culturing reduced weed density moderately and was significantly better than the weedy check but less effective than herbicides. Glyphosate alone provided moderate suppression and was statistically at par with glyphosate + urea, glyphosate + kaolin and glyphosate + oxyfluorfen. Glyphosate + sugar and glyphosate + ammonium sulphate were most effective and found significantly superior to all other treatments. Glyphosate + 2,4-D also provided strong suppression and was statistically at par with glyphosate + sugar and glyphosate + ammonium sulphate (Singh *et al.* 2025).

By 40 days after application, weedy check continued the highest *Cyperus* density, significantly exceeding all other treatments and confirming weed persistence without intervention. While inter-culturing offered moderate reduction over the control, its efficacy was statistically comparable to glyphosate alone or combined with kaolin or oxyfluorfen, highlighting the limited long-term impact of mechanical methods. In contrast, glyphosate + sugar and glyphosate + ammonium sulphate remained the most effective treatments, significantly hiding others while remaining at par with the glyphosate + 2,4-D application. Meanwhile, glyphosate combinations with urea, kaolin or oxyfluorfen provided only intermediate control showing no significant improvement over glyphosate applied alone.

The superior performance of glyphosate + sugar and glyphosate + ammonium sulphate is attributed to improved herbicide absorption and translocation. Sugar based adjuvants enhance retention on leaf surfaces and facilitate uptake, while ammonium sulphate reduces antagonistic effects of water hardness ions, improving glyphosate performance (Travlos *et al.* 2017, Basílio *et al.* 2024). Moderate adjuvants such as urea, kaolin, 2,4-D and oxyfluorfen provide partial enhancement through improved uptake or mechanical/oxidative stress, but their effect is less sustained over time (Idziak *et al.* 2023, Patel *et al.* 2023). Mechanical control methods, including weeding and inter-culturing were less effective in both short- and long-term suppression highlighting the limitations of cultural practices alone. Statistical validation at 20 and 40 DAA confirms that adjuvant assisted glyphosate applications are significantly more effective than mechanical control or glyphosate alone emphasizing the importance of integrated chemical-adjuvant strategies for sustainable *Cyperus* management (Chaudhari *et al.* 2024).

Mortality and regrowth of *Cyperus* spp.

Cyperus spp. management **(Table 1)** showed rapid chlorosis and necrosis within 7 days reaching total desiccation by 3-4 weeks. At 20 DAA, mortality was significantly highest in the glyphosate + 2,4-D treatment (89.68%), beating standalone glyphosate. This rapid kill is attributed to complementary modes of action; while glyphosate inhibits the EPSPS pathway, 2,4-D acts as a systemic auxin inducing vascular tissue collapse. This hormonal disruption significantly "primes" the plant, increasing metabolic sink activity and potentially accelerating the translocation of glyphosate into subterranean tuber chains (Larini *et al.* 2025). By 40 DAA, glyphosate + ammonium sulphate achieved significant superiority with complete (100.0%) mortality. However, it was statistically at par with glyphosate + 2,4-D (99.52%) and glyphosate + sugar (99.14%) forming a high efficacy cluster. This highlights the role of AS and humectants in mitigating antagonistic cations and acidifying the leaf surface to enhance cuticular flux (Daramola *et al.* 2022, Zangoueinejad *et al.* 2022).

Regrowth dynamics further confirmed the significant superiority of chemical suppression over mechanical intervention. Inter-culturing (twice) failed significantly resulting in a surge of regrowth (397.3 individuals/plot) by 40 DAA that was significantly higher than even the weedy check (24.0 individuals/plot). This counterproductive response confirms that mechanical tillage fragments rhizome chains and breaks apical dominance. In the absence of systemic herbicides, physical disturbance significantly

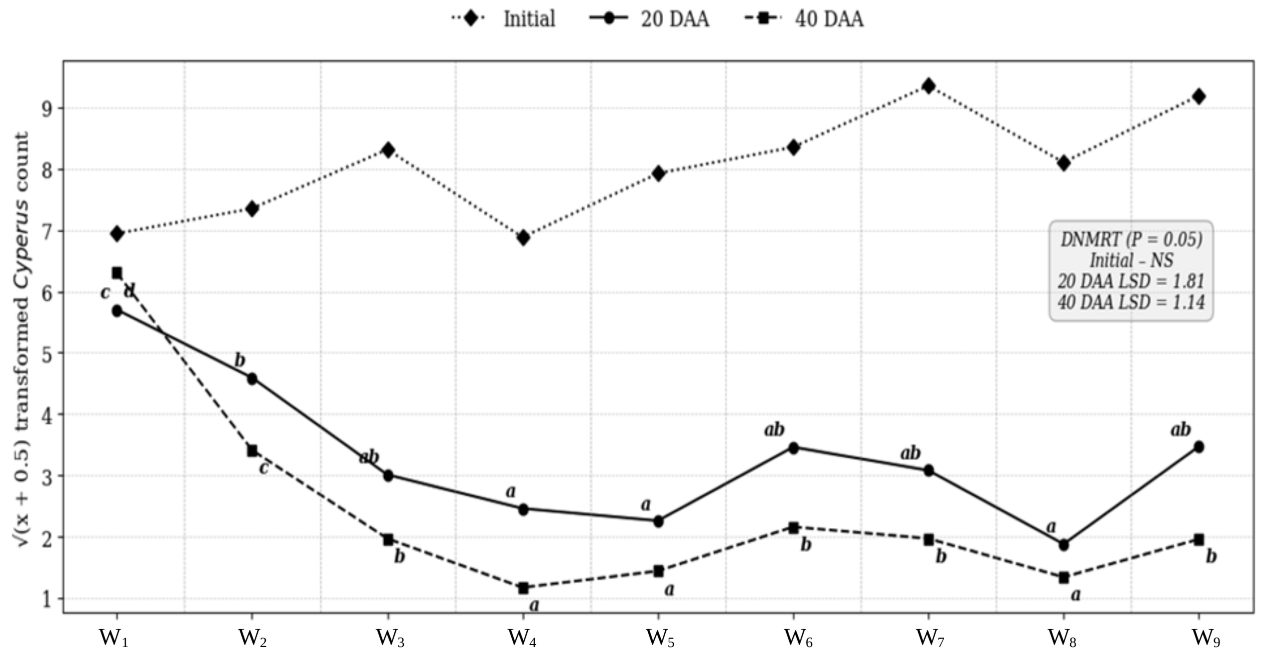


Figure 1. Effect of weed management on *Cyperus* spp. counts at Initial, 20 and 40 days after application.

(Values at 20 and 40 DAA were compared using Duncan's multiple range test (p=0.05); initial counts were not significant. Least significant difference (LSD) at 20 DAA = 1.81 and 40 DAA = 1.14. Different letters indicate significant differences between treatments]. (W_1: weedy (control; no weed management); W_2: inter-culturing (20 and 40 DAS); W_3: glyphosate 2.0 kg/ha; W_4: glyphosate 1.5 kg/ha + ammonium sulphate 2%; W_5: glyphosate 1.5 kg/ha + sugar 2%; W_6: glyphosate 1.5 kg/ha + urea 2%; W_7: glyphosate 1.5 kg/ha + kaolin 1.5 kg/ha; W_8: glyphosate 1.0 kg/ha + 2,4-D amine 1.0 kg/ha; W_9: 2.0 kg/ha + oxyfluorfen.

stimulates dormant secondary buds to sprout (Peerzada 2017). Conversely, chemical treatments achieved a significant residual suppression (>93%) of the tuber bank. The minimum regrowth (9.0 individuals/plot) observed in glyphosate + ammonium sulphate was statistically comparable to the glyphosate + 2,4-D and glyphosate + sugar treatments highlighting that biochemical exhaustion of reproductive organs is a significantly more sustainable strategy than physical disturbance (Palma *et al.* 2020, Chaudhari *et al.* 2024). These findings advocate for an integrated approach prioritizing glyphosate augmented with systemic partners or nitrogenous adjuvants for long-term sedge control.

Economic viability of *Cyprus* control efficacy

All glyphosate-based treatments differed significantly **(Figure 2)** in cost per percent control and *Cyperus* control efficiency. Application of glyphosate + ammonium sulphate and glyphosate + 2,4-D combined low cost (ranks I–II) with the highest *Cyprus* control efficacy (72.09 and 72.53%), whereas Inter-culturing and glyphosate + oxyfluorfen were costly with the lower CCE (46.61 and 62.13%). Intermediate treatments such as glyphosate + sugar, glyphosate + kaolin, and glyphosate alone showed moderate cost and *Cyprus* control efficacy. The higher cost in some treatments is primarily due to the use of more expensive adjuvants or combined chemicals and lower efficacy per unit cost, which

Table 1. Effect of glyphosate-adjuvant on mortality and regrowth of *Cyperus* spp.

Treatment	Dose (kg/ha)	Mortality (%)		Regrowth (no./plot)	
		20 DAA*	40 DAA*	20 DAA*	40 DAA*
Weedy check (control)	—	—	—	3.46 (11.67)	4.93 (24.00)
Inter-culturing (twice)	—	—	—	15.78 (249.7)	19.80 (397.3)
Glyphosate	2.0	69.33 (87.02)	82.97 (97.77)	3.36 (15.33)	4.41 (21.33)
Glyphosate + ammonium sulphate	1.5 + 2%	62.27 (77.99)	90.00 (100.0)	2.34 (5.33)	3.04 (9.00)
Glyphosate + sugar	1.5 + 2%	66.91 (83.96)	86.92 (99.14)	2.67 (6.67)	3.71 (13.67)
Glyphosate + urea	1.5 + 2%	68.43 (86.25)	80.81 (97.38)	3.06 (9.00)	3.98 (15.67)
Glyphosate + kaolin	1.5 + 1.5	70.97 (88.85)	83.57 (98.39)	3.94 (17.00)	4.68 (23.33)
Glyphosate + 2,4-D	1.0 + 1.0	73.12 (89.68)	87.70 (99.52)	3.18 (11.00)	4.17 (17.33)
Glyphosate + oxyfluorfen (ready-mix)	2.0	59.52 (72.57)	85.72 (98.64)	3.97 (17.33)	4.90 (26.00)
LSD (p=0.05)	--	12.91	7.21	2.44	2.42

Note: The treatment abbreviations used are DAA-Days after application. Figures in parentheses represent original values, while those outsides are transformed: square root ($\sqrt{x+0.5}$) for regrowth and arcsine ($\sin^{-1}\sqrt{x}$) for mortality.

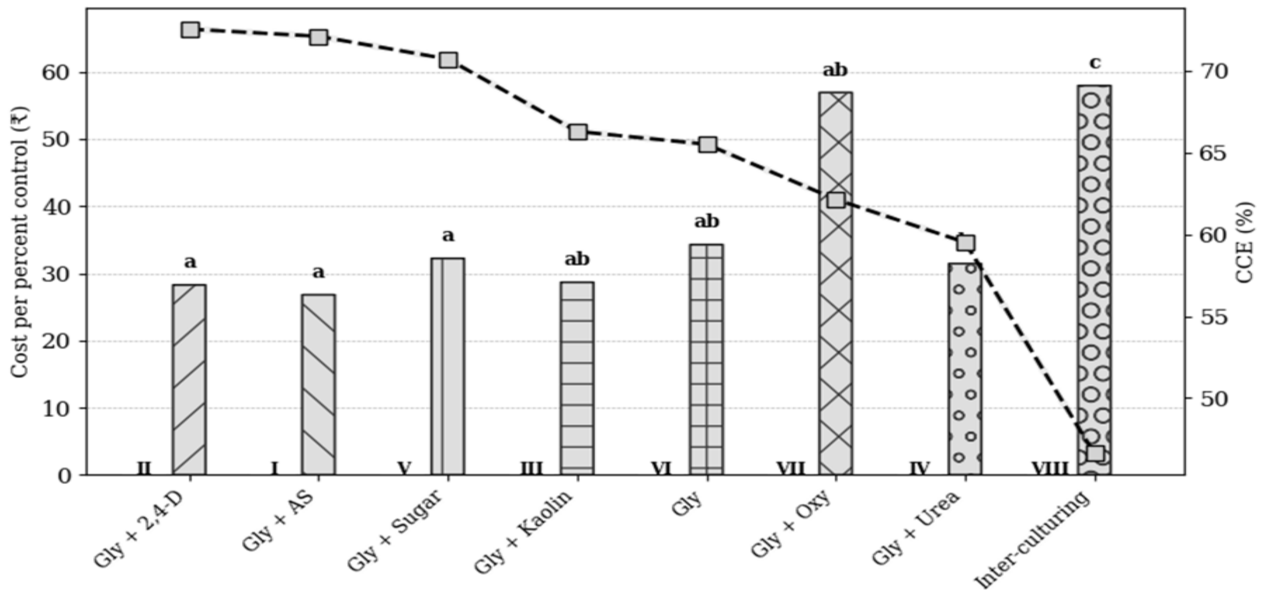


Figure 2. Impact of glyphosate-adjuvant on cost per percent control and *Cyperus* control efficiency

[Bars indicate cost per percent control with DNMRT letters above showing significant differences ($p < 0.05$). Cost rank (I–VIII) is shown to the left of each bar, where I = lowest cost]. Inter-culturing = 20 and 40 DAS; Gly = glyphosate 2.0 kg/ha; Gly + AS = glyphosate 1.5 kg/ha + ammonium sulphate 2%; Gly + Sugar = glyphosate 1.5 kg/ha + sugar 2%; Gly + Urea = glyphosate 1.5 kg/ha + urea 2%; Gly + Kaolin = glyphosate 1.5 kg/ha + kaolin 1.5 kg/ha; Gly + 2,4-D = glyphosate 1.0 kg/ha + 2,4-D amine 1.0 kg/ha; Gly + Oxy = glyphosate + oxyfluorfen (ready-mix) 2.0 kg/ha.

Table 2. The residual effect of herbicides on growth parameters of succeeding blackgram (Bioassay)

Treatment*	Plant stand (per m^2)	Plant height (cm)	Branches/ plant (no.)	Pods/ plant (no.)	Yield (g/plot)	
					Seed	Stover
Weedy check (control)	31.33	50.13	9.00	33.61	564	804
Inter-culturing twice at 20 and 40 DAS	31.33	51.47	9.73	33.79	565	863
Glyphosate 2.0 kg/ha at 20 DAS	31.33	53.13	9.33	35.60	581	863
Glyphosate 1.5 kg/ha + ammonium Sulphate 2% at 20 DAS	32.33	51.20	927	32.74	592	874
Glyphosate 1.5 kg/ha + sugar 2% at 20 DAS	31.33	53.80	9.67	32.40	571	878
Glyphosate 1.5 kg/ha + urea 2% at 20 DAS	32.67	51.93	9.67	34.20	591	859
Glyphosate 1.5 kg/ha + kaolin 1.5 kg/ha at 20 DAS	32.00	52.53	9.60	36.65	590	818
Glyphosate 1.0 kg/ha + 2,4-D amine salt 1.0 kg/ha (tank-mix) at 20 DAS	31.00	58.73	10.20	35.93	589	873
Glyphosate + oxyfluorfen (ready-mix) 2.0 kg/ha at 20 DAS	32.16	52.20	9.93	33.67	590	815
LSD (p=0.05)	NS	NS	NS	NS	NS	NS

*DAS = days after seeding

requires higher doses or repeated applications to achieve comparable control. Conversely, lower-cost treatments achieved high efficiency due to synergistic effects of adjuvants improving glyphosate uptake and weed control, reducing the amount of chemical needed. These results indicate that combining economic analysis with physiological assessment effectively identifies cost-effective and agronomically efficient weed management strategies (Heap 2021, Barbieri *et al.* 2022).

Carryover effect of herbicides on blackgram

The data (**Table 2)** revealed that herbicide carryover treatments had no significant effect on growth, development, and yield of blackgram, as all parameters were statistically non-significant. Uniform plant population indicated unaffected crop establishment, while plant height, branches per plant, and pods per plant showed no measurable variation. Seed and stover yields remained at par across treatments, confirming the absence of any measurable residual effect of the applied herbicides. These results suggest that under the experimental conditions, the residual activity of the tested herbicides did not interfere with physiological processes governing blackgram growth and productivity.

Blackgram yield was unaffected by sowing after six weeks of glyphosate application, indicating negligible residual effects, consistent with rapid microbial degradation and soil adsorption limiting carryover (Hernandez Guijarro *et al.* 2018, Robayo *et al.* 2024). Glyphosate residues are therefore unlikely to persist at levels that affect succeeding crop growth and yield (Zhan *et al.* 2018, Hernandez Guijarro *et al.* 2018).

Glyphosate combined with ammonium sulphate (AS), sugar, or 2,4-D effectively controlled *Cyperus* spp., achieving >99% mortality and minimal regrowth by 40 days. Mechanical methods were less effective and often stimulated rhizome sprouting. Adjuvant-combined glyphosate applications enhanced its uptake and translocation, offering a sustainable and cost-efficient management of dense population of perennial sedges.

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