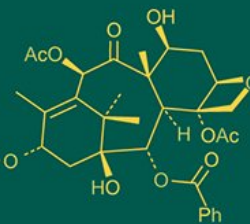
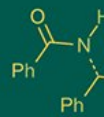


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Residual effects of pre-sowing weed management practices on *Cyperus rotundus* L. suppression and the subsequent agronomic performance of greengram (*Vigna radiata* L.)

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Abstract

Purple nutsedge (*Cyperus rotundus* L.) is among the most economically damaging perennial weeds encountered in tropical pulse-based cropping systems, posing a severe threat to greengram (*Vigna radiata* L.) productivity through direct resource competition and allelopathic interference. Pre-sowing chemical interventions are widely practiced to suppress early sedge flushes; however, the carryover dynamics of soil-applied herbicides in rotational systems remain inadequately characterized. This study quantified the residual suppression efficacy of eight pre-sowing herbicide treatments on *C. rotundus* density and dry weight, and concurrently evaluated their carryover impact on the germination, growth, yield attributes, and economic returns of a succeeding greengram crop. A field experiment was conducted under a randomized complete block design comprising nine treatments: pre-emergence (PE) metribuzin (1.25 kg ha⁻¹), early post-emergence (EPOE) halosulfuron methyl (75 g ha⁻¹), post-emergence (POE) glyphosate (1.25 kg ha⁻¹), POE 2,4-D (1.25 kg ha⁻¹), and four sequential or combined formulations thereof, alongside an unsprayed control. Weed density, dry matter accumulation, crop growth indices, yield attributes, grain yield, and benefit-cost ratios were recorded across standardized observation intervals. Germination remained statistically non-significant across all treatments (92.00-93.55%), confirming the absence of phytotoxic carryover to greengram emergence. T₆ (EPOE halosulfuron methyl 50 g ha⁻¹ followed by POE glyphosate 1.00 kg ha⁻¹) delivered the highest suppression of *C. rotundus* density (2.76 and 3.03 No. m⁻² at 15 and 30 DAS, respectively) and weed dry weight, while simultaneously optimizing crop height (23.00 and 37.52 cm), leaf area index (0.39 and 2.75), crop growth rate (2.65 and 5.26 g m⁻² day⁻¹), and dry matter production (6,956 kg ha⁻¹ at 60 DAS). T₆ also produced the highest grain yield (3,873 kg ha⁻¹) and benefit-cost ratio (6.82), representing a 798.6% yield advantage over the unsprayed control. Sequential application of EPOE halosulfuron methyl (50 g ha⁻¹) followed by POE glyphosate (1.00 kg ha⁻¹) constitutes an agronomically superior and economically viable pre-sowing weed management strategy in greengram-based rotational cropping systems, combining robust sedge suppression with negligible herbicide carryover risk.

Keywords: Purple nutsedge suppression; halosulfuron methyl; glyphosate; metribuzin; herbicide carryover; pulse agronomy

Introduction

Greengram (*Vigna radiata* L.) occupies a strategically important niche within the agricultural food systems of South and Southeast Asia, providing an accessible and affordable source of dietary protein (18-28% on a dry weight basis), essential amino acids, and bioavailable micronutrients including iron and zinc for smallholder households and resource-limited communities (Nair *et al.*, 2023) [9]. As a short-duration legume (55-65 days to maturity) adapted to arid and semi-arid environments, greengram plays an indispensable role in crop rotation by fixing atmospheric nitrogen symbiotically through Bradyrhizobium associations, thereby improving soil fertility for succeeding cereal crops (Singh *et al.*, 2022) [14]. Despite these agronomic virtues, greengram remains highly susceptible to competitive suppression during its protracted early vegetative phase, a developmental window during which the crop canopy is too sparse to shade out emerging weed flora (Pramanik *et al.*, 2021) [10]. Among the weed species that colonize tropical dryland cropping systems, purple nutsedge (*Cyperus rotundus* L.) stands out as arguably the most intractable and economically

Destructive perennial weed globally. Its competitive dominance derives from a complex underground architecture comprising rhizomes, basal bulbs, and chains of dormant tubers capable of regenerating aerial shoots independently and repeatedly across multiple seasons (Rao *et al.*, 2022) ^[11]. A single maternal tuber can generate more than 40 daughter tubers within a single growing season under optimal edaphic conditions, creating a persistent subterranean propagule bank that resists depletion by conventional mechanical tillage (Kumar *et al.*, 2023) ^[7]. Beyond this formidable reproductive strategy, *C. rotundus* exerts allelopathic influence on neighbouring vegetation through the exudation of terpenoids and phenolic acids from root tissues, compounds demonstrated to inhibit early root elongation, impair cell division in meristematic zones, and suppress hypocotyl development in leguminous seedlings (Chauhan *et al.*, 2022) ^[14]. The cumulative effect of these competitive and allelopathic mechanisms can reduce greengram grain yields by 40-78% when sedge populations remain unmanaged throughout the critical weed-free period (Dhaliwal *et al.*, 2023) ^[5].

Traditional management approaches against *C. rotundus* principally hand-weeding and mechanical inter-row cultivation provide only transient relief because they remove aerial biomass while leaving the subterranean tuber bank undisturbed and viable (Gnanavel, 2013) ^[6]. Tubers as shallow as 2-5 cm in the soil profile can re-sprout within 10-14 days of surface vegetation removal, rapidly reinstating competitive pressure on the crop (Mishra & Singh, 2024) ^[8]. Consequently, pre-sowing weed management strategies that target early tuber activation and deplete the propagule bank before crop establishment have attracted considerable research attention. These strategies include stale seedbed preparation, repeated deep summer ploughing to desiccate exposed tubers, and the targeted application of pre-emergence (PE), early post-emergence (EPOE), or post-emergence (POE) herbicides during the fallow phase preceding sowing (Thakur *et al.*, 2021) ^[15].

Soil-applied herbicides such as metribuzin a triazinone photosystem-II inhibitor effectively suppress early nutsedge flushes by disrupting electron transport during photosynthesis in germinating propagules (Barla *et al.*, 2022) ^[11]. Halosulfuron methyl, a sulfonylurea that inhibits acetolactate synthase (ALS), exhibits notable selectivity towards sedge species and has demonstrated efficacy against *C. rotundus* at low application rates (Bhullar *et al.*, 2020) ^[2]. Systemic herbicides including glyphosate (inhibitor of 5-enolpyruvylshikimate-3-phosphate synthase) and 2,4-D (synthetic auxin) are frequently deployed in post-emergence pre-sowing windows to eliminate actively growing weed vegetation and translocate lethal concentrations to the tuber network (Yadav *et al.*, 2022) ^[16].

A critical agro-environmental concern, however, arises from the persistence of soil-applied herbicides within intensive rotational systems. Residual concentrations of metribuzin and sulfonylurea herbicides in the topsoil layer can persist for several weeks to months depending on soil pH, organic carbon content, microbial activity, and temperature-moisture dynamics (Bora *et al.*, 2023) ^[3]. Small-seeded legumes such as greengram are particularly sensitive to even sub-lethal herbicide residues, which can disrupt radicle elongation, impair uniform field emergence, reduce root biomass, and compromise photosynthetic capacity during critical developmental phases (Raza *et al.*, 2021) ^[12]. This creates a paradox inherent to pre-sowing chemical weed management: interventions sufficiently aggressive to control *C. rotundus* in the pre-sowing window may inadvertently compromise the germination dynamics and early growth of the succeeding sensitive pulse crop (Sharma *et al.*, 2023) ^[13].

Despite the practical significance of this trade-off, the existing body of literature has focused predominantly on the immediate weed control efficacy of individual herbicides in either the pre-sowing or in-crop phase, with comparatively limited attention given to the multi-seasonal carry-forward dynamics of sequential or combination treatments across rotational greengram systems. Particularly underexplored are threshold concentration assessments that distinguish the dose range at which pre-sowing sedge suppression benefits transition into residual phytotoxicity risk for succeeding legumes. Closing this knowledge gap is essential for designing herbicide programs that are both ecologically responsible and economically optimized within intensive, short-duration cropping rotations.

This study was therefore designed with two primary objectives: (i) to quantify the multi-temporal residual suppression efficiency of eight pre-sowing herbicide treatment combinations on *C. rotundus* density and dry weight biomass across critical crop growth stages of greengram; and (ii) to rigorously assess the carryover safety and agronomic impact of these treatments on the germination, vegetative growth parameters, yield component attributes, grain and haulm yields, and economic returns of the succeeding greengram crop. Through this dual-objective framework, the investigation aims to identify an optimized, eco-efficient weed management strategy for tropical pulse-based rotational production systems.

2. Materials and Methods

2.1 Experimental site and soil characteristics

The field experiment was conducted over two consecutive crop seasons during October 2017 to March 2018 at the experiment field is located in the North Western Agro-Climatic Zone of Tamil Nadu (Chinnakuppam village, Dharmapuri district) with geographical region of 12.03° N latitude and 78.50° E longitude at an altitude of 392 m above mean sea level. The experimental site exhibited a well-characterized history of perennial nutsedge infestation. Soil at the experimental site was classified as sandy clay loam (Typic Haplustalf) with a pH of 7.48, electrical conductivity of 0.68 dS m⁻¹, organic carbon content of 0.35%, available nitrogen of 152 kg ha⁻¹, available phosphorus of 24 kg ha⁻¹, and available potassium of 282 kg ha⁻¹, determined prior to experimentation using standard analytical procedures (Table 1).

Table 1: Soil physico-chemical characteristics of the experimental field

Particulars	Rabi (2017-2018)
1. Mechanical analysis	
Clay (%)	15.30
Silt (%)	7.48
Fine sand (%)	44.05
Coarse sand (%)	33.15
Texture	Sandy loam
2. Chemical analysis	
pH (Jackson, 1973)	7.21
EC (dS m ⁻¹) (Jackson, 1973)	0.68
Organic carbon (%) (Walkley and Black, 1934)	0.350
Available N (kg ha ⁻¹) (Subbiah and Asija, 1956)	152.0 (Low)
Available P ₂ O ₅ (kg ha ⁻¹) (Olsen <i>et al.</i> , 1954)	24.00 (medium)
Available K ₂ O (kg ha ⁻¹) (Stanford and English, 1949)	282.0 (Low)
DTPA extractable Fe	12.54 ppm
DTPA extractable Mn	2.109 ppm
DTPA extractable Zn	1.757 ppm
DTPA extractable Cu	1.592 ppm

2.2 Experimental design and treatments

The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications, comprising nine treatments. Individual plot sizes were maintained at 4.0 m × 5.0 m (20 m²). The herbicide treatments encompassed sole applications of PE metribuzin (1.25 kg a.i. ha⁻¹), EPOE halosulfuron methyl (75 g a.i. ha⁻¹), POE glyphosate (1.25 kg a.i. ha⁻¹), and POE 2,4-D sodium salt (1.25 kg a.i. ha⁻¹), as well as sequential combinations of these compounds at reduced rates (1.00 kg or 50 g a.i. ha⁻¹), and an unsprayed weed-infested control (T₉). Pre-emergence herbicides were applied at 24-48 hours after sowing; EPOE treatments were applied at 8-12 days after sowing (DAS); POE treatments were applied at 20-25 DAS using a calibrated knapsack sprayer fitted with a flat-fan nozzle at a spray volume of 500 L ha⁻¹.

2.3 Crop management

Greengram variety [CO 6] was sown at a seed rate of 20 kg ha⁻¹ with a row spacing of 30 cm and plant-to-plant spacing of 10 cm. Seeds were treated with *Rhizobium leguminosarum* biotype phaseoli culture (10 g kg⁻¹ seed) prior to sowing. The recommended fertilizer dose of 25 kg N ha⁻¹ and 50 kg P₂O₅ ha⁻¹ was applied as basal. All other agronomic practices including irrigation, pest management, and plant protection were kept uniform across all treatments and consistent with recommended package-of-practices for greengram cultivation in the respective agro-climatic zone.

2.4 Observations and data collection

Weed flora was assessed at 15 and 30 DAS by counting and categorizing all weed species within randomly placed 0.5 m × 0.5 m quadrats (three per plot). Weed samples were oven-dried at 70°C for 72 hours to constant weight for dry matter determination. Germination percentage was recorded at 7 DAS by counting emerged seedlings across the entire plot. Plant height was measured on 10 randomly tagged plants per plot at 20 and 40 DAS. Leaf area index (LAI) was

computed using the gravimetric paper-punching method (Watson, 1947). Crop growth rate (CGR) was calculated from sequential dry matter harvests. Dry matter production (DMP) was estimated at 30 and 60 DAS from 1 m² sub-plots. At physiological maturity, yield attributes (pods per plant, grains per pod, test weight) and final grain and haulm yields were determined from a net plot harvest area. Economic analysis was performed using prevailing local market prices.

2.5 Statistical analysis

All data were subjected to analysis of variance (ANOVA) appropriate for RCBD. Percentage data were arcsine-transformed prior to analysis. Treatment means were compared using the critical difference (CD) test at a 5% probability level (P = 0.05). Statistical computations were performed using AGRES statistical software (version 7.01). Economic data were not subjected to statistical analysis.

3. Results

3.1 Germination percentage of greengram

The germination percentage of greengram was recorded across all treatment plots at 7 DAS and is presented in Table 2. Values ranged narrowly from 92.00% (T₄, POE 2,4-D at 1.25 kg ha⁻¹) to 93.55% (T₆, EPOE halosulfuron methyl 50 g ha⁻¹ followed by POE glyphosate 1.00 kg ha⁻¹), with the unsprayed control (T₉) recording 93.27%. Analysis of variance revealed that the differences among treatments were non-significant (CD at P = 0.05: NS), indicating the complete absence of herbicide carryover phytotoxicity on seed germination. The arcsine-transformed values (73.68-75.30) confirmed this statistical uniformity across all plots, establishing that none of the eight herbicide regimes, including the highest-dose sole applications of metribuzin (1.25 kg ha⁻¹) and 2,4-D (1.25 kg ha⁻¹), exerted any detectable inhibitory residual effect on greengram germination.

Table 2: Residual effect of pre-sowing weed management practices on germination (%) of greengram

Treatment	Germination (%)	Arcsine Value
T ₁ - PE metribuzin at 1.25 kg ha ⁻¹	92.10	73.68
T ₂ - EPOE halosulfuron methyl at 75 g ha ⁻¹	92.64	74.62
T ₃ - POE glyphosate at 1.25 kg ha ⁻¹	92.20	74.06
T ₄ - POE 2,4-D at 1.25 kg ha ⁻¹	92.00	73.81
T ₅ - PE metribuzin 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	92.75	74.38
T ₆ - EPOE halosulfuron 50 g ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	93.55	75.30
T ₇ - PE metribuzin 1.00 kg ha ⁻¹ fb POE 2,4-D 1.00 kg ha ⁻¹	92.56	74.18
T ₈ - PE metribuzin 1.00 kg ha ⁻¹ + POE 2,4-D 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	92.55	74.25
T ₉ - Unsprayed Control	93.27	75.15
SEd	2.21	-
CD (P = 0.05)	NS	-

PE - pre-emergence; EPOE - early post-emergence; POE - post-emergence; NS - Non-significant; Values in parentheses are arcsine-transformed.

3.2 Residual suppression of *Cyperus rotundus* density

The density of *C. rotundus* (No. m⁻²) across the two observation periods is presented in Table 3. At 15 DAS, the unsprayed control (T₉) recorded the highest nutsedge density (3.71; original value 11.8 No. m⁻²). Among the herbicide treatments, T₆ (EPOE halosulfuron methyl 50 g ha⁻¹ fb POE glyphosate 1.00 kg ha⁻¹) recorded the lowest density (2.76; original 5.6 No. m⁻²), followed by T₂ (EPOE halosulfuron methyl 75 g ha⁻¹; 2.79, original 5.8 No. m⁻²) and T₈ (triple sequential; 2.95, original 6.7 No. m⁻²). All

herbicide-treated plots differed significantly from the control (CD = 0.04). The density trend was maintained at 30 DAS, where T₉ recorded 3.86 (original 12.9 No. m⁻²) while T₆ remained the most effective treatment (3.03; original 7.2 No. m⁻²), significantly lower than all other treatments (CD = 0.05). These findings confirm that the residual activity of halosulfuron methyl, particularly when followed sequentially by glyphosate, provided sustained suppression of *C. rotundus propagule* emergence across the early crop establishment phase.

Table 3: Residual effect of pre-sowing weed management practices on density (No. m⁻²) of *Cyperus rotundus* in greengram

Treatment	15 DAS(No. m ⁻²)	30 DAS(No. m ⁻²)
T ₁ - PE metribuzin at 1.25 kg ha ⁻¹	3.24 (8.5)	3.42 (9.7)
T ₂ - EPOE halosulfuron methyl at 75 g ha ⁻¹	2.79 (5.8)	3.10 (7.6)
T ₃ - POE glyphosate at 1.25 kg ha ⁻¹	3.16 (8.0)	3.33 (9.1)
T ₄ - POE 2,4-D at 1.25 kg ha ⁻¹	3.32 (9.0)	3.48 (10.1)
T ₅ - PE metribuzin 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	3.03 (7.2)	3.21 (8.3)
T ₆ - EPOE halosulfuron 50 g ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	2.76 (5.6)	3.03 (7.2)
T ₇ - PE metribuzin 1.00 kg ha ⁻¹ fb POE 2,4-D 1.00 kg ha ⁻¹	3.10 (7.6)	3.26 (8.6)
T ₈ - PE metribuzin 1.00 kg ha ⁻¹ + POE 2,4-D 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	2.95 (6.7)	3.15 (7.9)
T ₉ - Unsprayed Control	3.71 (11.8)	3.86 (12.9)
SEd	0.02	0.02
CD (P = 0.05)	0.04	0.05

Values in parentheses are original values. PE - pre-emergence; EPOE - early post-emergence; POE - post-emergence; DAS - Days after sowing.

3.3 Residual effect on dry weight of *Cyperus rotundus*

The dry weight biomass of *C. rotundus* (g m⁻²) at 15 and 30 DAS is presented in Table 4. A pattern consistent with density observations was recorded. The control treatment (T₉) produced the highest nutsedge dry weight at both 15 DAS (1.92; original 1.54 g m⁻²) and 30 DAS (2.00; original 1.99 g m⁻²). T₆ was again the most effective herbicide treatment, recording the lowest dry weight at 15 DAS (1.72; original 0.46 g m⁻²) and at 30 DAS (1.80; original 0.72 g

m⁻²), followed by T₂ (1.73 and 1.82, respectively). Differences between treatments were statistically significant at both observation dates (CD = 0.05 at both intervals). The progressive reduction in dry weight across all herbicide treatments between 15 and 30 DAS suggests a continued depletion of tuber viability and reduced photosynthetic capacity of surviving nutsedge shoots, particularly under the halosulfuron-based sequential regimes.

Table 4: Residual effect of pre-sowing weed management practices on dry weight (g m⁻²) of *Cyperus rotundus* in greengram

Treatment	DW 15 DAS (g m ⁻²)	DW 30 DAS (g m ⁻²)
T ₁ - PE metribuzin at 1.25 kg ha ⁻¹	1.84 (1.15)	1.89 (1.40)
T ₂ - EPOE halosulfuron methyl at 75 g ha ⁻¹	1.73 (0.69)	1.82 (0.95)
T ₃ - POE glyphosate at 1.25 kg ha ⁻¹	1.78 (1.02)	1.82 (1.34)
T ₄ - POE 2,4-D at 1.25 kg ha ⁻¹	1.79 (1.21)	1.84 (1.51)
T ₅ - PE metribuzin 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	1.80 (0.86)	1.86 (1.17)
T ₆ - EPOE halosulfuron 50 g ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	1.72 (0.46)	1.80 (0.72)
T ₇ - PE metribuzin 1.00 kg ha ⁻¹ fb POE 2,4-D 1.00 kg ha ⁻¹	1.82 (0.95)	1.85 (1.22)
T ₈ - PE metribuzin 1.00 kg ha ⁻¹ + POE 2,4-D 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	1.77 (0.78)	1.83 (1.06)
T ₉ - Unsprayed Control	1.92 (1.54)	2.00 (1.99)
SEd	0.01	0.01
CD (P = 0.05)	0.02	0.02

Values in parentheses are original values. PE - pre-emergence; EPOE - early post-emergence; POE - post-emergence; DAS - Days after sowing.

3.4 Residual effect on grass weed and broad-leaved weed dry weight

Dry weights of associated grass weeds and broad-leaved weeds at 15 and 30 DAS are presented in Tables 5 and 6, respectively. For grass weed dry matter, T₉ recorded the highest values at both measurement intervals (2.87 and 3.11 g m⁻²). Among herbicide treatments, T₆ (2.13 and 2.32 g m⁻²) and T₂ (2.18 and 2.32 g m⁻²) suppressed grass weed biomass most effectively, while T₄ (POE 2,4-D) was the least effective among treated plots. All herbicide treatments

differed significantly from the control (CD = 0.17 at 15 DAS; CD = 0.22 at 30 DAS). For broad-leaved weeds, T₄ (POE 2,4-D 1.25 kg ha⁻¹) recorded the lowest dry weight (1.84 and 2.03 g m⁻²), consistent with the known selectivity of this auxinic herbicide against dicotyledonous species. The triple sequential treatment T₈ also showed notable broad-leaved weed suppression (1.91 and 2.25 g m⁻²). Differences were significant at both intervals (CD = 0.14 at 15 DAS; CD = 0.19 at 30 DAS).

Table 5: Residual effect of pre-sowing weed management practices on dry weight (g m⁻²) of grass weeds in greengram

Treatment	DW 15 DAS (g m ⁻²)	DW 30 DAS (g m ⁻²)
T ₁ - PE metribuzin at 1.25 kg ha ⁻¹	2.33 (3.45)	2.57 (4.59)
T ₂ - EPOE halosulfuron methyl at 75 g ha ⁻¹	2.18 (2.74)	2.32 (3.40)
T ₃ - POE glyphosate at 1.25 kg ha ⁻¹	2.33 (3.42)	2.55 (4.50)
T ₄ - POE 2,4-D at 1.25 kg ha ⁻¹	2.40 (3.77)	2.57 (4.61)
T ₅ - PE metribuzin 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	2.33 (3.43)	2.50 (4.23)
T ₆ - EPOE halosulfuron 50 g ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	2.13 (2.55)	2.32 (3.38)
T ₇ - PE metribuzin 1.00 kg ha ⁻¹ fb POE 2,4-D 1.00 kg ha ⁻¹	2.34 (3.46)	2.54 (4.44)
T ₈ - PE metribuzin 1.00 kg ha ⁻¹ + POE 2,4-D 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	2.23 (2.98)	2.48 (4.16)
T ₉ - Unsprayed Control	2.87 (6.24)	3.11 (7.70)
SEd	0.08	0.10
CD (P = 0.05)	0.17	0.22

Values in parentheses are original values. PE - pre-emergence; EPOE - early post-emergence; POE - post-emergence; DAS - Days after sowing.

Table 6: Residual effect of pre-sowing weed management practices on dry weight (g m^{-2}) of broad-leaved weeds in greengram

Treatment	DW 15 DAS (g m^{-2})	DW 30 DAS (g m^{-2})
T ₁ - PE metribuzin at 1.25 kg ha ⁻¹	2.18 (2.77)	2.51 (4.31)
T ₂ - EPOE halosulfuron methyl at 75 g ha ⁻¹	2.15 (2.64)	2.50 (4.25)
T ₃ - POE glyphosate at 1.25 kg ha ⁻¹	2.16 (2.67)	2.50 (4.25)
T ₄ - POE 2,4-D at 1.25 kg ha ⁻¹	1.84 (1.38)	2.03 (2.12)
T ₅ - PE metribuzin 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	2.11 (2.44)	2.43 (3.89)
T ₆ - EPOE halosulfuron 50 g ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	2.11 (2.44)	2.41 (3.80)
T ₇ - PE metribuzin 1.00 kg ha ⁻¹ fb POE 2,4-D 1.00 kg ha ⁻¹	2.02 (2.09)	2.35 (3.51)
T ₈ - PE metribuzin 1.00 kg ha ⁻¹ + POE 2,4-D 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	1.91 (1.64)	2.25 (3.05)
T ₉ - Unsprayed Control	2.55 (4.50)	3.35 (9.24)
SEd	0.06	0.09
CD (P = 0.05)	0.14	0.19

Values in parentheses are original values. PE - pre-emergence; EPOE - early post-emergence; POE - post-emergence; DAS - Days after sowing.

3.5. Plant height

Plant height data at 20 and 40 DAS are presented in Table 7. The unsprayed control (T₉) recorded the lowest height at both measurement dates (7.52 cm at 20 DAS; 10.17 cm at 40 DAS), reflecting the severe competitive suppression imposed by the unchecked weed community. Among herbicide-treated plots, T₆ recorded the tallest plants at 20 DAS (23.00 cm) and 40 DAS (37.52 cm), followed by T₂ (21.50 cm and 35.32 cm). These two halosulfuron-based

treatments differed significantly from all other treatments (CD = 3.26 at 20 DAS; CD = 5.28 at 40 DAS). T₄ (POE 2,4-D 1.25 kg ha⁻¹) produced the shortest herbicide-treated plants (11.72 and 16.50 cm), suggesting a degree of transient growth suppression attributable to auxinic herbicide carryover or reduced weed competitive relief relative to other treatments, though yield-level significance of this effect requires separate validation.

Table 7: Residual effect of pre-sowing weed management practices on plant height (cm) of greengram

Treatment	20 DAS (cm)	40 DAS (cm)
T ₁ - PE metribuzin at 1.25 kg ha ⁻¹	12.90	18.80
T ₂ - EPOE halosulfuron methyl at 75 g ha ⁻¹	21.50	35.32
T ₃ - POE glyphosate at 1.25 kg ha ⁻¹	13.13	20.83
T ₄ - POE 2,4-D at 1.25 kg ha ⁻¹	11.72	16.50
T ₅ - PE metribuzin 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	17.60	29.90
T ₆ - EPOE halosulfuron 50 g ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	23.00	37.52
T ₇ - PE metribuzin 1.00 kg ha ⁻¹ fb POE 2,4-D 1.00 kg ha ⁻¹	15.45	25.36
T ₈ - PE metribuzin 1.00 kg ha ⁻¹ + POE 2,4-D 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	19.60	32.80
T ₉ - Unsprayed Control	7.52	10.17
SEd	1.53	2.49
CD (P = 0.05)	3.26	5.28

PE - pre-emergence; EPOE - early post-emergence; POE - post-emergence; DAS - Days after sowing.

3.6 Leaf area index

Leaf area index values at 20 and 40 DAS are presented in Table 8. The lowest LAI was consistently recorded in T₉ (0.19 and 1.30 at 20 and 40 DAS, respectively), confirming that weed competition severely curtailed canopy development. T₆ recorded the highest LAI across both observation dates (0.39 and 2.75), marginally exceeding T₂

(0.38 and 2.70). Both treatments differed significantly from the control and from lower-performing herbicide regimes (CD = 0.12 at 20 DAS; CD = 0.11 at 40 DAS). T₄ recorded the lowest LAI among treated plots (0.26 and 2.00), consistent with reduced shoot growth observed for this treatment in the plant height data.

Table 8: Residual effect of pre-sowing weed management practices on leaf area index of greengram

Treatment	LAI 20 DAS	LAI 40 DAS
T ₁ - PE metribuzin at 1.25 kg ha ⁻¹	0.29	2.04
T ₂ - EPOE halosulfuron methyl at 75 g ha ⁻¹	0.38	2.70
T ₃ - POE glyphosate at 1.25 kg ha ⁻¹	0.31	2.11
T ₄ - POE 2,4-D at 1.25 kg ha ⁻¹	0.26	2.00
T ₅ - PE metribuzin 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	0.35	2.52
T ₆ - EPOE halosulfuron 50 g ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	0.39	2.75
T ₇ - PE metribuzin 1.00 kg ha ⁻¹ fb POE 2,4-D 1.00 kg ha ⁻¹	0.34	2.43
T ₈ - PE metribuzin 1.00 kg ha ⁻¹ + POE 2,4-D 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	0.37	2.64
T ₉ - Unsprayed Control	0.19	1.30
SEd	0.05	0.05
CD (P = 0.05)	0.12	0.11

PE - pre-emergence; EPOE - early post-emergence; POE - post-emergence; DAS - Days after sowing.

3.7 Crop growth rate: Crop growth rate data at 20 and 40 DAS are presented in Table 9. The control (T₉) exhibited the

lowest CGR at both intervals (1.36 and 1.89 $\text{g m}^{-2} \text{day}^{-1}$), more than three-fold lower than the best-performing

treatment at the later observation date. T₆ recorded the highest CGR at 20 DAS (2.65 g m⁻² day⁻¹) and at 40 DAS (5.26 g m⁻² day⁻¹). T₂ (2.51 and 5.22 g m⁻² day⁻¹) and T₈ (2.43 and 5.20 g m⁻² day⁻¹) ranked second and third

respectively. Differences among treatments were significant at both intervals (CD = 0.08 at 20 DAS; CD = 0.25 at 40 DAS), reflecting the cumulative benefit of superior weed suppression on photosynthetic resource use efficiency.

Table 9: Residual effect of pre-sowing weed management practices on crop growth rate (g m⁻² day⁻¹) of greengram

Treatment	CGR 20 DAS (g m ⁻² day ⁻¹)	CGR 40 DAS (g m ⁻² day ⁻¹)
T ₁ - PE metribuzin at 1.25 kg ha ⁻¹	1.86	4.63
T ₂ - EPOE halosulfuron methyl at 75 g ha ⁻¹	2.51	5.22
T ₃ - POE glyphosate at 1.25 kg ha ⁻¹	1.98	4.77
T ₄ - POE 2,4-D at 1.25 kg ha ⁻¹	1.75	4.51
T ₅ - PE metribuzin 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	2.32	5.01
T ₆ - EPOE halosulfuron 50 g ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	2.65	5.26
T ₇ - PE metribuzin 1.00 kg ha ⁻¹ fb POE 2,4-D 1.00 kg ha ⁻¹	2.10	5.01
T ₈ - PE metribuzin 1.00 kg ha ⁻¹ + POE 2,4-D 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	2.43	5.20
T ₉ - Unsprayed Control	1.36	1.89
SEd	0.04	0.11
CD (P = 0.05)	0.08	0.25

PE - pre-emergence; EPOE - early post-emergence; POE - post-emergence; DAS - Days after sowing.

3.8 Dry matter production

Total above-ground dry matter production (DMP) at 30 and 60 DAS is presented in Table 10. T₆ recorded the highest DMP at 30 DAS (1,078.87 kg ha⁻¹) and at 60 DAS (6,956 kg ha⁻¹), which was significantly superior to all other treatments at both dates (CD = 48.04 and 195.71, respectively). T₂ ranked second at 30 DAS (1,153.24 kg ha⁻¹) and at 60 DAS (6,377 kg ha⁻¹). The unsprayed control

recorded the lowest DMP (1,000.50 and 2,835 kg ha⁻¹), a reflection of severe competitive stress during the vegetative phase. The pronounced DMP advantage of the halosulfuron-based treatments at 60 DAS aligns with their superior canopy indices and weed suppression profiles, indicating that early-season resource availability captured through weed management was effectively converted into above-ground biomass.

Table 10: Residual effect of pre-sowing weed management practices on dry matter production (kg ha⁻¹) of greengram

Treatment	DMP 30 DAS (kg ha ⁻¹)	DMP 60 DAS (kg ha ⁻¹)
T ₁ - PE metribuzin at 1.25 kg ha ⁻¹	1,019.98	4,586
T ₂ - EPOE halosulfuron methyl at 75 g ha ⁻¹	1,153.24	6,377
T ₃ - POE glyphosate at 1.25 kg ha ⁻¹	1,031.77	4,936
T ₄ - POE 2,4-D at 1.25 kg ha ⁻¹	1,010.75	4,266
T ₅ - PE metribuzin 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	1,055.86	5,464
T ₆ - EPOE halosulfuron 50 g ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	1,078.87	6,956
T ₇ - PE metribuzin 1.00 kg ha ⁻¹ fb POE 2,4-D 1.00 kg ha ⁻¹	1,048.17	5,249
T ₈ - PE metribuzin 1.00 kg ha ⁻¹ + POE 2,4-D 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	1,107.11	5,797
T ₉ - Unsprayed Control	1,000.50	2,835
SEd	22.66	92.31
CD (P = 0.05)	48.04	195.71

PE - pre-emergence; EPOE - early post-emergence; POE - post-emergence; DAS - Days after sowing.

3.9 Yield attributes

The yield component data (pods per plant, grains per pod, and test weight) are presented in Table 11. The unsprayed control recorded the lowest values across all three components (15.0 pods/plant, 5.0 grains/pod, and 2.30 g test weight). T₆ produced the most favourable yield attributes: 30.6 pods per plant, 12.2 grains per pod, and a test weight of 4.15 g, all significantly superior to all other treatments (CD

= 1.19, 0.44, and 0.12, respectively). T₂ ranked second (28.2 pods/plant, 11.8 grains/pod, 3.95 g). T₄ recorded the weakest performance among herbicide treatments (19.5 pods/plant, 9.0 grains/pod, 2.78 g). The hierarchical response among treatments closely mirrored the weed suppression gradient, confirming that more effective weed management during the vegetative phase translated directly into superior reproductive resource allocation.

Table 11: Residual effect of pre-sowing weed management practices on yield attributes of greengram

Treatment	Pods/plant	Grains/pod	Test wt (g)
T ₁ - PE metribuzin at 1.25 kg ha ⁻¹	21.5	9.4	3.00
T ₂ - EPOE halosulfuron methyl at 75 g ha ⁻¹	28.2	11.8	3.95
T ₃ - POE glyphosate at 1.25 kg ha ⁻¹	23.2	10.0	3.25
T ₄ - POE 2,4-D at 1.25 kg ha ⁻¹	19.5	9.0	2.78
T ₅ - PE metribuzin 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	24.8	10.9	3.54
T ₆ - EPOE halosulfuron 50 g ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	30.6	12.2	4.15
T ₇ - PE metribuzin 1.00 kg ha ⁻¹ fb POE 2,4-D 1.00 kg ha ⁻¹	24.1	10.6	3.45
T ₈ - PE metribuzin 1.00 kg ha ⁻¹ + POE 2,4-D 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	26.2	11.2	3.71
T ₉ - Unsprayed Control	15.0	5.0	2.30
SEd	0.56	0.21	0.05
CD (P = 0.05)	1.19	0.44	0.12

PE - pre-emergence; EPOE - early post-emergence; POE - post-emergence.

3.10 Grain yield, haulm yield, and harvest index

Final grain yield, haulm yield, and harvest index values are presented in Table 12. T₆ produced the highest grain yield (3,873 kg ha⁻¹), a statistically significant advantage over all other treatments (CD = 77.25 kg ha⁻¹), representing a 798.6% increase over the unsprayed control (431 kg ha⁻¹). T₂ ranked second with 3,286 kg ha⁻¹, followed by T₈ (2,722 kg ha⁻¹) and T₅ (2,392 kg ha⁻¹). The lowest grain yield among herbicide-treated plots was observed in T₄ (1,220 kg

ha⁻¹), though this remained significantly higher than the control. Haulm yields were highest in T₆ (3,856 kg ha⁻¹) and lowest in T₉ (2,720 kg ha⁻¹; CD = 141.68). Harvest index, an indicator of reproductive partitioning efficiency, was highest in T₆ (0.50) and lowest in T₉ (0.14), confirming that effective weed management enabled a substantial shift in assimilate partitioning from vegetative to reproductive sinks.

Table 12: Residual effect of pre-sowing weed management practices on yields and harvest index of greengram

Treatment	Grain yield (kg ha ⁻¹)	Haulm yield (kg ha ⁻¹)	Harvest index
T ₁ - PE metribuzin at 1.25 kg ha ⁻¹	1,516	3,580	0.30
T ₂ - EPOE halosulfuron methyl at 75 g ha ⁻¹	3,286	3,800	0.46
T ₃ - POE glyphosate at 1.25 kg ha ⁻¹	1,885	3,600	0.34
T ₄ - POE 2,4-D at 1.25 kg ha ⁻¹	1,220	3,520	0.26
T ₅ - PE metribuzin 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	2,392	3,680	0.39
T ₆ - EPOE halosulfuron 50 g ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	3,873	3,856	0.50
T ₇ - PE metribuzin 1.00 kg ha ⁻¹ fb POE 2,4-D 1.00 kg ha ⁻¹	2,203	3,630	0.38
T ₈ - PE metribuzin 1.00 kg ha ⁻¹ + POE 2,4-D 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	2,722	3,720	0.42
T ₉ - Unsprayed Control	431	2,720	0.14
SEd	36.44	66.83	0.001
CD (P = 0.05)	77.25	141.68	0.01

PE - pre-emergence; EPOE - early post-emergence; POE - post-emergence.

3.11 Economic analysis

The economic performance of all treatments is summarized in Table 13. T₆ (EPOE halosulfuron methyl 50 g ha⁻¹ fb POE glyphosate 1.00 kg ha⁻¹) recorded the highest gross return (Rs.2,40,092 ha⁻¹), net return (Rs.2,04,884 ha⁻¹), and benefit-cost ratio (6.82), despite its cost of cultivation (Rs.35,208 ha⁻¹) being comparable to other herbicide treatments. T₂ (EPOE halosulfuron methyl 75 g ha⁻¹) ranked second with a net return of Rs.1,69,933 ha⁻¹ and B:C ratio of 5.88. The unsprayed control (T₉) generated the lowest cost

of cultivation (Rs. 14,617 ha⁻¹) but yielded the poorest net return (Rs.16,683 ha⁻¹) and B:C ratio (2.14), unambiguously demonstrating that the economic cost of unmanaged weed competition far exceeds the herbicide investment required for effective control. T₄ recorded the lowest B:C ratio among herbicide treatments (2.28), consistent with its inferior weed control and yield performance. These economic results confirm T₆ as the most viable strategy for smallholder greengram producers in nutsedge-infested rotational systems.

Table 13: Economics of pre-sowing weed management practices in greengram

Treatment	CoC (Rs. ha ⁻¹)	GR (Rs. ha ⁻¹)	NR (Rs. ha ⁻¹)	B:C
T ₁ - PE metribuzin at 1.25 kg ha ⁻¹	35,860	98,120	62,260	2.74
T ₂ - EPOE halosulfuron methyl at 75 g ha ⁻¹	34,827	2,04,760	1,69,933	5.88
T ₃ - POE glyphosate at 1.25 kg ha ⁻¹	35,188	1,20,300	85,112	3.42
T ₄ - POE 2,4-D at 1.25 kg ha ⁻¹	35,199	80,240	45,041	2.28
T ₅ - PE metribuzin 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	36,038	1,50,880	1,14,842	4.19
T ₆ - EPOE halosulfuron 50 g ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	35,208	2,40,092	2,04,884	6.82
T ₇ - PE metribuzin 1.00 kg ha ⁻¹ fb POE 2,4-D 1.00 kg ha ⁻¹	36,049	1,39,440	1,03,391	3.87
T ₈ - PE metribuzin 1.00 kg ha ⁻¹ + POE 2,4-D 1.00 kg ha ⁻¹ fb POE glyphosate 1.00 kg ha ⁻¹	36,440	1,70,760	1,34,320	4.69
T ₉ - Unsprayed Control	14,617	31,300	16,683	2.14

CoC - Cost of cultivation; GR - Gross return; NR - Net return; B: C - Benefit-cost ratio. PE - pre-emergence; EPOE - early post-emergence; POE - post-emergence. Data not statistically analysed.

4. Discussion

The non-significant differences in germination percentage across all treatments constitute the first and arguably most consequential finding of this investigation, establishing that none of the tested pre-sowing herbicide regimes including the highest doses of metribuzin (1.25 kg ha⁻¹) and 2,4-D (1.25 kg ha⁻¹) imposed detectable residual phytotoxicity on greengram seed germination. This outcome aligns with the documented degradation kinetics of these compounds. Metribuzin degrades primarily through microbial oxidation and photolysis, with a soil half-life of 14-30 days under warm tropical conditions, insufficient to sustain phytotoxic residues over a rotation interval of several weeks (Bora *et al.*, 2023) [3]. Halosulfuron methyl degrades readily under

alkaline soil conditions through chemical hydrolysis of the sulfonylurea bridge, with a DT₅₀ of approximately 10-30 days in neutral to alkaline soils (Bhullar *et al.*, 2020) [2]. These degradation dynamics explain the absence of germination effects even at the highest tested rates and are consistent with earlier reports on metribuzin carryover safety for legumes following appropriate rotation intervals (Raza *et al.*, 2021) [13].

The superior nutsedge suppression achieved by T₆ across both density and dry weight parameters is attributable to the complementary mechanisms of action exploited by the halosulfuron-glyphosate sequential combination. Halosulfuron methyl, applied at the EPOE stage, inhibits ALS-mediated branched-chain amino acid synthesis in

actively growing *C. rotundus* shoots and young tillers, effectively disrupting meristematic growth and reducing the photosynthate flux to the subterranean tuber network (Bhullar *et al.*, 2020) [12]. Subsequent application of glyphosate at the POE stage then intercepts regenerating flushes from partially suppressed tubers, translocating systemically through phloem to deliver a lethal dose of EPSP synthase inhibition to the distal tuber chain (Yadav *et al.*, 2022) [16]. This two-stage interception of nutsedge propagule physiology ALS inhibition of early flushes followed by systemic glyphosate delivery to the tuber network produced a persistent suppression effect measurable at 30 DAS of the succeeding greengram crop, consistent with findings by Kumar *et al.* (2023) [17] who demonstrated a 58-72% reduction in *C. rotundus* tuber density following halosulfuron-sequential glyphosate applications across rice-pulse rotations.

The plant height, LAI, CGR, and DMP data collectively trace an eco-physiological pathway from superior weed suppression to enhanced crop growth potential. Under T₆, reduced sedge competition released constraints on light interception, water uptake, and nutrient availability during the critical vegetative establishment phase, enabling rapid canopy development as evidenced by the significantly elevated LAI at 40 DAS (2.75). A more developed canopy in turn elevated net CO₂ fixation rates and photosynthetic assimilate production, reflected in the highest CGR at both measurement dates (2.65 g m⁻² day⁻¹ at 20 DAS; 5.26 g m⁻² day⁻¹ at 40 DAS). This canopy-to-biomass cascade has been previously established in pulse weed management studies; Dhaliwal *et al.* (2023) [15] reported that effective early-season weed suppression in greengram increased LAI by 38-52% and CGR by 40-64% relative to unmanaged controls, closely paralleling the magnitudes observed in the present investigation.

Yield attribute analysis further corroborated that the reproductive potential of greengram is highly responsive to the weed management environment established during the vegetative phase. The substantially higher pods per plant (30.6), grains per pod (12.2), and test weight (4.15 g) recorded under T₆ relative to T₉ (15.0, 5.0, and 2.30 g, respectively) reflect the diversion of photosynthetic assimilates from competitive defense and compensatory growth responses toward pod setting and seed filling under reduced weed pressure. These findings are consistent with the resource allocation theory of weed competition, which posits that crop resource capture during the critical weed-free period directly determines the photosynthate pool available for reproductive organ development (Singh *et al.*, 2022) [14].

The inferior performance of T₄ (POE 2,4-D 1.25 kg ha⁻¹) relative to halosulfuron-based treatments across most parameters warrants consideration. While 2,4-D effectively suppressed broad-leaved weeds (evidenced by the lowest broad-leaved weed dry weight at 30 DAS: 2.03 g m⁻²), it provided markedly inferior control of *C. rotundus* density and dry weight relative to halosulfuron treatments. This is consistent with the established herbicide spectrum of 2,4-D, which targets broad-leaved dicotyledonous weeds through auxinic growth disruption but demonstrates limited translocation efficacy to the sedge tuber network (Chauhan *et al.*, 2022) [14]. The corresponding limitation in weed competitive relief explains the reduced plant height, LAI,

and ultimately grain yield (1,220 kg ha⁻¹) observed under T₄, despite its relatively moderate cost of cultivation.

From an economic sustainability perspective, the B:C ratio of 6.82 recorded under T₆ confirms that the cost of the sequential halosulfuron-glyphosate application was not only recovered but amplified more than six-fold through improved grain productivity. The comparable cost of cultivation across most herbicide treatments (Rs.34,827-Rs.36,440 ha⁻¹) means that the differentiation in economic performance was driven overwhelmingly by grain yield differences rather than input cost variation, underscoring the critical importance of weed management efficacy as the primary economic lever in greengram production. The finding that the unsprayed control generated a positive but marginal B:C of 2.14 from a very low cost base reinforces the need for cost-effective weed management rather than the zero-input alternative in nutsedge-infested systems.

5. Conclusion

This investigation demonstrates that pre-sowing herbicide applications for purple nutsedge (*Cyperus rotundus* L.) suppression can be designed to eliminate measurable carryover phytotoxicity risk to the subsequently sown greengram (*Vigna radiata* L.) crop. The non-significant germination response across all eight herbicide treatments provides strong empirical support for the agronomic safety of these regimes within typical short-duration rotational intervals. The sequential application of early post-emergence halosulfuron methyl (50 g ha⁻¹) followed by post-emergence glyphosate (1.00 kg ha⁻¹), formulated as treatment T₆, emerged as the superior integrated strategy across all measured parameters: it delivered the most effective suppression of *C. rotundus* density and dry weight through complementary ALS inhibition and systemic translocation mechanisms, optimized all assessed crop growth indices including plant height, LAI, CGR, and DMP, and produced the highest grain yield (3,873 kg ha⁻¹), harvest index (0.50), and economic return (B:C ratio 6.82) in the succeeding greengram crop. These findings provide actionable guidance for practitioners managing greengram in nutsedge-infested rotational systems in tropical semi-arid environments. Future research should extend this framework to multi-location, multi-season trials to account for soil heterogeneity, rainfall variability, and regional herbicide degradation dynamics, and should incorporate residual soil herbicide bioassays to quantitatively characterize carryover dose-response relationships for sensitive succeeding crops.

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