



RESEARCH ARTICLE

Effect of herbicides on weeds, rhizospheric microorganisms, tea green leaf yield and nutrient uptake in tea plantation

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ABSTRACT

Field experiment was conducted in the Tarai region of Jalpaiguri, West Bengal, India during 2021 and 2022 to evaluate the effect of post-emergence herbicides on weeds, non-target soil organisms, nutrient dynamics and productivity of tea (var. TV-25) under natural weed infestations in tea garden. The experimental treatments were comprised of: post-emergence application (PoE) of five doses of 2-methyl-4-chlorophenoxyacetic acid (MCPA): 0.5, 0.8, 1.0, 1.25 and 1.5 kg/ha; 2,4-D Sodium salt 1.0 kg/ha PoE and untreated control. A randomized complete block design replicated thrice was used. MCPA 1.50 kg/ha PoE was most effective against broad-leaved weeds, achieving higher weed control efficiency (> 85%) and producing the highest total tea green leaf yield. No phytotoxicity was observed on mature tea leaves due to any of the herbicidal treatment. Although transient reductions in rhizospheric micro-flora (total bacteria, fungi, and actinomycetes) were detected after herbicide application, microbial communities recovered over time, indicating no persistent adverse effects due to herbicides tested. Maximum nutrients uptake and soil available nutrients were recorded with higher dose of MCPA. MCPA at 1.5 kg/ha was observed as the best substitute for others post-emergent herbicide to manage broad-leaved weeds in tea garden.

Keywords: MCPA, Soil Microbes, Soil nutrient uptake, Tea plantation, Weed management

INTRODUCTION

Tea (*Camellia sinensis*) is one of the most important perennial crops in the north-eastern region of India as well as the northern region of West Bengal. It is a significant cash crop used for domestic consumption and export (FAO 2024). West Bengal stands at the second position in the list of tea producing states with 420.91 million kilograms of tea production in the year 2022-23, which is roughly 30% of the national produce (Tea Board of India 2023). It not only contributes to Indian economy but also helps in employment generation (Saha 2024). India has an annual turnover of 776 million USD from tea industry (IBEF 2024). It is most commonly used in the preparation of non-alcoholic caffeine containing beverages. Tea has been consumed socially and habitually by people since 3000 BC but

apart from the stringent taste, its medicinal properties are often overlooked. However, traditional healers have long believed that taking tea is a means of prolonging life. Nutritional and therapeutic importance of tea arises from its unique combination of large number of constituents such as proteins, carbohydrates, amino acids (L-theanine), lipids, vitamins, minerals, alkaloids (theophylline, caffeine and theobromine) and polyphenols (Alemu *et al.* 2025). Previously tea was taken only as a stimulant drink, but today it has proved that it activates the central nervous system, which may aid the body's ability to burn calories and unwanted fats through thermogenic process (Rondanelli *et al.* 2021). A manifold increase in production of tea in India is mainly attributed to efficient and integrated agricultural practices including efficient weed management practices.

Weed management is a fundamental practice, failure of which may result in severe losses in terms of production and economic return. The reduction in tea leaves yield due to weeds can be as high as 12 to 21% (Kundu *et al.* 2020) depending upon the management practices followed. Besides reducing the yield, weeds also have adverse effects on tea *viz.*

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restricted branching, frame development in young tea, reduce plucking efficiency, harbor and serve as an alternate host for some important insect and disease pests of tea (Kumar *et al.* 2017). Weeds remove huge quantities of nitrogen, phosphorous and potassium from soil than a beverage crop leading to low tea yield (Roy *et al.* 2021). Weeds are dynamic in nature and a shift in their abundance and dominance is likely with changes in management practices. Because of the non-availability of labor at the critical time of weeding and high labor costs weed management practices are rapidly shifting towards chemical methods (Rao 2022).

The studies on effect of pre- and post-emergence herbicides to manage weeds in tea are meagre. Among different popular group of herbicides used worldwide, phenoxyacetic acid herbicides are widely used due to their selective action against broad-leaved weeds (Paszko *et al.* 2016; Kundu *et al.* 2020). Low price and high selectivity prompted their wide usage in modern, highly efficient agriculture. The most common representatives of this group are 2,4-dichlorophenoxyacetic acid (2,4-D) and 2-methyl-4-chlorophenoxyacetic acid (MCPA) (Paszko *et al.* 2016). They are synthetic auxins *i.e.* phytohormones which are involved in a range of physiological process essential for the proper plant growth. Their mode of action is based on mimicking indole-3-acetic acid (IAA). They stimulate plant development by cell division and elongation, vascular differentiation, oxygen species (ROS) production. Contrary to natural auxins, synthetic formulations are active for a significantly longer time, thereby exerting prolonged effects on root formation and apical dominance (Gao *et al.* 2024). On the other hand, high herbicide concentrations significantly disturb the proper plant growth and trigger damage processes leading to the final plant destruction (Romero Puertas *et al.* 2022).

The present study was carried out to identify the optimum dose MCPA to manage diverse weed flora in tea garden without compromising the tea productivity.

MATERIALS AND METHODS

A field experiment was conducted at Sunrise Tea Estate, Batabari, Jalpaiguri at 88°80' E longitudes and 26°88' N latitudes in 2021 and 2022 (September to December) in a pre-established tea garden (var. TV-25). Randomized Complete Block Design was used with seven treatments replicated thrice. Soil pH of the experimental block was acidic (6.60) in reaction, blackish grey in colour mostly due to high organic

matter and poor bases, rich in available major nutrients (N, P, K). The experimental site was situated in warm and temperate climate. Temperature reaches maximum in June and it starts dropping from middle of October and recorded minimum in January. Rainfall started during May and very erratic thereafter up to October (average annual rainfall is 3000 mm). The relative humidity gradually decreases from July to December.

When weeds are at active vegetative growth stage (4-6 leaf), the tested herbicide MCPA 750 SL (MCPA) in different doses, *viz.* 0.5, 0.8, 1.0, 1.25 and 1.5 kg/ha and standard check 2,4-D Sodium salt 58% SL (2,4-D Sodium salt) 1.0 kg/ha were sprayed using Knapsack sprayer with a flood jet nozzle WFN 0.040 in a spray volume of 500 lit/ha. The observations were recorded on weed density (m^{-2}) and weed dry weight (weed biomass) (g/m^2) at 20, 40 and 60 days after application (DAA) by placing a quadrat of $0.5 \times 0.5 m^2$ randomly in each plot. The count and dry weight of weeds were analyzed after subjecting the original data to square root transformation ($\sqrt{x + 0.5}$). Reduction in weed density (%), weed biomass (%) and herbicide efficiency index (HEI) were worked out using equations as below.

$$\text{Reduction in weed number (\%)} = \frac{WD_c - WD_t}{WD_c} \times 100 \dots (i)$$

Where WD_c is the weed density (no./ m^2) in control plot; WD_t is the weed density (no./ m^2) in treated plot.

$$\text{Reduction in weed biomass (\%)} = \frac{WDM_c - WDM_t}{WDM_c} \times 100 \dots (ii)$$

Where WDM_c is the weed biomass ($g. m^{-2}$) in control plot; WDM_t is the weed biomass (g/m^2) in treated plot.

$$\text{Herbicide efficiency Index (HEI)} = \frac{Y_t - Y_c}{Y_t} \times \frac{WDM_c}{WDM_t} \dots (iii)$$

Where Y_t is the crop yield from treated plot; Y_c is the crop yield from control plot. WDM_c is the weed biomass (g/m^2) in control plot; WDM_t is the weed biomass ($g. m^{-2}$) in treated plot.

Weed control efficiency (WCE) was calculated based on the data recorded on 20, 40 and 60 DAA as per the formula given below:

$$WCE = \frac{X - Y}{X} \times 100 \dots (iv)$$

Where, X = Weed biomass in unweeded plot; Y = Weed biomass in treated plot.

The observations on the level of phytotoxicity due to application of tested herbicide were recorded on 1, 3, 5, 7 and 10 DAA. The parameters of phytotoxicity on chlorosis, necrosis, wilting, scorching, hyponasty and epinasty were observed to assess the phytotoxicity according to Biswas *et al.*

(2023). Yield data of green leaf tea was also recorded month wise from each picking for 3 months and calculated total yield of 3 months from each herbicidal treatment including plots of untreated weedy check.

Soil was collected at initial, 7, 14, 30 and 45 DAA with an auger (5 cm diameter) from the mid-points between tea rows randomly at five locations per plot from a depth of 15 cm and bulked, having almost 200–250 g fresh weight. The colony-forming units (cfu) of fungi, bacteria, and actinomycetes were enumerated in Czapek's Dox medium, nutrient agar, and actinomycetes isolation agar (Hi media), respectively, following serial dilution technique and agar/pour plate method using a 1 mL soil solution for plating (Alexander 1978). The microbes were incubated at 30 °C after serial dilution and spreading of the soil solution on the respective plates. The populations of bacteria per plate were scored within 3 days, whereas the populations of fungi and actinomycetes were observed after an incubation period of 5–7 days (Mondal *et al.* 2018). The nitrogen, phosphorous and potassium content of the sample were analyzed by micro-kjeldahl method, vanadomolybdo phosphoric yellow colour method and flame photometric method, respectively and subsequently the nutrient uptake by weeds and green leaf of tea was computed on hectare basis as given by Sunil *et al.* (2011).

Data on crops and weeds were analyzed using the analysis of variance (ANOVA) technique to evaluate the differences among treatments, and the means were separated using the least significant difference (LSD) at the 5% level (Gomez and Gomez 1984). The variance over the years was estimated for

homogeneity of data by Bartlett's chi-square test. The effect of the years was non-significant and there were no significant interactions between treatments and years. Therefore, the data were pooled over the years and subjected to ANOVA.

RESULTS AND DISCUSSION

Weed density and biomass

The experimental plots were infested with mixed weed flora where broad-leaved weeds were the most dominating followed by grasses and sedges, irrespective of the dates of observations at 20, 40 and 60 DAA. Weed density and biomass were significantly higher in weedy check. Amongst the evaluated herbicidal treatments MCPA 1250 g/ha was most effective against monocot weeds, though treatments were non-significant among each other (Table 1). The highest dose of MCPA (1500 g/ha) proved significantly ($p=0.05$) superior over standard check herbicide 2,4-D salt to control *Borreria hispida* and *Ludwigia octovalvis* which was closely followed by MCPA at 1250 g/ha. During the total experiment periods all other broad-leaved weeds followed the same trend as previously. The reduction of total weed density over control was lowest with MCPA 500 g/ha and it continuously increased with the increasing dose of MCPA, accounting 42.75 % reduction in total weed density with MCPA at 1500 g/ha than unweeded control plot at 20 DAA (Table 2). Gao *et al.* (2019) and Kundu *et al.* (2020) reported more than 80 % control of weeds with herbicides applied alone or as mixtures in tea garden.

Among the evaluated treatments, the lower dry biomass of monocot weeds was observed with

Table 1. Effect of weed control treatments on density (no./m²) of grasses, sedges, monocot weeds and broad-leaved weeds: *B. hispida*, *L. octovalvis*, *S. media* and *A. viridis* at 20, 40 and 60 DAA in tea (pooled over of two years)

Treatment	Grasses and sedges						Broad-leaved weeds								
	Monocot weeds			<i>Borreria hispida</i>			<i>Ludwigia octovalvis</i>			<i>Stellaria media</i>			<i>Amaranthus viridis</i>		
	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA
MCPA 500 g/ha	6.24 (38.43)	6.38 (40.19)	6.69 (44.22)	3.03 (8.67)	3.34 (10.63)	3.65 (12.83)	2.60 (6.27)	3.03 (8.69)	3.14 (9.37)	2.06 (3.73)	2.52 (5.85)	2.83 (7.51)	2.09 (3.87)	2.23 (4.49)	2.52 (5.85)
MCPA 800 g/ha	6.28 (38.94)	6.47 (41.38)	6.75 (45.05)	2.87 (7.73)	3.32 (10.55)	3.60 (12.47)	2.47 (5.61)	2.85 (7.61)	3.08 (8.97)	2.01 (3.55)	2.39 (5.21)	2.63 (6.43)	1.96 (3.33)	2.19 (4.28)	2.43 (5.39)
MCPA 1000 g/ha	6.19 (37.80)	6.50 (41.77)	6.66 (43.79)	2.78 (7.25)	3.28 (10.28)	3.60 (12.43)	2.41 (5.33)	2.79 (7.26)	3.01 (8.57)	1.91 (3.13)	2.29 (4.76)	2.55 (6.00)	1.89 (3.07)	2.15 (4.12)	2.26 (4.62)
MCPA 1250 g/ha	6.17 (37.51)	6.30 (39.14)	6.67 (43.93)	2.74 (7.03)	3.20 (9.77)	3.49 (11.67)	2.25 (4.57)	2.71 (6.84)	3.01 (8.54)	1.87 (3.00)	2.25 (4.57)	2.46 (5.57)	1.87 (3.00)	2.09 (3.88)	2.22 (4.45)
MCPA 1500 g/ha	6.21 (38.07)	6.33 (39.58)	6.56 (42.50)	2.69 (6.75)	3.14 (9.35)	3.41 (11.15)	2.20 (4.33)	2.61 (6.32)	2.88 (7.77)	1.88 (3.03)	2.23 (4.47)	2.41 (5.33)	1.87 (3.00)	1.96 (3.35)	2.04 (3.65)
2,4-D sodium salt 1000 g/ha	6.23 (38.35)	6.54 (42.25)	6.76 (45.19)	2.92 (8.00)	3.29 (10.31)	3.65 (12.80)	2.49 (5.71)	2.83 (7.53)	3.04 (8.73)	2.14 (4.07)	2.40 (5.26)	2.62 (6.37)	1.96 (3.33)	2.19 (4.30)	2.37 (5.13)
Untreated control	6.34 (39.72)	6.57 (42.68)	6.81 (45.87)	4.36 (18.47)	4.60 (20.68)	4.73 (21.92)	3.09 (9.03)	3.28 (10.25)	3.67 (12.94)	2.67 (6.61)	3.00 (8.50)	3.50 (11.72)	2.86 (7.67)	3.03 (8.68)	3.28 (10.25)
LSD ($p=0.05$)	NS	NS	NS	0.02	0.50	0.04	0.04	0.03	0.01	0.01	0.07	0.01	0.12	0.01	0.02

Values in the parentheses are original which were subjected to $\sqrt{x+0.5}$ transformations; DAA: days after application; NS: Non-significant

MCPA 1250 g/ha PoE which was statistically at par with highest dose of same herbicide (Table 3). But the later one recorded lower biomass of broad-leaved weeds viz. *Borreria hispida*, *Ludwigia octovalvis*, *Stelleria media*, *Amaranthus viridis* irrespective of the dates of observation. Lower biomass of *Pouzolzia zeylanica* at 20 DAA was observed with MCPA 1250 g/ha PoE which was statistically at par with MCPA 1500 g/ha PoE (Table 4). Another broad-leaved weed species, viz. *Ageratum conyzoides* and *Commelina benghalensis* recorded highest biomass with MCPA at 750 g/ha, among the herbicide treated plots. The weed biomass was reduced by 67.07 % with MCPA 1500 g/ha compared to control at 20 DAA (Table 4).

Subsequent dates of observation (40 DAA and 60 DAA) also followed the same trend.

Weed control efficiency and herbicide efficiency index

The weed control efficiency based on the weed dry matter at different dates of observations varied significantly among the herbicide treatments (Table 5). MCPA 1500 g/ha recorded the highest weed control efficiency (WCE) of 85.40 %, 81.00 % and 77.45 % at 20, 40 and 60 DAA, respectively. MCPA 1250 g/ha also recorded satisfactory WCE (> 80 %) at 20 DAA closely followed by MCPA at 1000 g/ha and the same dose of 2,4-D Sodium salt. Herbicide

Table 2. Effect of weed control treatments on weed density (no. /m²) of *P. zeylanica*, *A. conyzoides*, *C. benghalensis* and other BLWs at 20, 40 and 60 DAA and percentage reductions in total weed densities in tea (pooled over of two years)

Treatment	Broad-leaved weeds												Total weed density reduction (%) over control*		
	<i>Pouzolzia zeylanica</i>			<i>Ageratum conyzoides</i>			<i>Commelina benghalensis</i>			Others					
	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA
MCPA 500 g/ha	1.87 (3.00)	2.30 (4.78)	2.59 (6.20)	1.68 (2.33)	1.98 (3.41)	2.24 (4.50)	1.48 (1.70)	1.69 (2.35)	2.07 (3.80)	1.58 (2.00)	2.04 (3.67)	2.83 (7.51)	34.29	31.63	28.51
MCPA 800 g/ha	1.78 (2.67)	2.15 (4.14)	2.40 (5.28)	1.58 (2.00)	1.93 (3.23)	2.17 (4.22)	1.46 (1.62)	1.68 (2.32)	1.82 (2.82)	1.58 (2.00)	2.01 (3.55)	2.63 (6.43)	36.68	33.08	31.30
MCPA 1000 g/ha	1.68 (2.31)	1.98 (3.42)	2.18 (4.24)	1.47 (1.67)	1.76 (2.60)	1.95 (3.32)	1.43 (1.55)	1.57 (1.97)	1.77 (2.65)	1.49 (1.73)	1.98 (3.44)	2.55 (6.00)	40.07	35.24	35.43
MCPA 1250 g/ha	1.58 (2.00)	1.93 (3.24)	2.18 (4.24)	1.36 (1.35)	1.76 (2.60)	1.84 (2.90)	1.40 (1.45)	1.56 (1.93)	1.66 (2.25)	1.44 (1.57)	1.83 (2.86)	2.46 (5.57)	42.29	39.13	37.69
MCPA 1500 g/ha	1.51 (1.77)	1.87 (3.00)	2.13 (4.04)	1.35 (1.33)	1.64 (2.18)	1.78 (2.68)	1.37 (1.38)	1.43 (1.55)	1.75 (1.50)	1.35 (1.33)	1.76 (2.60)	2.41 (5.33)	42.75	41.11	41.18
2,4-D sodium salt 1000 g/ha	1.69 (2.35)	2.04 (3.65)	2.27 (4.66)	1.54 (1.87)	1.87 (3.0)	2.10 (3.91)	1.58 (2.00)	1.65 (2.22)	3.34 (1.96)	1.47 (1.67)	1.94 (3.25)	2.62 (6.37)	36.78	33.49	32.47
Untreated control	2.92 (8.00)	3.27 (10.19)	11.58 (3.48)	2.80 (7.33)	3.04 (8.75)	3.18 (9.60)	2.05 (3.70)	2.23 (4.48)	5.95 (6.00)	2.55 (8.70)	3.04 (11.72)	3.50 (11.72)	0.00	0.00	0.00
LSD (p=0.05)	0.03	0.16	0.29	0.16	0.13	0.23	0.20	0.12	0.13	0.05	0.19	0.15	0.07	0.07	0.05

Values in the parentheses are original which were subjected to $\sqrt{x+0.5}$ transformations; DAA: days after application.

*Total weed density reduction (%) over control was calculated based on original (non-transformed) data.

Table 3. Effect of weed control treatments on weed biomass (g/ m²) of grasses, sedges, monocot weeds and broad-leaved weeds: *B. hispida*, *L. octovalvis*, *S. media* and *A. viridis* at 20, 40 and 60 DAA in tea (pooled over of two years)

Treatment	Grasses and sedges			Broad-leaved weeds											
	Monocot weeds			<i>Borreria hispida</i>			<i>Ludwigia octovalvis</i>			<i>Stelleria media</i>			<i>Amaranthus viridis</i>		
	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA
MCPA 500 g/ha	3.53 (11.96)	3.81 (14.04)	4.17 (16.86)	1.87 (3.01)	2.22 (4.42)	2.67 (6.62)	1.82 (2.81)	2.22 (4.45)	2.49 (5.72)	1.08 (0.67)	1.36 (1.36)	1.57 (1.95)	1.54 (1.87)	1.70 (2.38)	2.03 (3.61)
MCPA 800 g/ha	3.46 (11.45)	3.78 (13.81)	4.11 (16.4)	1.72 (2.46)	2.09 (3.87)	2.40 (5.27)	1.69 (2.37)	2.07 (3.77)	2.37 (5.1)	0.92 (0.35)	1.10 (0.72)	1.19 (0.91)	1.40 (1.47)	1.62 (2.13)	1.89 (3.07)
MCPA 1000 g/ha	3.58 (12.34)	3.76 (13.63)	4.13 (16.59)	1.64 (2.19)	2.02 (3.59)	2.35 (5.03)	1.52 (1.82)	1.80 (2.75)	2.08 (3.81)	0.88 (0.28)	1.06 (0.63)	1.13 (0.77)	1.24 (1.05)	1.46 (1.62)	1.56 (1.92)
MCPA 1250 g/ha	3.41 (11.16)	3.91 (14.8)	4.20 (17.12)	1.63 (2.15)	1.99 (3.45)	2.28 (4.71)	1.51 (1.79)	1.84 (2.88)	2.13 (4.05)	0.85 (0.23)	1.01 (0.52)	1.03 (0.57)	1.26 (1.08)	1.44 (1.58)	1.56 (1.93)
MCPA 1500 g/ha	3.46 (11.44)	3.80 (13.94)	4.22 (17.33)	1.53 (1.85)	1.86 (2.95)	2.12 (4.01)	1.38 (1.41)	1.71 (2.42)	1.97 (3.39)	0.85 (0.23)	0.99 (0.48)	0.99 (0.49)	1.22 (0.99)	1.28 (1.14)	1.45 (1.6)
2,4-D sodium salt 1000 g/ha	3.55 (12.08)	3.87 (14.48)	4.17 (16.9)	1.77 (2.63)	2.08 (3.81)	2.45 (5.48)	1.54 (1.88)	1.93 (3.22)	2.24 (4.53)	1.02 (0.54)	1.13 (0.78)	1.21 (0.96)	1.33 (1.27)	1.53 (1.85)	1.71 (2.44)
Untreated control	3.50 (11.74)	3.79 (13.89)	4.10 (16.29)	3.14 (9.38)	3.45 (11.42)	3.55 (12.11)	2.54 (5.94)	2.80 (7.33)	3.11 (9.17)	1.80 (2.75)	2.09 (3.85)	2.39 (5.19)	2.13 (4.02)	2.36 (5.05)	2.65 (6.51)
LSD (p=0.05)	0.03	0.02	0.02	0.02	0.01	0.06	0.01	0.04	0.05	0.03	0.01	0.01	0.01	0.02	0.005

Values in the parentheses are original which were subjected to $\sqrt{x+0.5}$ transformations; DAA: days after application.

efficiency index (HEI) reflects the efficacy of a herbicidal treatment in killing weeds and its effect on the crop (Kundu *et al.* 2025). In this study, MCPA with its highest dose, proved itself as a most efficient (0.56) than other herbicides in terms of HEI. In contrast, MCPA at 750 g/ha was the least efficient herbicide with a HEI value of only 0.17 (Table 5).

Tea green leaf yield

All the treatments significantly recorded higher green leaf yield in comparison to weedy check during both years of experiment (Table 5). Among the treatments tested, MCPA 1500 g/ha yielded maximum green leaf of 0.96 t/ha, 0.98 t/ha and 0.96 t/ha from the month of October to December respectively, which ultimately reflected in the total yield green tea leaf (2.90 t/ha). It was statistically at par with MCPA 1000 g/ha and 1250 g/ha (Table 5). The Figure 1 shows a positive linear relationship between weed

control efficiency (%) and green leaf yield (t/ha). Green leaf yield increases as weed control efficiency improves, following the regression equation $y = 0.0195x + 1.3844$, with a strong coefficient of determination ($R^2 = 0.8697$) (Figure 1). This indicates that higher weed control efficiency substantially contributes to increased green tea leaf yield. Similar trend was observed with herbicide efficiency index, weed density reduction and biomass while contrasting relationship was observed with microbial population (Figure 2) demonstrating that it is essential to control weeds effectively in tea garden. A similar observation was reported by Kumar *et al.* (2017) and Kundu *et al.* (2020).

Phytotoxicity

No phytotoxicity symptoms regarding epinasty, hyponasty, vein clearing, necrosis, leaf tip and surface injury and wilting of plants were observed on

Table 4. Effect of weed control treatments on weed biomass (g/m²) of *P. zeylanica*, *A. conyzoides*, *C. benghalensis* and other BLWs at 20, 40 and 60 DAA and percentage reductions in total weed biomass in tea (pooled over of two years)

Treatment	Broad-leaved weeds												Total weed biomass (g m ⁻²) reduction (%) over control*		
	<i>Pouzolzia zeylanica</i>			<i>Ageratum conyzoides</i>			<i>Commelina benghalensis</i>			Other BLWs					
	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA	20 DAA	40 DAA	60 DAA
MCPA 500 g/ha	1.13 (0.77)	1.43 (1.55)	1.70 (2.4)	1.46 (1.64)	1.93 (3.21)	2.14 (4.07)	1.29 (1.17)	1.61 (2.08)	1.64 (2.2)	1.13 (0.77)	1.64 (2.18)	2.04 (3.65)	53.50	46.72	41.32
MCPA 800 g/ha	1.01 (0.53)	1.25 (1.07)	1.42 (1.51)	1.33 (1.26)	1.73 (2.48)	2.07 (3.78)	1.15 (0.83)	1.37 (1.37)	1.52 (1.82)	1.07 (0.65)	1.51 (1.79)	1.82 (2.8)	59.72	53.68	49.32
MCPA 1000 g/ha	0.86 (0.24)	1.05 (0.6)	1.14 (0.79)	1.17 (0.86)	1.49 (1.71)	1.83 (2.85)	1.09 (0.68)	1.21 (0.96)	1.41 (1.49)	0.93 (0.36)	1.32 (1.23)	1.65 (2.22)	62.64	60.09	55.79
MCPA 1250 g/ha	0.81 (0.16)	0.96 (0.43)	1.05 (0.6)	1.06 (0.63)	1.49 (1.73)	1.59 (2.04)	1.11 (0.73)	1.23 (1.01)	1.30 (1.2)	0.94 (0.39)	1.35 (1.31)	1.64 (2.19)	65.47	58.61	57.11
MCPA 1500 g/ha	0.82 (0.18)	0.93 (0.36)	1.01 (0.53)	1.02 (0.55)	1.30 (1.2)	1.57 (1.97)	1.04 (0.58)	1.06 (0.63)	1.14 (0.81)	0.86 (0.24)	1.18 (0.9)	1.46 (1.62)	67.07	64.12	60.43
2,4-D sodium salt 1000 g/ha	0.96 (0.42)	1.03 (0.57)	1.32 (1.23)	1.26 (1.08)	1.59 (2.03)	1.94 (3.26)	1.09 (0.69)	1.24 (1.05)	1.57 (1.98)	1.06 (0.63)	1.47 (1.67)	1.87 (3)	60.00	56.00	50.42
Untreated control	2.21 (4.39)	2.53 (5.89)	2.61 (6.29)	2.77 (7.18)	3.10 (9.12)	3.23 (9.92)	2.08 (3.84)	2.30 (4.77)	2.72 (6.9)	2.08 (3.81)	2.48 (5.63)	2.89 (7.85)	0.00	0.00	0.00
LSD (p=0.05)	0.01	0.03	0.02	0.003	0.02	0.07	0.02	0.01	0.01	0.03	0.01	0.17	0.86	1.20	0.79

Values in the parentheses are original which were subjected to $\sqrt{x+0.5}$ transformations; DAA: days after application. *Total weed density reduction (%) over control was calculated based on original (non-transformed) data

Table 5. Effect of treatments on weed control efficiency (%) and green leaf yield (t/ha) of tea (pooled over of two years)

Treatment	Weed control efficiency (%)				Tea green leaf yield (t/ha)											
	HEI			HEI	October			November			December			Total		
	20 DAA	40 DAA	60 DAA		Year I	Year II	Pooled	Year I	Year II	Pooled	Year I	Year II	Pooled	Year I	Year II	Pooled
MCPA 500 g/ha	69.23	59.23	52.74	0.17	0.77	0.86	0.81	0.89	0.85	0.79	0.86	0.82	2.37	2.61	2.49	
MCPA 800 g/ha	75.99	67.58	62.06	0.24	0.79	0.88	0.82	0.90	0.86	0.81	0.88	0.85	2.42	2.66	2.54	
MCPA 1000 g/ha	81.89	75.33	70.47	0.38	0.84	0.94	0.87	0.97	0.92	0.84	0.94	0.89	2.55	2.84	2.69	
MCPA 1250 g/ha	82.67	75.67	72.96	0.47	0.88	0.97	0.90	1.00	0.95	0.88	0.98	0.93	2.66	2.95	2.80	
MCPA 1500 g/ha	85.40	81.00	77.45	0.56	0.91	1.01	0.93	1.03	0.98	0.91	1.01	0.96	2.75	3.06	2.90	
2,4-D sodium salt 1000 g/ha	77.87	71.77	64.22	0.27	0.81	0.90	0.85	0.94	0.89	0.79	0.88	0.84	2.45	2.72	2.58	
Untreated control	0.00	0.00	0.00	0.00	0.60	0.66	0.62	0.71	0.67	0.65	0.67	0.66	1.87	2.04	1.96	
LSD (p=0.05)	---	---	---	-	0.07	0.07	0.08	0.08	0.08	0.07	0.07	0.07	0.199	0.198	0.198	

HEI- Herbicide efficiency index

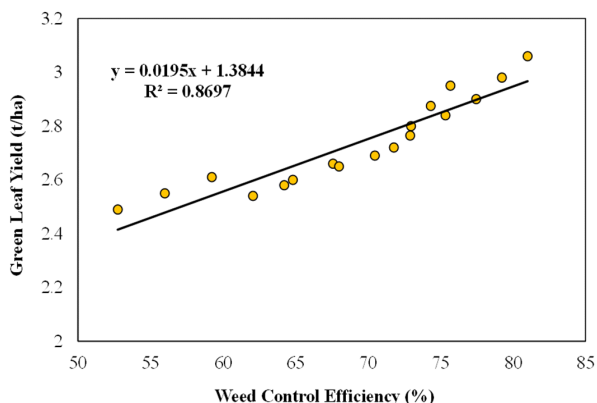


Figure 1. Relationship between weed control efficiency and tea leaf yield

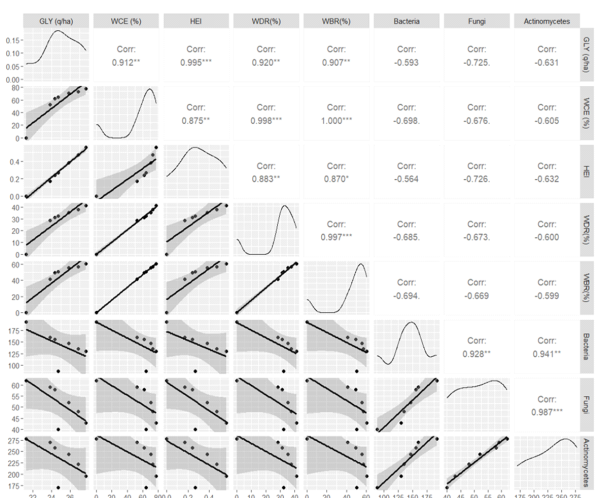


Figure 2. Pearsons correlation between different parameters observed in the study

tea due to application of tested herbicides on 1, 3, 7, 10 and 15 DAA.

Soil micro-organism populations

Different weed management treatments significantly ($p=0.05$) influenced the microbial populations at different tea growing phases. Microbes were least affected when treatment plots were free

from herbicides (*i.e.* weedy check). Bacterial population sharply reduced (from $180.75 \text{ CFU} \times 10^4/\text{g}$ to $45.50 \text{ CFU} \times 10^4/\text{g}$) by 2,4-D Sodium salt 1000 g/ha followed by MCPA 1500 g/ha (from $174.83 \text{ CFU} \times 10^4/\text{g}$ to $53.42 \text{ CFU} \times 10^4/\text{g}$) at 7 DAA from initial but in case of former herbicide due to its high residuality, bacterial population remained low at 45 DAA than others (**Figure 3a**). Fungi and actinomycetes populations follow the same trend as bacterial population irrespective of all dates of observations (**Figure 3b and 3c**). These results are in tune with the findings of Kundu *et al.* (2020). The observed decline in microbial population may be attributed to the continuous application of chemical herbicides, which significantly alters the taxonomic composition of the rhizospheric microbiome by exerting selective pressure that favors opportunistic pathogens over beneficial symbionts (Cusaro *et al.* 2024). These chemical interventions often result in a marked reduction in microbial richness, specifically diminishing overall populations. Moreover, certain herbicides exhibit direct toxicity to soil microorganisms by interfering with the shikimic acid pathway, which suppresses the proliferation of diverse bacterial and fungal taxa (Velmourougane *et al.* 2021).

Nutrient removal by weeds

Uptake of N, P and K by weeds followed the trend of weed biomass. Total uptake of nitrogen, phosphorus and potassium by weeds at 60 DAA recorded significantly lowest (7.05, 0.90, 1.60 kg/ha respectively) with MCPA 1500 g/ha due to effective control of all the categories of weeds (**Figure 4**). Nutrient removal by weeds were continuously increased with decreasing the HEI. Because of no herbicide application, maximum nutrient was removed under weedy check treatment as observed by Chacko *et al.* (2022).

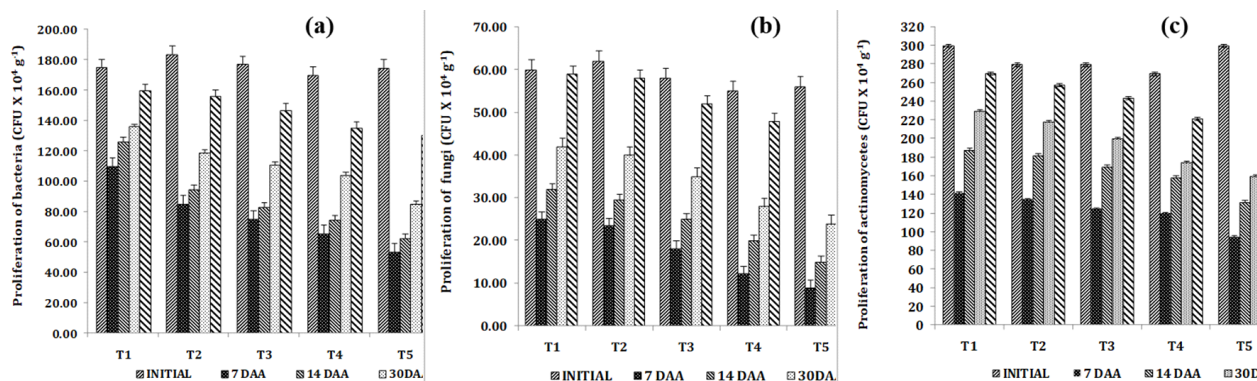


Figure 3. Microbial populations in soil as affected by weed control treatments at Initial, 7 days, 14 days, 30 days and 45 days after herbicide application (DAA): (a) bacterial; (b) fungal; (c) actinomycetal (based on pooled data of two years). Error bars represent LSD ($p=0.05$)

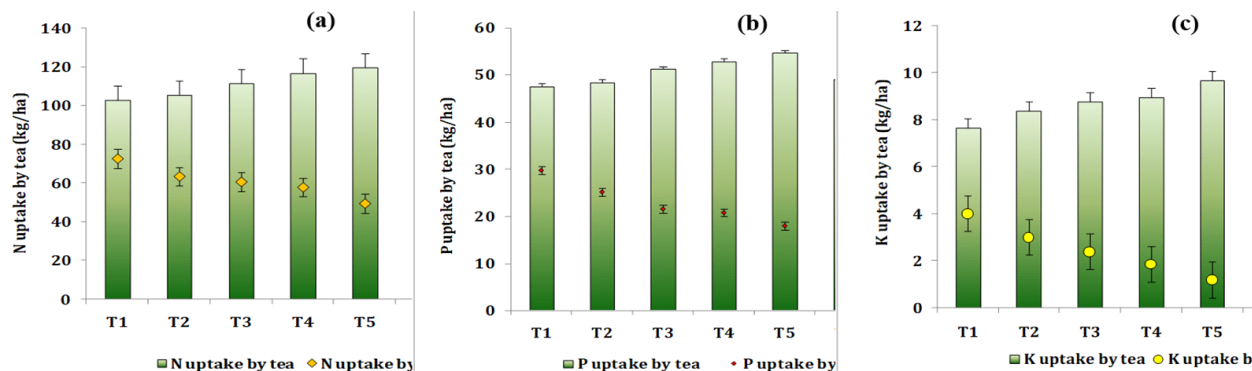


Figure 4. Nutrient uptake (kg/ha) by tea green leaves and weeds: (a) nitrogen; (b) phosphorous; (c) potassium (based on pooled data of two years). Error bars represent LSD ($p=0.05$)

Nutrient uptake by tea

The nutrient uptake by tea was inversely proportional to nutrient uptake by weeds. All weed control treatments significantly superior to weedy check in increasing NPK uptake by tea at 60 DAA (Figure 4). Irrespective of three major nutrients total maximum uptake (119.54 kg/ha, 54.73 kg/ha and 9.67 kg/ha NPK respectively) was noticed with MCPA 1500g/ha which was closely followed by descending doses MCPA (Figure 4a). Raj and Syriac (2017) also reported that maximum uptake of soil available nutrients by the crop was achieved from the higher of dose post-emergent herbicidal application followed by its lower doses.

CONCLUSION

MCPA 1500 g/ha controlled diversified broad-leaved weeds in tea garden during the critical crop-weed interference period that resulted in nearly ~48% yield increment of green tea leaves over control without showing any phytotoxicity symptoms on plants. There was no persistent detrimental effect of the applied herbicides on the rhizospheric microbial population and on soil available nutrients. Furthermore, the same treatment contributed to a noticeable enhancement in nutrient uptake by tea leaves, reaffirming its agronomic safety and effectiveness.

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