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# Efficacy of herbicides on weed control, rhizospheric micro-organisms, soil properties and leaf qualities in tea plantation

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**ABSTRACT**

Field trials were conducted in Tarai region of Jalpaiguri, West Bengal, India (26°88′ N latitude; 88°32′ E longitude, and 122 m above mean sea level) under natural weed infestations in tea garden during 2017 and 2018 to evaluate the efficacy of herbicides on weed flora, non-target soil organisms, leaf quality and productivity of tea (var. *TV-23*). The pattern of nutrient uptake and soil physico-chemicals properties were also itemized. The treatments were comprised of three doses of glufosinate ammonium 13.5% SL (0.27, 0.34, 0.45 kg/ha), glyphosate 41% SL (1.23 kg/ha), paraquat dichloride 24% SL (0.60 kg/ha) and weedy check within a randomized complete block design, replicated four times. The results revealed that glufosinate ammonium at 0.45 kg/ha was the most efficient against grassy and broad-leaf weeds with higher weed control efficiency (> 90%) and total green leaf yield (3.0 t/ha and 2.96 t/ha). Herbicides did not show any phytotoxicity symptoms on the matured tea plants throughout the observation period. An initial detrimental effect on rhizospheric micro-flora (total bacteria, fungi, and actinomycetes) was imposed by residual toxicity of herbicides but at later stage, no harmful effects were observed. Maximum nutrients uptake and soil available nutrients were determined under the higher dose of glufosinate ammonium. Tea leaf quality did not significantly influence by weed management practices. Based on overall performance, the glufosinate ammonium 0.45 kg/ha may be considered as the best substitute for others post-emergent herbicide against the complex weed floras in tea garden.

## INTRODUCTION

India adorned as the second-largest tea producer and consumer in the world by producing more than 1000 million kg of industrial tea from an area of 579.35 thousand hectares (Tea Board of India 2017). The annual turnover of 8 million USD (Bandana *et al.* 2015) from the tea industry not only contributes to the Indian economy but also in employment generation. Amongst the tea producing states, West Bengal acquires second position with the production of 329.7 million kilograms annually, contributes 26% of the national production (Tea Board of India 2017).

Tea, being a perennial crop, remains productive for several decades. So, the long term cultivation of tea in the same location affects the soil quality, specifically the nutrient content is exhausted (Dang 2002). A proficient and integrated agricultural practice including dexterous weed management practices can improve tea production. The competition for nutrients, sunshine, moisture and other resources with weeds reduce tea leaves yield from 12 to 21% (Ilango *et al.* 2010), if weed control practices are not imposed in critical weed infestation period. Weeds meddle with routine operations in the tea garden and act as an anchorage for some insect and disease pest (Wilson 2005). They also impede branching, frame development in young tea and trim down the plucking efficiency (Kumar *et al.* 2017). So, weeding is an important practice for sustainable tea crop production.

Various weed management approaches are advocated for tea plantations. Taking up of preventive measures are advantageous as it minimize the weed seed bank in the soil, which alleviates the present and future population of weed (Banerjee *et al.* 2019). Presently, the involvement of higher cost and manpower crisis at the peak period, mechanical weed control practice becomes unsatisfactory and has been largely replaced by chemical weed control by using herbicides (Biswas *et al.* 2019, Kundu *et al.* 2020a). The mode of action of herbicides performs through the disruption of essential plant physiological processes namely photosynthesis, mitosis and the biosynthesis of pigments and essential amino acids (Kundu *et al*. 2020b). Further, it demands less time, less labour and causing less potential of injuring tea roots and the stem collar (Mirghasemi *et al.* 2012).

Glufosinate ammonium is a broad-spectrum post-emergence herbicide that can be used as a substitute for the glyphosate and others post-emergent non-selective herbicides. It is chemically known as 2-amino-4-hydroxymethyl phosphinoyl butanoic acid having the ability to control annual and perennial weeds non-selectively in both crop and fallow lands when applied as post-emergence (Reddy 2003). To kill the targeted weed species completely, thorough spray coverage of glufosinate is essential, as the permeability of the herbicide through underground rhizomes and stolons is limited (Everman *et al.* 2009). It acts as a glutamine synthetase inhibitor which converts glutamate and ammonia to glutamine (Reddy *et al.* 2011). The inhibition of glutamine synthesis also disrupts the nitrogen assimilation in the plant body, directly and indirectly, slows down the photosynthesis rate by inhibiting the electron flow. The stagnation of ammonia reduces the cell membrane pH which uncouples photo-phosphorylation (Senseman 2007). However, leaf chlorosis within 3-5 DAA (days after application) followed by necrosis within 1-2 weeks is the most common symptom observed in glufosinate treated plot.

Keeping the aforesaid points in view, the present experiment was conducted to optimize the dose of glufosinate ammonium 13.5% SL against the diversified weed flora to enhance the productivity of tea without hampering the tea leaf quality.

## MATERIALS AND METHODS

The field experiment was conducted at Tarai region of Jalpaiguri (26° 88′ N latitude; 88° 32′ E longitude), West Bengal in two consecutive seasons of 2017 (September-December) and 2018 (July-October) in a pre-established tea garden. The soil of the experimental site was loamy in texture having slightly acidic pH (5.37) and rich in available major three nutrients (213.88 kg N, 16.01 kg P and 222.14 kg K/ha). The soil color was blackish grey mainly due to presence of high organic matter and poor in bases. The experimental site was situated in a warm and temperate climate. The temperature reached the maximum (34.5$^0$C) in June and it starts dropping from the middle of October and recorded a minimum (11.8$^0$C) in January. Rainfall started during May and very erratic up to October (average annual rainfall 3000 mm). The relative humidity gradually decreased from July to December, accounting 98% and 75% as maximum and minimum values. The field trial was laid out in a randomized complete block design in a tea (var. *TV-23*) garden consisting of seven treatments including three different doses of glufosinate ammonium (13.5% SL) i.e. 0.27, 0.34 and 0.45 kg/ha along with glyphosate 41% SL 1.2 kg/ha and paraquat dichloride 24% SL 0.6 kg/ha and one weedy check as a control plot with four replications. The herbicides were applied in the month of September and August during two seasons, respectively at the active vegetative growth stage (4-6 leaf) of weeds by using knapsack sprayer with a flood jet nozzle WFN 0.040 in a spray volume of 500 L/ha. Bio-efficacy evaluation was recorded at 40 days after application (DAA) according to the numbers and total dry weight of the major weed flora by placing a quadrate of 0.5 × 0.5 m randomly in each plot.

Reduction in weed number (%), reduction in dry weight (%), and herbicide efficiency index (HEI) were worked out by using the following:

Reduction in weed number (%) =

$$\frac{WD_c - WD_t}{WD_c} \times 100$$

Where $WD_c$ and $WD_t$ indicate the weed density (no./m$^2$) in the control plot and in the treated plot, respectively.

Reduction in weed dry weight (%) =

$$\frac{WDM_c - WDM_t}{WDM_c} \times 100$$

Where $WDM_c$ and $WDM_t$ indicate the weed dry matter weight (g/m$^2$) in the control plot and in the treated plot, respectively.

Herbicide Efficiency Index (HEI) =

$$HEI = \frac{Y_t - Y_c}{Y_t} \times \frac{WDM_c}{WDM_t}$$

Where $Y_t$ is the crop yield from the treated plot; $Y_c$ is the crop yield from the control plot. Weed control efficiency was calculated based on the data recorded 40 DAA as per the formula is given below:

$$WCE = \frac{X - Y}{X} \times 100$$

Where, X indicates the value of the dry weight of weeds in the unweeded plot.

Y indicates the value of the dry weight of weeds in the treated plot.

The soil was collected at initial, 3, 7, 15, 30 and 45 DAA (days after application) with an auger (5 cm diameter) from the mid-points between tea rows in 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. Then the serial dilution technique and agar/pour plate methods were followed by 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 (Das *et al.* 2010; Mondal *et al.* 2018).

Green tea leaf and weed samples from each treatment were collected, oven dried, and ground for analyzing total recoveries of N, P and K at harvest, as per standard methods. At harvest, soil samples were collected from each plot at 0-15 cm depth and analyzed for different physico-chemical properties of post-harvest soil following standard procedures. Bio-chemical properties of tea leaf, namely per cent content of moisture, water extract, alkalinity of water, total ash, water soluble ash, soluble ash, acid insoluble ash and crude fiber in tea leaf were estimated following standard methods given in FSSAI Manual (2015).Total antioxidant activity (% DPPH reduction/mg fresh wt) and total polyphenol content (µg/ml) were determined following the protocols suggested by Armoskaite *et al.* (2011).

The weed density and dry weight were analyzed after subjecting the original data to the square root transformation ($\sqrt{x+0.5}$). The STAR Software version 2.0.1 of International Rice Research Institute, Philippines, 2013 was used for analyzing recorded data on selected parameters. The treatment means were separated using the least significant difference (LSD) at the 5% level of significance.

## RESULTS AND DISCUSSION

### Weed population and biomass

The experimental plots were mostly infested by broad-leaf weeds (BLWs) followed by grassy weeds. Densities and biomass of weeds were significantly (P=0.05) higher in weedy check **(Table 1** and **2)**. In contrast, among tested herbicides, glufosinate ammonium (GA) 13.5% SL 0.45 kg/ha was found to be the most effective against *Borreria articularis*, *Ageratum houstonianum* as well as other BLWs during 2017, while *Commelina benghalensis* was effectively suppressed with the application of glyphosate 41% SL 1.23 kg/ha; being statistically at par with glufosinate ammonium 13.5% SL 0.34 kg/ha **(Table 1)**. The total grassy weed population was significantly (P=0.05) declined where the treatment plot received the highest dose of glufosinate ammonium (0.45 kg/ha) and this treatment was also proved its superiority for suppressing *Panicum repens* at 40 DAA **(Table 1)**. Other grassy weed species, namely *Sporobolus indicus* and *Digitaria setigera* were efficiently controlled by spraying of glufosinate ammonium (0.34 kg/ha); being statistically at par with its highest dose (0.45 kg/ha) during 2017. It was also revealed that among the tested herbicides, the reduction of total grassy and BLWs density over control was lowest (84.2%, and 73.0%, respectively) with the application of glufosinate ammonium 0.27 kg/ha and the extent of reduction was continuously increased with its higher doses, accounting 91% reduction with glufosinate ammonium 0.45 kg/ha over unweeded control plot. More than 80% weed control with chemical herbicide alone or mixture over control was also confirmed by other investigators (Mirghasemi *et al.* 2012). Among the chemical weed management practices, the lower dry biomass of BLWs was accumulated for both the years with post-emergence application of glufosinate ammonium 0.45 kg/ha; being statistically at par with the result observed from glyphosate treated plot **(Table 2)**. Similar types of results were observed for grassy weeds also during both the years of study. Furthermore, weed dry weight was mostly suppressed (~ 93%) by the herbicide glufosinate ammonium with its higher dose **(Table 3)**. These results also confirmed by Banerjee *et al.* (2018) who found maximum effectiveness of glufosinate ammonium 625 g/ha against versatile weed flora in terms of weed density and dry matter accumulation at different time interval.

### Weed control efficiency and herbicide efficiency index

Weed control efficiency (WCE) varied from 74 to 94% and 76 to 97% in grassy and BLWs, respectively during 2017 **(Table 3)**. These results were almost alike for 2018. The application of glufosinate ammonium 0.45 kg/ha showed WCE, accounting 93.6 and 96.6% for BLWs and grassy weeds, respectively in 2017. Experimental plot receiving glyphosate 1.23 kg/ha also exhibited satisfactory WCE in grassy weeds (> 95%) for both of the years **(Table 3)**. The herbicide efficiency index

**Table 1. Effects of different weed control treatments on grassy weed population (no./m²) in tea cultivation at 40 DAA**

| Treatment | *Sporobulus indicus* | | *Digitaria setigera* | | *Panicum repens* | | Others | | Total | | Reduction (%) of TWD over control* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| Glufosinate ammonium (0.27 kg/ha) | 1.74 (1.83) | 1.78 (1.84) | 2.37 (2.05) | 2.42 (2.07) | 1.39 (1.69) | 1.42 (1.70) | 2.25 (2.01) | 2.29 (2.02) | 7.75 (3.29) | 7.91 (3.32) | 73.49 | 73.00 |
| Glufosinate ammonium (0.34 kg/ha) | 0.58 (1.27) | 0.59 (1.28) | 0.52 (1.23) | 0.53 (1.24) | 1.05 (1.53) | 1.07 (1.54) | 1.57 (1.76) | 1.62 (1.78) | 3.72 (2.44) | 3.80 (2.46) | 87.27 | 87.03 |
| Glufosinate ammonium (0.45 kg/ha) | 0.93 (1.48) | 0.95 (1.49) | 0.72 (1.36) | 0.73 (1.37) | 0.70 (1.35) | 0.71 (1.35) | 1.35 (1.67) | 1.38 (1.68) | 3.70 (2.43) | 3.77 (2.45) | 87.34 | 87.13 |
| Glyphosate (1.23 kg/ha) | 1.97 (1.91) | 2.00 (1.92) | 1.54 (1.75) | 1.58 (1.77) | 0.82 (1.41) | 0.83 (1.42) | 0.45 (1.18) | 0.46 (1.19) | 4.78 (2.70) | 4.87 (2.72) | 83.65 | 83.38 |
| Paraquat dichloride (0.6 kg/ha) | 1.05 (1.53) | 1.07 (1.54) | 2.06 (1.95) | 2.10 (1.96) | 4.64 (2.66) | 4.73 (2.69) | 1.23 (1.62) | 1.27 (1.63) | 8.98 (3.51) | 9.17 (3.54) | 69.28 | 68.70 |
| Untreated control | 6.72 (3.10) | 6.86 (3.13) | 10.92 (3.81) | 10.62 (3.77) | 7.42 (3.23) | 7.57 (3.26) | 4.17 (2.55) | 4.25 (2.57) | 29.23 (5.92) | 29.30 (5.92) | 0.00 | 0.00 |
| LSD (p=0.05) | 0.46 | 0.72 | 0.42 | 0.42 | 0.36 | 0.86 | 0.42 | 0.51 | 0.63 | 0.63 | 0.16 | 0.53 |

Original figures in parentheses were subjected to square-root transformation ($\sqrt{x+0.5}$) before statistical analysis; DAA, Days after application; LSD, Least significant difference; *Reduction (%) of total weed density (TWD) over control was calculated based on original (non-transformed) data.

**Table 2. Effects of different weed control treatments on broad leaf weed population (no./m²) in tea cultivation at 40 DAA**

| Treatment | *Borreria articularis* | | *Ageratum houstonianum* | | *Commelina benghalensis* | | Others | | Total | | Reduction (%) of TWD over control* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| Glufosinate ammonium (0.27 kg/ha) | 2.90 (2.21) | 2.77 (2.18) | 1.96 (1.91) | 1.87 (1.88) | 2.44 (2.07) | 2.32 (2.03) | 3.94 (2.49) | 3.77 (2.45) | 11.23 (3.86) | 10.73 (3.79) | 74.19 | 84.25 |
| Glufosinate ammonium (0.34 kg/ha) | 1.05 (1.53) | 0.56 (1.26) | 0.83 (1.42) | 1.68 (1.80) | 1.50 (1.74) | 2.21 (2.00) | 1.23 (1.62) | 3.34 (2.34) | 4.61 (2.66) | 6.71 (3.10) | 89.40 | 90.15 |
| Glufosinate ammonium (0.45 kg/ha) | 0.58 (1.27) | 0.56 (1.26) | 0.62 (1.30) | 0.59 (1.28) | 2.32 (2.03) | 0.77 (1.39) | 1.02 (1.52) | 3.12 (2.28) | 4.54 (2.64) | 6.13 (2.99) | 89.57 | 91.00 |
| Glyphosate (1.23 kg/ha) | 0.58 (1.27) | 0.58 (1.27) | 1.75 (1.83) | 0.63 (1.30) | 0.82 (1.41) | 2.24 (2.01) | 1.46 (1.72) | 3.37 (2.35) | 4.61 (2.66) | 6.83 (3.12) | 89.40 | 89.97 |
| Paraquat dichloride (0.6 kg/ha) | 4.75 (2.69) | 4.53 (2.64) | 3.40 (2.35) | 3.25 (2.31) | 3.48 (2.38) | 3.32 (2.33) | 2.59 (2.12) | 11.18 (3.85) | 14.23 (4.28) | 22.29 (5.23) | 67.29 | 67.28 |
| Untreated control | 9.62 (3.61) | 9.19 (3.54) | 18.14 (4.77) | 17.32 (4.67) | 7.31 (3.21) | 6.98 (3.15) | 8.45 (3.42) | 34.64 (6.40) | 43.51 (7.11) | 68.12 (8.76) | 0.00 | 0.00 |
| LSD (p=0.05) | 0.52 | 0.67 | 0.43 | 0.82 | 0.48 | 0.65 | 0.61 | 0.78 | 0.93 | 1.5 | 0.27 | 0.86 |

Original figures in parentheses were subjected to square-root transformation ($\sqrt{x+0.5}$) before statistical analysis; DAA, Days after application; LSD, Least significant difference; * Reduction (%) of total weed density (TWD) over control was calculated based on original (non-transformed) data.

(HEI) indicates the weed-killing potential of herbicidal treatment and its phytotoxicity on the crop (Mishra *et al.* 2016). In this study, each year glufosinate ammonium with its highest dose proved its superiority over other herbicides each year. In contrast, paraquat dichloride 0.60 kg/ha exhibited least weed killing potential, as seen in HEI values for 2017 and 2018 **(Table 3)**.

## Green leaf yield

The data on green leaf yield **(Table 4)** revealed that all the treatments recorded significantly (P=0.05) higher green leaf yield over weedy check. Among the different herbicidal applications, the plot treated with glufosinate ammonium 0.45 kg/ha yielded maximum green leaf during August to October, which had ultimately been reflected in total yield of green tea leaf production (3 t/ha) in 2017. During 2018, the maximum yield (2.96 t/ha) was obtained with glufosinate ammonium 0.45 kg/ha while the untreated weedy check resulted in poor yield (2.48 t/ha). Kumar et al. (2017) established that the maximum green leaf yield of tea (1.17 t/ha) was obtained from the treatment received the higher dose of post-emergence herbicides followed by lower doses. The efficiency of glufosinate ammonium with its utmost

**Table 3. Effects of different weed control treatments on the total dry weight of weeds, weed biomass reduction, WCE and HEI in tea cultivation at 40 DAA**

| Treatment | Total weed dry weight ($g/m^2$) | | | | Reduction of TWB (%) over control | | | | WCE (%) | | | | HEI | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BLW | | Grassy weeds | | BLW | | Grassy weeds | | BLW | | Grassy weeds | | 2017 | 2018 |
| | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 | | |
| Glufosinate ammonium (0.27 kg/ha) | 6.36 | 5.78 | 3.59 | 2.89 | 82.67 | 81.64 | 83.33 | 85.64 | 81.70 | 83.69 | 83.20 | 85.64 | 0.60 | 0.50 |
| Glufosinate ammonium (0.34 kg/ha) | 2.87 | 2.60 | 1.54 | 2.45 | 92.18 | 91.74 | 92.85 | 87.83 | 91.74 | 91.84 | 92.80 | 87.83 | 2.38 | 1.88 |
| Glufosinate ammonium (0.45 kg/ha) | 2.43 | 1.97 | 0.72 | 0.68 | 93.38 | 93.74 | 96.66 | 96.62 | 93.51 | 93.59 | 96.63 | 96.62 | 3.70 | 2.96 |
| Glyphosate (1.23 kg/ha) | 2.66 | 2.32 | 0.92 | 0.70 | 92.75 | 92.63 | 95.73 | 96.52 | 93.21 | 93.45 | 95.70 | 96.52 | 2.75 | 1.48 |
| Paraquat dichloride (0.6 kg/ha) | 9.43 | 10.57 | 5.23 | 4.89 | 74.31 | 66.43 | 75.71 | 75.71 | 72.87 | 73.69 | 75.53 | 75.71 | 0.14 | 0.11 |
| Untreated control | 36.70 | 31.49 | 21.53 | 20.13 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| LSD (p=0.05) | 1.82 | 2.53 | 0.97 | 1.14 | 0.67 | 0.35 | 0.87 | 0.51 | - | - | - | - | - | - |

WCE, Weed control efficiency; HEI, Herbicide efficiency index; BLW, Broad leaf weed; TWB, Total weed biomass

**Table 4. Effects of different weed control treatments on green tea leaf yield and post-harvest soil nutrient status in tea cultivation**

| Treatment | Tea leaf yield (t/ha) | | | | | | | | Available N (kg/ha) | | Available P (kg/ha) | | Available K (kg/ha) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2017 | | | | 2018 | | | | | | | | | |
| | Aug. | Sept. | Oct. | Total | Sept. | Oct. | Nov. | Total | 2017 | 2018 | 2017 | 2018 | 2017 | 2018 |
| Glufosinate ammonium (0.27 kg/ha) | 0.94 | 0.97 | 0.76 | 2.67 | 1.00 | 0.97 | 0.75 | 2.72 | 245.3 | 218.7 | 19.3 | 19.0 | 253.7 | 254.3 |
| Glufosinate ammonium (0.34 kg/ha) | 1.09 | 1.00 | 0.84 | 2.93 | 1.08 | 0.99 | 0.83 | 2.90 | 249.6 | 228.5 | 20.4 | 20.9 | 263.8 | 261.3 |
| Glufosinate ammonium (0.45 kg/ha) | 1.11 | 1.01 | 0.88 | 3.00 | 1.09 | 1.00 | 0.87 | 2.96 | 252.1 | 234.8 | 22.0 | 22.5 | 266.6 | 265.5 |
| Glyphosate (1.23 kg/ha) | 1.20 | 0.97 | 0.72 | 2.89 | 1.08 | 0.96 | 0.70 | 2.73 | 250.5 | 228.4 | 22.8 | 21.6 | 259.1 | 263.0 |
| Paraquat dichloride (0.6 kg/ha) | 0.98 | 0.83 | 0.68 | 2.49 | 0.96 | 0.91 | 0.68 | 2.56 | 247.6 | 220.8 | 21.2 | 20.2 | 256.8 | 257.1 |
| Untreated control | 0.99 | 0.75 | 0.67 | 2.40 | 0.97 | 0.86 | 0.66 | 2.49 | 207.6 | 203.5 | 17.2 | 19.0 | 225.1 | 234.3 |
| LSD (p=0.05) | 0.06 | 0.06 | 0.07 | 0.08 | 0.08 | 0.07 | 0.06 | 0.07 | 6.34 | 6.3 | 3.45 | 3.7 | 6.34 | 6.8 |

dose to control the broad spectrum weed flora also reported by Banerjee *et al.* (2018). They revealed that maximum dose of glufosinate ammonium yielded 3.60 t/ha tea green leaf. These results were in tune with the findings of Ghosh *et al.* (2005) and Patra *et al.* (2016).

A strong correlation ($R^2$= 0.92 and 0.88 in 2017 and 2018, respectively) was found between herbicide efficiency index and tea leaf yield **(Figure 1)**. These results highlighted the poor competitive ability of crops with weeds and the need to control them effectively by suitable herbicides having good killing potential during whole growing season. Chauhan and Opena (2013) also found similar correlation between yields and weed biomass at harvest.

### Effect on soil micro-organism

Different weed management treatments significantly (p=0.05) influence the microbial populations at different tea growing phases. All the herbicidal treatments showed an initial depression in the colony count having concomitant effect on growth of soil micro flora (total bacteria, fungi, and actinomycetes). Microbes were least affected where the plots remained free from herbicides (*i.e.* weedy check). The bacterial population sharply declined from 39.43 (initial) to 21.90 CFU × $10^4$/g of soil (at 7 DAA) by the residual effect of glufosinate ammonium 0.45 kg/ha after the ending of second seasons, closely followed by glyphosate 1.23 kg/ha **(Figure 2a)**. Thereafter, the bacterial population increased continuously until 60 DAA because of the rapid degradation of herbicides by soil microorganisms. However, the fungi population was counted lower at 7 DAA with the treatment glyphosate 1.23 kg/ha **(Figure 2b)**. Total actinomycetes populations at the end of growing season exhibited the similar trends to that of bacterial populations **(Figure 2c)**. These results were in tune with the findings of Das *et al.* (2010) who reported that the optimum dose of herbicides generally have no longer phototoxic effects on the total rhizospheric bacterial population in the soil. This might be due to the fact that microorganisms have the potentiality to degrade the herbicide molecule and utilize them as a source of biogenic elements that helps their physiological processes (Bera and Ghosh 2013). However, before degradation, the toxicity of herbicides on

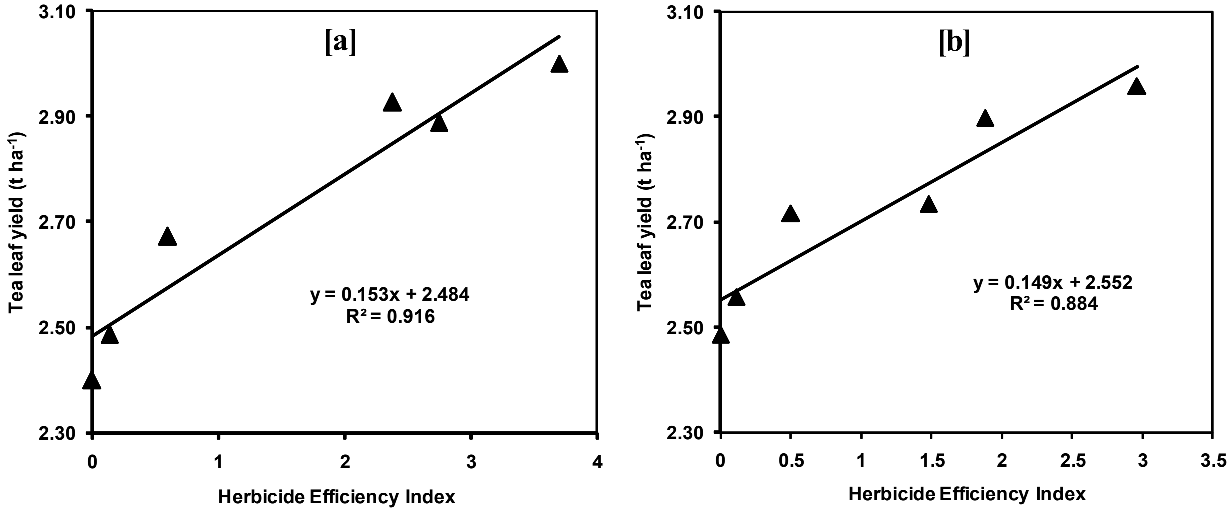


**Figure 1. Relationship between herbicide efficiency index (HEI) and tea leaf yield during 2017 [a] and 2018 [b]**

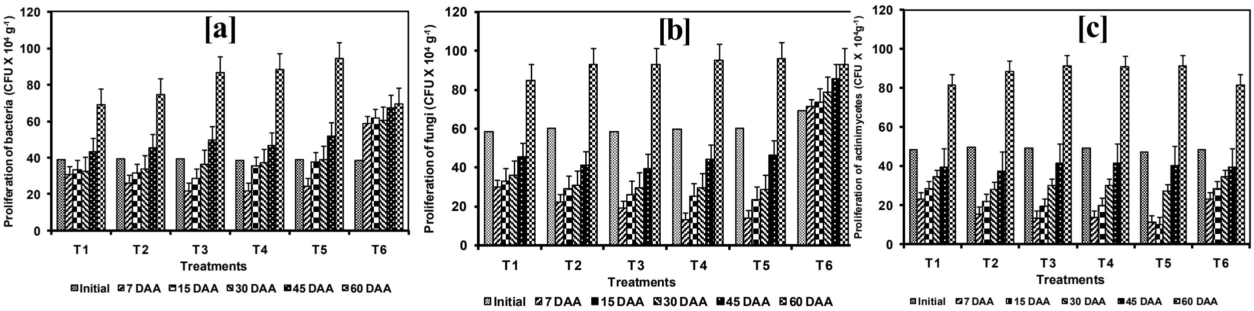


**Figure 2. Microbial populations in soil as affected by weed control treatments at different time intervals during 2018 [a=bacteria, b=fungi, c=actinomycetes]; DAA, days after application.** Error bars represent LSD (p=0.05).

microorganisms might be reflected by reducing their abundance and activity. Later on, degraded organic herbicides provide carbon-rich substrates which in turn maximize the microbial population in the rhizosphere (Jarvan *et al.* 2014) and influence the transformations and availability of plant nutrients in the soil (Das and Debnath 2006).

### Nutrient removal by weeds

Uptake of N, P and K by weeds was positively correlated with weed biomass **(Figure 3a and 3b)**. Total uptake of N, P and K was significantly lowest at 60 DAA with the application of glufosinate ammonium 0.45 kg/ha due to effective control of all the categories of weeds in 2017 **(Figure 3)**. In 2018, the same treatment caused lower nutrient removal; being statistically at par with the application of glyphosate 41% SL. Nutrient removal by weeds increased continuously with decreasing herbicide efficiency index. Because of no herbicide application, the maximum nutrient was removed under weedy check treatment. The findings of Dayaram (2013) were similar with these results. Raj and Syriac (2017) also observed that minimum removal of soil available nutrients by weeds was recorded from the higher dose post-emergent herbicidal application followed by its lower doses. Similarly, an increase in nutrient uptake by increasing the weed population was also reported by Babar and Velayudham (2012).

### Nutrient uptake by tea

The nutrient uptake by tea plants was inversely proportional to nutrient uptake by weeds **(Figure 3)**. All weed control treatments were significantly (p=0.05) superior to weedy check in increasing NPK uptake by tea at 60 DAA. Total nutrient uptake was significantly improved with the highest dose of glufosinate ammonium closely followed by its subsequent lower dose in 2018 **(Figure 3a)**. Better control of weeds resulted from herbicide application minimized the crop-weed competition and enhanced nutrient availability as well as uptake **(Figure 3b)**. Nutrient uptake by crop is also a function of nutrient content in the dry matter production. This results were in agreement with the findings of Nath *et al.* (2014).

### Soil physico-chemical properties

Results depicted that the application of tested herbicides had no significant influence on different

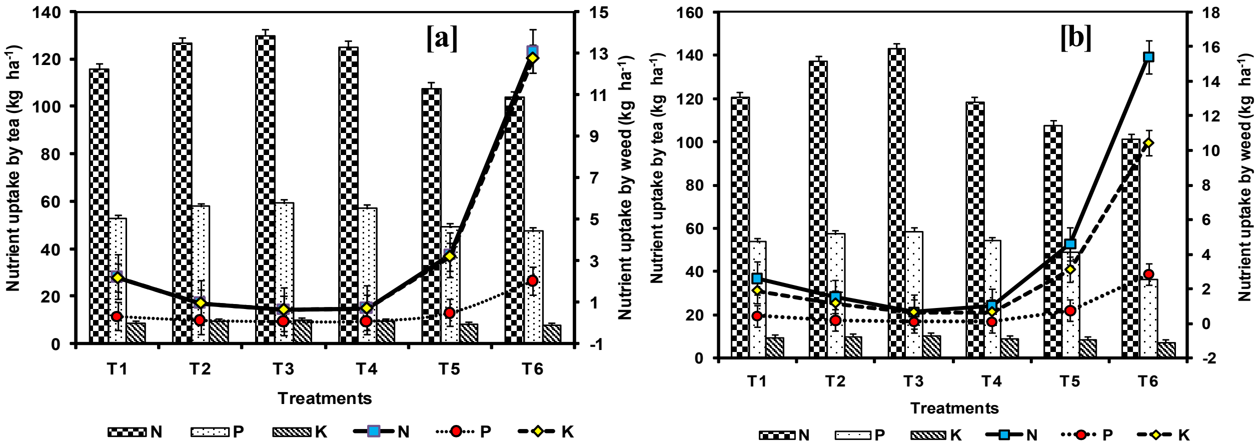


**Figure 3. Nutrient uptake (kg/ha) by tea (column) and weed (line) during 2017 [a] and 2018 [b].**

Error bars represent LSD (p=0.05).

**Table 5. Effects of different weed control treatments on green tea leaf quality at harvest (mean data of 2 years)**

| Treatment | Moisture (%) | Water extract (%) | Total Ash (%) | WSA (%) | AWSA (%) | AIA (%) | CF (%) | AOA (%) | TPC (µg/ml) |
|---|---|---|---|---|---|---|---|---|---|
| Glufosinate ammonium (0.27 kg/ha) | 7.25 | 34.25 | 5.94 | 60.92 | 2.19 | 0.20 | 4.96 | 51.02 | 0.010 |
| Glufosinate ammonium (0.34 kg/ha) | 7.55 | 34.32 | 6.08 | 61.28 | 1.84 | 0.14 | 5.14 | 49.61 | 0.020 |
| Glufosinate ammonium (0.45 kg/ha) | 7.43 | 34.24 | 5.97 | 61.62 | 2.23 | 0.17 | 5.01 | 50.00 | 0.017 |
| Glyphosate (1.23 kg/ha) | 7.21 | 34.10 | 6.14 | 61.57 | 1.98 | 0.18 | 4.87 | 49.52 | 0.042 |
| Paraquat dichloride (0.6 kg/ha) | 7.15 | 33.94 | 6.21 | 60.84 | 2.13 | 0.12 | 5.11 | 50.21 | 0.024 |
| Untreated control | 7.57 | 34.28 | 6.32 | 61.37 | 2.08 | 0.18 | 5.08 | 51.32 | 0.031 |
| LSD (p=0.05) | NS | NS | NS | NS | NS | NS | NS | NS | NS |

WSA, Water soluble ash; AWSA, Alkalinity of Water Soluble Ash; AIA, Acid insoluble ash; CF, Crude Fibre; AOA, Antioxidant Activity; TPC, Total Polyphenol Content; NS, Non-significant

physico-chemical properties *viz.* soil pH, electrical conductivity (EC), bulk density (BD) and water holding capacity (WHC) in both the years of study.

The critical appraisal of N, P and K availability at harvest stage revealed that two doses of glufosinate ammonium *viz.* 0.45 kg/ha and 0.34 kg/ha and the application of glyphosate 1.23 kg/ha were more effective in maintaining a high level of available N, P and K content in the soil during both the years **(Table 4)**. The maximum removal of all three major nutrients was observed in the weedy check situation. This might be due to severe competition exerted by the rapid growth of weed population throughout the experimental periods having a competitive advantage in absorbing more soil available nutrients over the crop. Improvement of soil nutrient availability due to the control of weeds was also reported earlier by Dayaram (2013).

## Quality assessment of tea leaf

The cultivation of tea from the Darjeeling region is globally well known for its fine quality and flavour. The results obtained from the present study revealed that the tested herbicides had no significant influence to alter the tea leaf quality **(Table 5)**. However, the moisture content of tea leaf which is related to its storage and stability was ranged from 7.15 to 7.57 and the values of water extract per cent were greater than 32% irrespective of all treatments (**Table 5**), which met the all standard values of ISO 3702 (2011). The other values namely, total ash per cent, water-soluble ash and its alkalinity, acid insoluble ash and crude fibre per cent, and total polyphenol content also met the all standard values of ISO 3702 (2011). The phenolic compounds that are present in tea leaves are known to be one of the main factors in determining the drinking quality (Yao *et al.* 2005).

## Conclusion

The present experiment discerns the effectiveness of herbicides on various weed floras in the tea garden, their residual effects on non-target organisms and soil properties. It can be concluded that herbicide glufosinate ammonium 13.5% SL 0.45 kg/ha had the highest potential to control diversified weed flora in tea garden within a critical crop-weed infestation period that resulted in about 19% yield increment of green tea leaves over control without showing any phytotoxicity on plants. There was no long-term adverse effect of the applied herbicides on the microbial population in soil rhizosphere and on soil available nutrients. Additionally, the improvement of nutrient uptake by tea leaves was also observed with the same treatment. The results of this study also concluded that the bio-chemical quality parameters of the tea were within the safe limit and can be used for both domestic consumption and commercial intension.

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