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ECO-WEEDING IN OKRA: ASSESSING HERBICIDE-FREE STRATEGIES, MULCHING AND THEIR ROLE IN NUTRIENT OPTIMIZATION AND WEED SUPPRESSION

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ABSTRACT

Efficient weed management is central to improving nutrient use efficiency and sustaining soil fertility in vegetable cropping systems. This study evaluated the impact of various weed control strategies, including black polythene mulch, integrated chemical approaches, and manual weeding, on nutrient uptake by okra (*Abelmoschus esculentus*) and nutrient depletion by weed flora under field conditions. Results revealed that black polythene mulching significantly reduced weed biomass and nutrient removal by weeds across all stages of crop development (15, 30, 60, and 90 days after sowing). It also enhanced nitrogen (N), phosphorus (P), and potassium (K) uptake by the okra crop, particularly during the critical early growth stages. Among all treatments, black polythene mulch and the weed-free check consistently recorded the lowest nutrient losses and the highest crop nutrient assimilation, while un-weeded control plots exhibited the greatest nutrient depletion, confirming the competitive dominance of weeds under unmanaged conditions. The integration of herbicidal treatments with inter-cultivation further improved nutrient conservation but was marginally less effective than polythene mulch. These findings underscore the efficacy of black polythene mulching not only as a physical weed barrier but also as a nutrient management tool that fosters sustainable okra production. The study advocates for its adoption as part of integrated weed and nutrient management strategies to enhance yield potential and agro-ecological resilience in vegetable-based systems.
***Keywords*: Okra, Weed Management, Black Polythene Mulch, Nutrient Uptake, Nutrient Depletion**

Introduction

Okra (*Abelmoschus esculentus* L. Moench), a member of the Malvaceae family, is widely recognized for its nutritional richness and agronomic versatility. Ranking as the sixth most consumed vegetable crop globally, it holds particular significance in India, which leads in global production with approximately 380,000 hectares under cultivation and an annual yield of 3.684 million tons (Sahu and Dwivedi, 2021). Favoring warm and humid subtropical to tropical climates, okra thrives best within a temperature range of 24–27°C and exhibits remarkable tolerance to drought and heat stress (Gangashetty *et al*., 2010). Its immature pods are nutrient-dense, containing carbohydrates, proteins, unsaturated fatty acids like oleic and linoleic acids, essential vitamins (B and C), folic acid, calcium, and phosphorus (Swamy, 2023; Sasipriya and Gangaprasad, 2021). Additionally, okra mucilage has drawn increasing interest for its wide spectrum of bioactive properties, including antioxidant, antimicrobial, antidiabetic, and antiulcerogenic effects, highlighting its potential as a functional food (Dantas *et al*., 2021).

Despite its favorable attributes, okra production is often hindered by intense weed competition, which limits nutrient availability and reduces overall crop performance. Weeds act as persistent competitors for essential resources like water, nutrients, and light, negatively affecting crop yield and quality (Qin *et al*., 2015; Jaysawal *et al*., 2018; Kumar *et al*., 2019). In this context, mulching has emerged as a sustainable, eco-friendly, and cost-effective agronomic practice for integrated weed and nutrient management. Mulches, either organic (e.g., crop residues, straw) or synthetic (e.g., polyethylene films), not only suppress weed growth by limiting light penetration but also conserve soil moisture, regulate temperature, and reduce erosion (Jordan *et al*., 2010; Mucina *et al*., 2006).

Among the various mulching materials, black polyethylene mulch (BPM) has demonstrated notable efficacy in enhancing nutrient dynamics and weed control. Its impermeable surface prevents weed germination while modifying the soil microclimate to favor root proliferation and nutrient uptake. Several recent studies have confirmed that BPM significantly improves the uptake of nitrogen (N), phosphorus (P), and potassium (K) by okra plants while concurrently minimizing nutrient depletion by weeds (Reddy *et al*., 2023; Kumar *et al*., 2022). By reducing nutrient leaching and weed-induced competition, BPM ensures greater nutrient use efficiency and promotes vigorous crop growth. Furthermore, crops grown under BPM tend to mature earlier and yield better-quality produce, reinforcing its importance in high-intensity vegetable cultivation systems (Chopra and Koul, 2020).

Taken together, these attributes establish mulching, particularly with black polyethylene, as a pivotal strategy in optimizing okra production. This paper explores the role of mulching in nutrient management and weed suppression in okra, with a focus on recent advances and practical implications for sustainable agriculture.

Materials and Methods

Test Cultivar Description

The experiment utilized the okra cultivar ‘Arka Anamika,’ an interspecific hybrid derived from a cross between *Abelmoschus esculentus* (IIHR 20-31) and *A. manihot* spp. *tetraphyllus*, the latter being recognized for its resistance to Yellow Vein Mosaic Virus (YVMV). The hybrid was further stabilized through backcrossing. ‘Arka Anamika’ is characterized by tall plants with robust branching and produces tender, long, spineless green pods with 5–6 ridges and a mild fragrance. Notable morphological traits include purple pigmentation at the petal base and green stems with a purplish hue. The variety offers a crop duration of 130–135 days, yields approximately 20 tonnes per hectare, and is widely appreciated for its shelf life, culinary quality, and YVMV resistance.

Experimental Site

The field trial was carried out at the Post graduate Research Block, Department of Vegetable Science, College of Horticulture, Sri Konda Laxman Telangana Horticulture University (SKLTGHU), located at Rajendranagar, Hyderabad, during the *Kharif* cropping season.

Climatic Conditions

The experimental location falls under a semi-arid subtropical climate. During the study period, the average maximum temperatures ranged between 29.7°C and 31.8°C, while minimum temperatures varied from 16.6°C to 18.3°C. Mean relative humidity fluctuated from 83.5%–93.1% during the forenoon and 58.2%–70.3% in the afternoon. The cumulative rainfall recorded throughout the cropping season was 699 mm. Daily sunshine averaged 5.7 hours, with evaporation rates between 2.9 mm and 5.4 mm (mean 3.9 mm). Wind speed ranged from 2.1 to 8.0 km/h, averaging 4.2 km/h. These agro-meteorological conditions were conducive for optimal okra growth.

Soil Analysis

A composite soil sample representing the experimental field was collected from a depth of 15–20 cm after removing surface debris. The sample was air-dried, sieved (2 mm), and analyzed to determine its chemical and physical properties, values and method of analysis are presented in table 1 and 2 respectively.

Table 1: Chemical properties of the experimental soil prior to sowing *(Composite sample, 0–20 cm depth)*

Parameter	Value	Method of Analysis
Soil pH (1:2.5 soil: water)	7.51	Glass electrode method (Jackson, 1973)
Electrical conductivity (dS/m)	0.22	Solubridge method (Piper, 1966)
Total nitrogen (kg ha^{-1})	537.6	Kjeldahl digestion (Chapman and Pratt, 1961)
Available nitrogen (kg ha^{-1})	192	Alkaline permanganate (Subbaiah and Asija, 1956)
Available phosphorus (kg ha^{-1})	5	Olsen’s method (Olsen *et al*., 1954)
Available potassium (kg ha^{-1})	272	Neutral ammonium acetate method (Jackson, 1973)
Organic carbon (%)	0.57	Walkley and Black wet digestion (Walkley & Black, 1934)

Table 2 : Physical composition of the experimental soil

Texture Component	Proportion (%)	Method of Analysis
Sand	71.9	International pipette method (Piper, 1966)
Silt	7.8	International pipette method (Piper, 1966)
Clay	18.5	International pipette method (Piper, 1966)

Plant Sample, Collection and Nutrient Analysis

At harvest, plant samples from both okra and associated weed biomass were collected for dry matter estimation and subsequent nutrient analysis. The nutrient uptake for nitrogen (N), phosphorus (P), and potassium (K) was quantified using established protocols:

- **Nitrogen**: Determined using the Kjeldahl method and reported as a percentage of dry weight (Jackson, 1967).
- **Phosphorus**: Estimated via the vanado-molybdate method in a diacid digest. Absorbance was recorded using a spectrophotometer with a blue filter, and concentration was extrapolated from a standard curve (Jackson, 1967).
- **Potassium**: Measured from the diacid extract using a flame photometer (Jackson, 1967).

Results and Discussion

Nitrogen Uptake

The data on nitrogen uptake by okra at different growth stages are presented in Table 3. At 30 days after sowing (DAS), the highest nitrogen uptake (1.58 kg/ha) was recorded in plots mulched with black polythene. This early advantage can be attributed to the mulch's ability to conserve soil moisture, stabilize soil temperature, and suppress early weed emergence, thereby promoting nitrogen mineralization and root proliferation (Kai *et al*., 2022; Ahmed *et al*., 2020; Solomon *et al*., 2024). The findings align with Maurya *et al*. (2017), who highlighted that mulched conditions enhance nutrient flow and uptake efficiency in okra.

Mechanical inter-row weeding combined with intra-row hand weeding also recorded appreciable nitrogen uptake at both 30 DAS (1.39 kg/ha) and 60 DAS (34.6 kg/ha), positioning it as a robust alternative. This is supported by recent findings (Gaurav *et al*., 2018; Jalendhar *et al*., 2016), which indicate that manual weeding improves root-soil contact and reduces weed competition, enhancing nutrient availability. Prativa *et al*. (2023) further emphasized that hand and mechanical weeding are particularly beneficial during vegetative stages due to improved soil aeration and weed control efficiency.

Conversely, un-weeded control plots exhibited the lowest nitrogen uptake throughout the crop cycle (0.61 kg/ha at 30 DAS and 19.7 kg/ha at 60 DAS), emphasizing the critical role of weed suppression in nutrient utilization (Tadesse *et al*., 2024). Studies have shown that nutrient loss is highest in un-weeded conditions due to competition from vigorous weed flora (Gaurav *et al*., 2018).

By 90 DAS, nitrogen uptake peaked in plots managed with mechanical + hand weeding (96.8 kg/ha), marginally outperforming mulched plots (94.9 kg/ha). This suggests that while black polythene mulch is more effective during the early and mid-vegetative stages, manual weeding strategies offer sustained nutrient acquisition during later developmental phases when crop demand intensifies and mulch effectiveness may diminish due to degradation or lateral weed encroachment (Tadesse *et al*., 2024).

The results suggest a dynamic shift in nitrogen uptake efficiency: early-stage benefits are dominated by mulching, whereas at maturity, active weed management through physical means proves more effective. The integration of both methods could offer a strategic advantage in optimizing nutrient use across the crop growth stages (Ahmed *et al*., 2020; Chaudhary *et al*., 2023).

Phosphorus Uptake

As shown in Table 4, black polythene mulch significantly improved phosphorus uptake at all growth stages. At 30 DAS, uptake was highest under mulch (0.31 kg/ha), followed closely by mechanical + hand weeding (0.27 kg/ha). This trend persisted at 60 DAS (5.78 kg/ha) and 90 DAS (19.80 kg/ha), establishing mulch as a consistent enhancer of phosphorus acquisition (Neupane *et al*., 2023).

Phosphorus is largely immobile in soil, relying on diffusion for movement toward root zones. Mulch facilitates this process by stabilizing soil moisture, thus creating favorable conditions for nutrient solubility and availability (Othieno, 1973; Ahmed *et al*., 2020). The suppression of competing weeds further ensures that phosphorus remains accessible to okra roots rather than being intercepted by undesired flora (Solomon *et al*., 2024).

Moreover, the mulch-induced enhancement in microbial activity, especially phosphate-solubilizing organisms, likely contributes to higher phosphorus uptake. These findings echo those of Sekhon *et al.* (2008) and Neupane *et al.* (2023), who reported increased phosphorus use efficiency under mulched conditions in various horticultural crops.

Potassium Uptake

Table 5 summarizes the potassium uptake across different treatments and growth stages. At 30 DAS, maximum uptake (1.85 kg/ha) was recorded in plots with black polythene mulch, followed by mechanical + hand weeding (1.63 kg/ha). A similar pattern was observed at 60 DAS, with uptake values of 38.51 kg/ha (mulch) and 32.12 kg/ha (manual weeding). However, by 90 DAS, the trend reversed slightly, mechanical + hand weeding surpassed mulch, recording 88.40 kg/ha against 86.20 kg/ha.

The superiority of mulching during early growth stages stems from its ability to minimize water loss and facilitate mass flow, the primary transport mechanism for potassium (Hassan *et al.*, 2017; Ahmed *et al.*, 2020). As plants mature, however, the soil-loosening effect and improved aeration from manual weeding boost root activity and nutrient translocation, particularly in potassium's case, which is vital for fruit development and osmotic regulation (Merwe and Prins, 2012).

The late-stage advantage of manual weeding aligns with findings of Prativa *et al.* (2023) and Tadesse *et al.* (2024), who reported enhanced potassium uptake in crops managed under physically weeded or loosened soil conditions.

Integrated Discussion

The experimental findings affirm the critical role of weed management in optimizing nutrient uptake in okra. Both black polythene mulch and combined mechanical + hand weeding significantly enhanced nitrogen, phosphorus, and potassium acquisition compared to unweeded controls, which exhibited the poorest performance across all parameters. Enhanced nutrient uptake under mulch is primarily driven by favorable microclimatic alterations, moisture conservation, weed suppression, and temperature modulation, facilitating better nutrient mobility and root-soil interaction (Solomon *et al.*, 2024).

Manual weeding, although more labor-intensive, becomes increasingly effective during later growth stages. Its ability to remove late-emerging weeds and improve soil structure boosts nutrient availability, especially for nutrients like potassium that rely on root-soil contact and adequate aeration for absorption (Prativa *et al.*, 2023; Tadesse *et al.*, 2024; Merwe and Prins, 2012).

These results align with previous literature emphasizing that integrated weed management strategies enhance nutrient uptake by reducing interspecies competition and supporting root health (Gaurav *et al.*, 2018; Jalendhar *et al.*, 2016; Patel *et al.*, 2017). Notably, the findings underscore the value of adaptive weed control techniques, where early-stage mulching may be followed by strategic manual weeding to sustain nutrient uptake as plant demands evolve.

Table 3: Influence of different weed management practices on nitrogen uptake by crop (kg ha^{-1})

Treatment		30 DAS	60 DAS	90 DAS
T_1	Oxyfluorfen 23.5% EC 0.2 kg ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* inter-cultivation at 45 DAS.	0.92^{de}	29.8^{e}	66.0^{f}
T_2	Pendimethalin 38.7% CS 675 g ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* inter-cultivation at 45 DAS.	1.00^{cd}	25.6^{i}	69.7^{e}
T_3	Oxadiargyl 80% WP 90 g ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* inter-cultivation at 45 DAS.	1.01^{c}	27.5^{g}	69.6^{e}
T_4	Oxyfluorfen 23.5% EC 0.2 kg ha^{-1} (PE) followed by rice straw mulch (5t ha^{-1}) at 7-10 DAS.	0.80^{f}	27.1^{h}	61.5^{gh}
T_5	Pendimethalin 38.7% CS 675 g ha^{-1} *fb* rice straw mulch (5t ha^{-1}) at 7-10 DAS.	0.88^{e}	27.8^{f}	58.4^{hi}
T_6	Oxadiargyl 80% WP 90 g ha^{-1} *fb* rice straw mulch (5t ha^{-1}) at 7-10 DAS	0.89^{e}	28.0^{f}	57.5^{i}
T_7	Rice straw mulch at 7-10 DAS (5t ha^{-1}).	1.00^{cd}	27.2^{h}	70.5^{de}
T_8	Black polythene mulch.	1.58^{a}	34.9^{a}	94.2^{b}

T_9	Stale seed bed followed by inter cropping with green leafy vegetable (palak).	1.03^{c}	30.5^{d}	72.5^{d}
T_{10}	Mechanical weeding at 15, 30, 60 DAS.	0.96^{d}	32.0^{c}	75.5^{c}
T_{11}	Mechanical weeding (inter row) followed by hand weeding (intra row) at 30 and 60 DAS - (weed free check).	1.39^{b}	34.6^{b}	96.8^{a}
T_{12}	Un-weeded Control	0.61^{g}	19.7^{j}	38.9^{j}
SE (m)±		0.02	0.08	0.73
CD at 5%		0.06	0.22	2.15

Table 4: Influence of different weed management practices on phosphorus uptake by crop (kg ha^{-1})

Treatment		30 DAS	60 DAS	90 DAS
T_1	Oxyfluorfen 23.5% EC 0.2 kg ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* inter-cultivation at 45 DAS.	0.18^{c}	4.93^{ab}	11.20^{c}
T_2	Pendimethalin 38.7% CS 675 g ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* inter-cultivation at 45 DAS.	0.20^{b}	4.24^{bc}	11.94^{c}
T_3	Oxadiargyl 80% WP 90 g ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* inter-cultivation at 45 DAS.	0.20^{b}	4.56^{b}	11.93^{c}
T_4	Oxyfluorfen 23.5% EC 0.2 kg ha^{-1} (PE) followed by rice straw mulch (5t ha^{-1}) at 7-10 DAS.	0.16^{c}	4.48^{b}	10.50^{c}
T_5	Pendimethalin 38.7% CS 675 g ha^{-1} *fb* rice straw mulch (5t ha^{-1}) at 7-10 DAS.	0.17^{c}	4.60^{b}	9.85^{cd}
T_6	Oxadiargyl 80% WP 90 g ha^{-1} *fb* rice straw mulch (5t ha^{-1}) at 7-10 DAS	0.18^{c}	4.64^{b}	11.26^{c}
T_7	Rice straw mulch at 7-10 DAS (5t ha^{-1}).	0.20^{b}	4.50^{b}	14.10^{b}
T_8	Black polythene mulch.	0.31^{a}	5.78^{a}	19.80^{a}
T_9	Stale seed bed followed by inter cropping with green leafy vegetable (palak).	0.20^{b}	5.05^{a}	14.18^{b}
T_{10}	Mechanical weeding at 15, 30, 60 DAS.	0.19^{bc}	5.30^{a}	14.06^{bc}
T_{11}	Mechanical weeding (inter row) followed by hand weeding (intra row) at 30 and 60 DAS - (weed free check).	0.27^{b}	5.73^{a}	18.60^{ab}
T_{12}	Un-weeded Control	0.12^{c}	3.25^{c}	6.45^{d}
SE (m)±		0.04	0.92	2.33
CD at 5%		0.08	1.00	4.84

Table 5: Influence of different weed management practices on potassium uptake by crop (kg ha^{-1})

Treatment		30 DAS	60 DAS	90 DAS
T_1	Oxyfluorfen 23.5% EC 0.2 kg ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* inter-cultivation at 45 DAS.	1.08^{b}	31.82^{bc}	49.62^{cd}
T_2	Pendimethalin 38.7% CS 675 g ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* inter-cultivation at 45 DAS.	1.17^{b}	27.37^{d}	52.88^{c}
T_3	Oxadiargyl 80% WP 90 g ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* inter-cultivation at 45 DAS.	1.18^{b}	29.42^{c}	52.83^{c}
T_4	Oxyfluorfen 23.5% EC 0.2 kg ha^{-1} (PE) followed by rice straw mulch (5t ha^{-1}) at 7-10 DAS.	0.94^{c}	24.32^{de}	44.50^{d}
T_5	Pendimethalin 38.7% CS 675 g ha^{-1} *fb* rice straw mulch (5t ha^{-1}) at 7-10 DAS.	1.03^{bc}	26.54^{d}	43.20^{d}
T_6	Oxadiargyl 80% WP 90 g ha^{-1} *fb* rice straw mulch (5t ha^{-1}) at 7-10 DAS	1.05^{b}	23.12^{e}	46.20^{d}
T_7	Rice straw mulch at 7-10 DAS (5t ha^{-1}).	1.17^{b}	27.56^{cd}	62.45^{b}

T_8	Black polythene mulch.	1.85[a]	38.51[a]	86.20[a]
T_9	Stale seed bed followed by inter cropping with green leafy vegetable (palak).	1.22[b]	32.64[b]	62.78[b]
T_{10}	Mechanical weeding at 15, 30, 60 DAS.	1.13[b]	34.24[ab]	62.26[b]
T_{11}	Mechanical weeding (inter row) followed by hand weeding (intra row) at 30 and 60 DAS - (weed free check).	1.63[a]	32.12[b]	88.40[a]
T_{12}	Un-weeded Control	0.72[c]	21.01[e]	36.97[e]
SE (m)±		0.52	2.96	3.01
CD at 5%		0.22	4.39	4.83

Nutrient Removal by Weeds (kg ha^{-1})

The influence of various weed management practices on nutrient removal by weed flora was found to be significant across all stages of crop growth, as illustrated in Tables 6–8. Timely and integrated interventions notably curtailed nutrient depletion, highlighting their critical role in sustaining soil fertility in okra cultivation systems.

Nitrogen Removal by Weeds

At 15 DAS, the highest nitrogen loss was observed in the un-weeded control plots, where weed flora extracted 11.18 kg/ha of nitrogen, underlining the severity of early-stage weed competition. Similar findings were reported by Sannagoudar *et al.* (2021a) and Gaurav *et al.* (2018), who attributed high nutrient removal in untreated plots to unchecked weed biomass. Plots managed with mechanical inter-row weeding and intra-row hand weeding at 30 and 60 DAS also exhibited considerable nitrogen removal (10.63 kg/ha), indicating partial control of nutrient-competitive weeds.

Conversely, the most nutrient-efficient treatment, a pre-emergence application of oxyfluorfen 23.5% EC (0.2 kg/ha) followed by post-emergence propaquizafop 10% EC (62.5 g/ha) and inter-cultivation at 45 DAS, recorded minimal nitrogen loss (0.82 kg/ha), statistically on par with consistent mechanical weeding (0.84 kg/ha). These results align with recent reports by Chaudhary *et al.* (2023) and Tanveer *et al.* (2022), who emphasized the effectiveness of integrated herbicide-based strategies in curbing nutrient competition from weeds while preserving soil health.

By 30 DAS, nitrogen removal peaked at 34.14 kg/ha in the un-weeded plots, a consequence of aggressive weed proliferation. In contrast, the weed-free check and black polythene mulch treatments exhibited drastically reduced nitrogen losses (0.68 and 1.25 kg/ha, respectively). These findings are corroborated by Otuaro *et al.* (2024) and Neupane *et al.* (2023), who noted that mulching effectively suppresses early weed emergence and minimizes nitrogen depletion. The trend persisted through 60 DAS and 90 DAS, with un-weeded controls continuing to record the highest nitrogen removal (54.38 and 63.06 kg/ha, respectively). Minimal nitrogen depletion was maintained in black polythene mulch (3.67 and 3.84 kg/ha) and weed-free plots (3.41 and 4.42 kg/ha), consistent with the observations of Tadesse *et al.* (2024) and Kumar *et al.* (2020), who highlighted the importance of weed exclusion in maximizing nutrient-use efficiency in okra.

Phosphorus Removal by Weeds

Phosphorus removal by weeds followed a similar trend. At 15 DAS, un-weeded plots recorded the highest phosphorus depletion (1.99 kg/ha), slightly higher than the weed-free check (1.89 kg/ha). This was likely due to residual weed activity before full crop canopy establishment. These results support the findings of Jalendhar *et al.* (2016) and Bavaji and Somasundaram (2017), who reported early-stage phosphorus competition in unmanaged plots.

The most effective treatments, oxyfluorfen followed by propaquizafop with inter-cultivation, and black polythene mulch, resulted in minimal phosphorus removal (0.15 and 0.24 kg/ha, respectively). These outcomes are in agreement with Deshmukh *et al.* (2021) and Ahmad *et al.* (2015), who demonstrated the nutrient-preserving advantages of mulching and integrated weed management.

At 30 DAS, un-weeded plots showed exacerbated phosphorus removal (6.46 kg/ha), while black polythene mulch (0.24 kg/ha) and the weed-free check (0.13 kg/ha) effectively limited nutrient loss. This trend continued through 60 and 90 DAS, with the un-weeded control extracting up to 8.41 kg/ha of phosphorus. In contrast, mulch and weed-free treatments consistently recorded the lowest phosphorus losses (0.51–0.59 kg/ha), consistent with findings from Neupane *et al.* (2023), Tadesse *et al.* (2024), and Verma *et al.* (2022), all of whom emphasized the phosphorus-conserving benefits of mulch-based strategies in vegetable systems.

Potassium Removal by Weeds

Potassium depletion by weeds was particularly pronounced in un-weeded plots, with 14.39 kg/ha removed at 15 DAS. Interestingly, the weed-free check also recorded a notable potassium removal of 13.68 kg/ha, possibly due to early weed establishment before effective canopy closure. These findings are consistent with Gaurav *et al.* (2018) and Sinchana (2020), who reported significant early-stage nutrient uptake by fast-growing weed flora.

Integrated weed management using pre-emergence oxyfluorfen followed by post-emergence propaquizafop and inter-cultivation drastically reduced potassium removal (1.05 kg/ha), closely followed by mechanical weeding (1.08 kg/ha). Similar observations were made by Chaudhary *et al.* (2023) and Tanveer *et al.* (2022), who emphasized the role of proactive weed control in conserving soil potassium.

By 30 DAS, potassium removal remained highest in un-weeded plots (11.83 kg/ha), while the weed-free check (0.82 kg/ha) and black polythene mulch (1.53 kg/ha) were highly effective in minimizing nutrient loss. This pattern was sustained at 60 and 90 DAS, where potassium extraction in un-weeded plots reached 51.46 and 63.90 kg/ha, respectively. The lowest removals were again observed in black polythene mulch (3.47 and 3.89 kg/ha) and weed-free treatments (3.22 and 4.48 kg/ha), consistent with studies by Nagegowda *et al.* (2020) and Patel *et al.* (2017), who demonstrated the potassium-conserving effects of mulching and integrated practices in okra systems.

Integrated Discussion

Effective weed management, particularly using black polythene mulch, herbicide combinations, and manual weeding, significantly mitigated nutrient depletion by weeds across growth stages. Reduced nutrient losses in these treatments are attributed to lower weed biomass and density, which, in turn, alleviated competition for essential macronutrients such as nitrogen, phosphorus, and potassium. These findings align with those of Kujur *et al.* (2015) and Satyareddi *et al.* (2015), who showed that timely weed control enhances nutrient uptake by crops and improves yield.

In contrast, unweeded control plots consistently recorded the highest nutrient losses, validating earlier reports by Sannagoudar *et al.* (2021a), Verma *et al.* (2022), and Otuaro *et al.* (2024). These plots experienced excessive weed proliferation, which led to intense competition for soil nutrients and reduced crop vigor. Recent studies by Tanveer *et al.* (2022) and Tadesse *et al.* (2024) further emphasize the importance of adopting integrated, eco-friendly strategies, including mulching, timely mechanical weeding, and herbicide application, to improve soil nutrient retention and support sustainable okra production.

Table 6: Influence of different weed management practices on nitrogen removal by weeds (kg ha^{-1})

Treatment		15 DAS	30 DAS	60 DAS	90 DAS
T_1	Oxyfluorfen 23.5% EC 0.2 kg ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* intercultivation at 45 DAS.	0.82^a	3.41^d	4.27^c	9.89^b
T_2	Pendimethalin 38.7% CS 675 g ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* intercultivation at 45 DAS.	1.55^d	4.85^f	4.83^d	10.77^c
T_3	Oxadiargyl 80% WP 90 g ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* intercultivation at 45 DAS.	1.63^e	5.63^g	7.62^e	14.20^d
T_4	Oxyfluorfen 23.5% EC 0.2 kg ha^{-1} (PE) followed by rice straw mulch (5t ha^{-1}) at 7-10 DAS.	0.94^b	3.86^e	14.96^g	19.56^e
T_5	Pendimethalin 38.7% CS 675 g ha^{-1} *fb* rice straw mulch (5t ha^{-1}) at 7-10 DAS.	2.27^f	9.49^h	19.50^i	22.58^f
T_6	Oxadiargyl 80% WP 90 g ha^{-1} *fb* rice straw mulch (5t ha^{-1}) at 7-10 DAS	2.44^g	12.01^i	18.83^h	27.02^h
T_7	Rice straw mulch at 7-10 DAS (5t ha^{-1}).	2.67^h	12.45^j	20.53^j	24.12^g
T_8	Black polythene mulch.	1.35^c	1.25^b	3.67^b	3.84^a
T_9	Stale seed bed followed by inter cropping with green leafy vegetable (palak).	4.32^i	15.29^k	26.65^k	31.25^i
T_{10}	Mechanical weeding at 15, 30, 60 DAS.	0.84^a	2.85^c	14.68^f	32.38^j
T_{11}	Mechanical weeding (inter row) followed by hand weeding (intra row) at 30 and 60	10.63^j	0.68^a	3.41^a	4.42^a

	DAS - (weed free check).				
T_{12}	Unweeded Control	11.18[k]	34.14[l]	54.38[l]	63.06[k]
SE (m)±		0.01	0.01	0.03	0.24
CD at 5%		0.03	0.04	0.10	0.70

Table 7: Influence of different weed management practices on phosphorus removal by weeds (kg ha^{-1})

Treatment		15 DAS	30 DAS	60 DAS	90 DAS
T_1	Oxyfluorfen 23.5% EC 0.2 kg ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* intercultivation at 45 DAS.	0.15[a]	0.65[c]	0.66[b]	1.32[b]
T_2	Pendimethalin 38.7% CS 675 g ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* intercultivation at 45 DAS.	0.28[b]	0.92[d]	0.75[b]	1.44[b]
T_3	Oxadiargyl 80% WP 90 g ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* intercultivation at 45 DAS.	0.29[b]	1.07[d]	1.18[c]	1.89[c]
T_4	Oxyfluorfen 23.5% EC 0.2 kg ha^{-1} (PE) followed by rice straw mulch (5t ha^{-1}) at 7-10 DAS.	0.17[a]	0.73[c]	2.31[d]	2.61[d]
T_5	Pendimethalin 38.7% CS 675 g ha^{-1} *fb* rice straw mulch (5t ha^{-1}) at 7-10 DAS.	0.41[c]	1.79[c]	3.01[ef]	3.01[e]
T_6	Oxadiargyl 80% WP 90 g ha^{-1} *fb* rice straw mulch (5t ha^{-1}) at 7-10 DAS	0.44[c]	2.27[e]	2.91[e]	3.60[g]
T_7	Rice straw mulch at 7-10 DAS (5t ha^{-1}).	0.48[c]	2.35[e]	3.17[f]	3.22[f]
T_8	Black polythene mulch.	0.24[ab]	0.24[a]	0.57[ab]	0.51[a]
T_9	Stale seed bed followed by inter cropping with green leafy vegetable (palak).	0.77[d]	2.89[f]	4.11[g]	4.17[h]
T_{10}	Mechanical weeding at 15, 30, 60 DAS.	0.15[a]	0.54[b]	2.27[d]	4.32[h]
T_{11}	Mechanical weeding (inter row) followed by hand weeding (intra row) at 30 and 60 DAS - (weed free check).	1.89[ef]	0.13[a]	0.53[a]	0.59[a]
T_{12}	Unweeded Control	1.99[f]	6.46[g]	8.39[h]	8.41[i]
SE (m)±		0.02	0.05	0.08	1.01
CD at 5%		0.10	0.16	0.23	0.16

Table 8: Influence of different weed management practices on potassium removal by weeds (kg ha^{-1})

Treatment		15 DAS	30 DAS	60 DAS	90 DAS
T_1	Oxyfluorfen 23.5% EC 0.2 kg ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* intercultivation at 45 DAS.	1.05[a]	4.15[b]	4.04[a]	10.02[b]
T_2	Pendimethalin 38.7% CS 675 g ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* intercultivation at 45 DAS.	1.99[d]	5.90[c]	4.57[a]	10.92[b]
T_3	Oxadiargyl 80% WP 90 g ha^{-1} (PE) *fb* propaquizafop 10% EC 62.5 g ha^{-1} at 2-3 leaf stage (PoE) *fb* intercultivation at 45 DAS.	2.09[e]	6.85[c]	7.21[b]	14.39[c]
T_4	Oxyfluorfen 23.5% EC 0.2 kg ha^{-1} (PE) followed by rice straw mulch (5t ha^{-1}) at 7-10 DAS.	1.21[b]	4.69[bc]	14.16[d]	19.82[d]
T_5	Pendimethalin 38.7% CS 675 g ha^{-1} *fb* rice straw mulch (5t ha^{-1}) at 7-10 DAS.	2.93[f]	11.54[d]	18.45[e]	22.88[e]
T_6	Oxadiargyl 80% WP 90 g ha^{-1} *fb* rice straw mulch (5t ha^{-1}) at 7-10 DAS	3.15[g]	14.61[e]	17.82[e]	27.38[f]
T_7	Rice straw mulch at 7-10 DAS (5t ha^{-1}).	3.43[h]	15.14[f]	19.43[e]	24.44[f]
T_8	Black polythene mulch.	1.74[c]	1.53[a]	3.47[a]	3.89[a]

T_9	Stale seed bed followed by inter cropping with green leafy vegetable (palak).	5.56[i]	18.59[g]	25.22[f]	31.67[g]
T_{10}	Mechanical weeding at 15, 30, 60 DAS.	1.08[a]	3.47[b]	13.89[c]	32.81[h]
T_{11}	Mechanical weeding (inter row) followed by hand weeding (intra row) at 30 and 60 DAS - (weed free check).	13.68[j]	0.82[a]	3.22[a]	4.48[a]
T_{12}	Unweeded Control	14.39[k]	41.53[h]	51.46[g]	63.90[i]
SE (m)±		0.12	0.42	0.83	0.76
CD at 5%		0.04	1.24	2.43	2.23

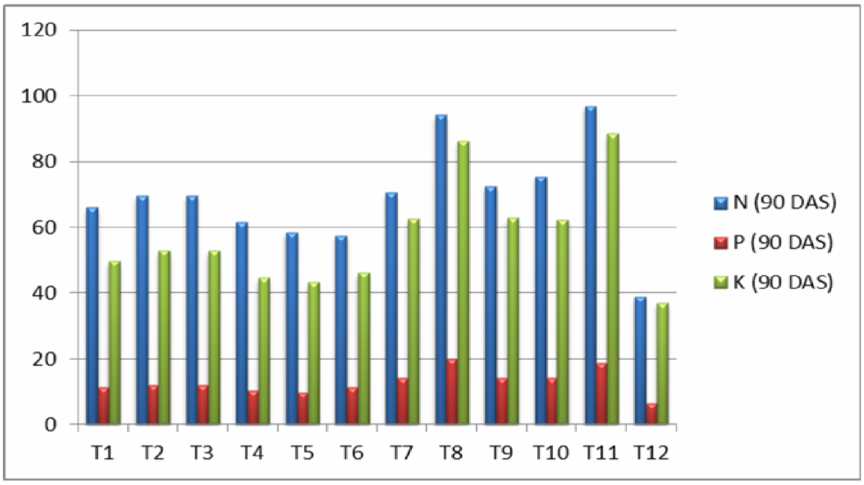

Fig. 1: NPK uptake by crop at 90 DAS

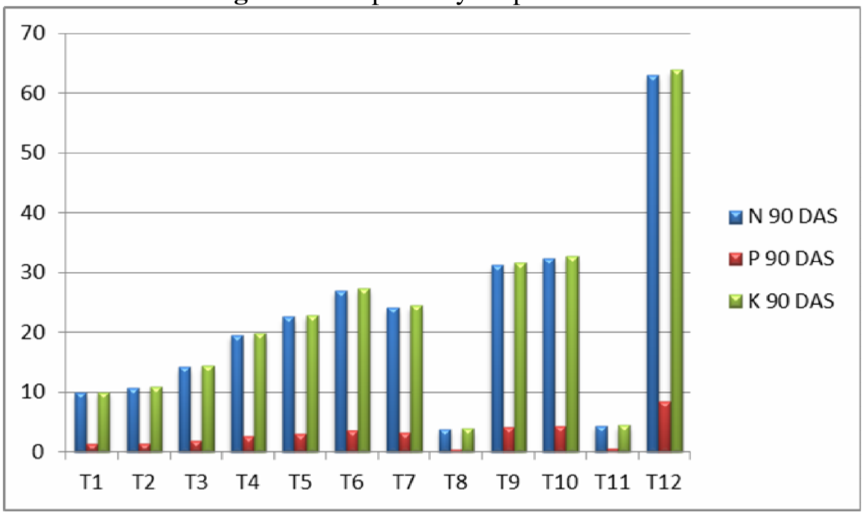

Fig. 2: NPK removal by weeds at 90 DAS

Conclusion

The present study underscores the pivotal role of black polythene mulch as an ecologically sound and agronomically efficient weed management strategy in okra cultivation. Acting as a dual-function intervention, the mulch not only served as a robust physical barrier that significantly suppressed weed emergence and biomass but also optimized the nutrient dynamics in the crop–weed–soil system. Notably, nutrient uptake of nitrogen (N), phosphorus (P), and potassium (K) by okra was markedly enhanced during the critical growth phases at 30 and 60 DAS under black polythene mulch, aligning with peak nutrient demand periods of the crop.

Interestingly, while the black polythene mulch sustained superior nutrient uptake during early and mid-growth stages, the weed-free check surpassed all treatments in nutrient absorption by 90 DAS, suggesting that strategic integration of mulching with manual weeding could sustain nutrient availability into the later phenological stages. In contrast, the unweeded control plots exhibited the highest nutrient losses to weed flora throughout all observed stages (15, 30, 60, and 90 DAS), reaffirming the detrimental impact of unmanaged weed growth on soil fertility and crop nutrition.

These findings collectively position black polythene mulching not merely as a weed suppressant but as a vital tool for nutrient stewardship. Its ability to conserve nutrients, reduce interspecies competition, and enhance nutrient assimilation by the crop contributes to more resilient and productive okra farming systems. Therefore, the adoption of black polythene mulch, particularly when synchronized with crop growth stages, represents a sustainable intensification practice that supports higher yields, reduces agrochemical dependency, and advances climate-smart horticulture.

Weed control by black polythene mulch at 15 DAS

Weed control by black polythene mulch at 30 DAS

Weed control by black polythene mulch at 60 DAS

Weed control by black polythene mulch at 90 DAS

Unweeded control plot

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