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Investigation of Different Tea spent Waste Variants (Green Tea, Tea Dust, and Tea Granules) on the Growth and Biomass Production of Fenugreek (*Trigonella foenum-graecum)* for Sustainable Agriculture

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Abstract

Tea waste, an abundant agro-industrial byproduct, has garnered attention as a potential organic soil amendment due to its rich bioactive compounds and nutrient content. The rising global demand for sustainable agricultural practices has intensified interest in the valorization of agro-industrial waste. This study investigates the potential of post-consumer tea-spent residues—Green Tea (GT), Tea Granules (TG), and Tea Dust (TD), along with their sugar and milk-based variants (GTS, TGS, TDS, TGMS, TDMS) as nutrient-rich soil amendments and plant growth enhancers. Comprehensive proximate and mineral analyses were conducted, followed by soil quality assessment and plant growth trials using *Trigonella foenum-graecum* (fenugreek). Soil treated with GT and TG variants exhibited improved physicochemical properties, including increased moisture retention, higher water-holding capacity, and enhanced porosity. Plant growth assessments revealed significantly enhanced germination rates, chlorophyll-a content, and carotenoids in GT and TG-amended soils, compared to controls and raw TD treatments. These findings underscore the dual benefits of tea-spent residues as nutrient sources and plant growth promoters. The study highlights a sustainable pathway for agro-waste valorization, supporting circular bioeconomy models and eco-friendly farming. Further research is recommended to optimise application rates and investigate long-term effects on plant health and soil microbiota.

Keywords: Tea Waste, Fenugreek (*Trigonella foenum-graecum*), Plant Growth, Organic Amendment, Sustainable Agriculture

1. Introduction

Sustainable agricultural practices are essential to meet the growing global demand for food while minimizing environmental degradation. Organic amendments derived from agrarian waste have emerged as a promising solution to enhance soil fertility, improve crop productivity, and reduce reliance on synthetic fertilizers [1]. One such agro-industrial byproduct is tea waste, which is produced in large quantities worldwide. The tea industry generates significant amounts of waste in the form of spent tea leaves, tea dust, and tea granules, often discarded as landfill waste or used for composting [2]. However, the potential of tea waste as a natural plant growth promoter remains underexplored. Tea waste is rich in bioactive compounds, including polyphenols, flavonoids, tannins, and caffeine, as well as essential macronutrients such as nitrogen (N), phosphorus (P), and potassium (K)[3]. These compounds have been reported to influence plant growth and soil microbial activity. While some studies suggest that tea waste may improve soil organic matter and enhance plant growth, others indicate that excessive amounts may have inhibitory effects due to high tannin and caffeine content [4][5]. Therefore, understanding the specific effects of different types of tea waste on plant growth is crucial for developing sustainable agricultural applications.

Tea waste is categorized into different types based on its processing and particle size. Green tea waste is generally richer in antioxidants and bioactive compounds, whereas tea dust and granules contain higher concentrations of tannins and caffeine[6]. The variations in chemical composition suggest that different types of tea waste may exert distinct influences on plant physiology, growth patterns, and biomass accumulation. Research on organic soil amendments, particularly tea waste, has primarily focused on their role in improving soil health, microbial activity, and nutrient availability [7]. However, limited studies have examined the direct impact of different types of tea waste on crop growth, particularly in leguminous plants like fenugreek.

Fenugreek (*Trigonella foenum-graecum*) is a widely cultivated legume known for its medicinal, nutritional, and soil-enhancing properties. As a nitrogen-fixing crop, it plays a significant role in soil fertility management and sustainable farming systems. Hence by knowing its adaptability and economic value, fenugreek serves as an ideal model plant to evaluate the effects of tea waste amendments. This study examines the impact of three different types of tea waste such as green tea, tea dust, and tea granules on the germination rate, growth and biomass production of fenugreek.

Several studies have reported the benefits of organic waste amendments on crop performance. For instance, composted agricultural residues have been shown to improve soil structure, enhance microbial diversity, and increase crop yields [8]. Similarly, biochar and other organic amendments derived from food processing waste have demonstrated their potential as plant growth stimulators [9]. However, the specific role of tea waste in promoting or inhibiting plant growth remains a subject of debate. Some research indicates that moderate application of tea waste can enhance seed germination, root elongation, and biomass production, while excessive use may lead to growth suppression due to phytotoxic compounds[10].

Despite these findings, few studies have systematically investigated the comparative effects of different types of tea waste on plant growth. Most research has focused on tea waste composting or its impact on soil microbial activity rather than its direct effect on crop performance. Additionally, the underlying mechanisms through which tea waste influences plant growth whether through nutrient enrichment, hormonal modulation, or allelopathic interactions are not well understood. This research aims to fill this gap by providing a comprehensive evaluation of the impact of tea waste on fenugreek growth.

The primary objective of this study is to assess the influence of different types of tea waste such as green tea, tea dust, and tea granules on the growth and biomass accumulation of fenugreek (*Trigonella foenum-graecum*). Specifically, the study aims to evaluate the effects of tea waste amendments on seed germination, shoot growth, and root development. Analyze the influence of different tea waste types on biomass production and chlorophyll content. Determine the optimal application levels of tea waste to maximize plant growth while minimizing plant growth while minimizing any potential phytotoxic effects and provide insights into the possible use of tea waste as a sustainable organic amendment in agriculture.

Drawing on prior research and the established composition of tea waste, we hypothesise that moderate application of green tea waste will enhance fenugreek growth by increasing nutrient availability and stimulating physiological responses. In contrast, excessive application of tea dust, owing to its high tannin and caffeine content, may inhibit plant growth. Tea granules, with their intermediate composition, are anticipated to exhibit a variable response depending on concentration and method of application.

The findings from this study will contribute to the growing body of knowledge on sustainable agricultural practices by evaluating an innovative use of tea waste as an organic amendment. If tea waste proves to be a viable growth enhancer for fenugreek, it could be integrated into organic farming systems, reducing agricultural waste and promoting circular economy approaches. Furthermore, the study will provide guidelines on optimal application levels to balance the benefits and potential risks associated with tea waste amendments. With the increasing emphasis on sustainable agriculture and waste valorization, exploring the potential of agro-industrial byproducts like tea waste is crucial. This study aims to systematically assess the effects of different tea waste types on fenugreek growth, providing valuable insights for researchers, farmers, and policymakers. The results will help determine whether tea waste could be effectively utilized as a natural biofertilizer, contributing to more sustainable and eco-friendly agricultural practices.

2. Materials and Methods

2.1 Chemicals

Tea granules and Tea dust of Prakash Brand are procured from Prakash Tea agency, Bangalore. Green tea was procured from Attri Pure Green Tea, Kengeri, Bangalore. All the chemicals used in this experiment are analytical grade chemicals, which are procured from Himedia Laboratories, Bangalore.

2.2 Sample Preparation and Tea Processing

The green tea powder, tea granules, and tea dust were mixed with water in a 1:10 ratio and boiled for 15 min. The decoction samples were evaluated every 5 min, immediately cooled and stored at 4°C until further bioactive content profiling and antioxidant activities were performed [11]. Similarly, the same experiment was conducted with green tea powder, sugar, and water in a ratio of 10g green tea, tea granules, tea dust:25g Sugar:500ml water and boiled for 15 min. Similarly, the same experiment was conducted with tea granules and tea dust powder, sugar, milk, and water in a ratio of 10g tea granules, tea dust:25g Sugar:250ml water:250ml milk and boiled for 15 min. Above all processed tea residues were collected, dried and the nutritional and nutraceutical potentials of the residues were analysed [11].

2.3 Experimental Design

The experiment was designed with nine treatment groups: Control, Green Tea (GT), Tea Granules (TG), and Tea dust (TD), Green Tea + Sugar (GTS), Tea Granules + Sugar (TGS), Tea Dust +sugar (TDS), Tea Granules + Milk +Sugar (TGMS), Tea Dust + milk + Sugar (TDMS). Each treatment, except the control, was further evaluated at three concentration levels (5%,10%, and 15%). The study was conducted using a seedling tray setup, as illustrated in Figure 1.

Each well contained 24 g of soil, which was mixed with cocopeat, compost, and the respective organic waste amendments as specified in Table 1. Each treatment was replicated five times, with 10 seeds sown per replicate. Environmental parameters, including temperature and humidity, were monitored throughout the experiment. Before to seed sowing, a composite soil mixture was analyzed to assess its initial physicochemical properties. Plant growth parameters, including shoot length, root length, and leaf number were measured for three representative biological replicates per treatment group. Overall, the experiment was conducted for 15 days.

Table 1. Experimental design of the tea waste percentage and other soil components

Group Name	Tea Waste (%)	Coco peat (g)	Compost (g)	GT (g)	TG (g)	TD (g)	GTS (g)	TGS (g)	TDS (g)	TGMS (g)	TDMS (g)
Control	0	12	12	0	0	0	0	0	0	0	0
GT	5	12	10.8	1.2	0	0	0	0	0	0	0
	10	12	9.6	2.4	0	0	0	0	0	0	0
	15	12	8.4	3.6	0	0	0	0	0	0	0
TG	5	12	10.8	0	1.2	0	0	0	0	0	0
	10	12	9.6	0	2.4	0	0	0	0	0	0
	15	12	8.4	0	3.6	0	0	0	0	0	0
TD	5	12	10.8	0	0	1.2	0	0	0	0	0
	10	12	9.6	0	0	2.4	0	0	0	0	0
	15	12	8.4	0	0	3.6	0	0	0	0	0
GTS	5	12	10.8	0	0	0	1.2	0	0	0	0
	10	12	9.6	0	0	0	2.4	0	0	0	0

	15	12	8.4	0	0	0	3.6	0	0	0	0
TGS	5	12	10.8	0	0	0	0	1.2	0	0	0
	10	12	9.6	0	0	0	0	2.4	0	0	0
	15	12	8.4	0	0	0	0	3.6	0	0	0
TDS	5	12	10.8	0	0	0	0	0	1.2	0	0
	10	12	9.6	0	0	0	0	0	2.4	0	0
	15	12	8.4	0	0	0	0	0	3.6	0	0
TGMS	5	12	10.8	0	0	0	0	0	0	1.2	0
	10	12	9.6	0	0	0	0	0	0	2.4	0
	15	12	8.4	0	0	0	0	0	0	3.6	0
TDMS	5	12	10.8	0	0	0	0	0	0	0	1.2
	10	12	9.6	0	0	0	0	0	0	0	2.4
	15	12	8.4	0	0	0	0	0	0	0	3.6

Green Tea (GT), Tea Granules (TG), Tea dust (TD), Green Tea + Sugar (GTS), Tea Granules + Sugar (TGS), Tea Dust +sugar (TDS), Tea Granules + Milk +Sugar (TGMS), Tea Dust + milk + Sugar (TDMS).

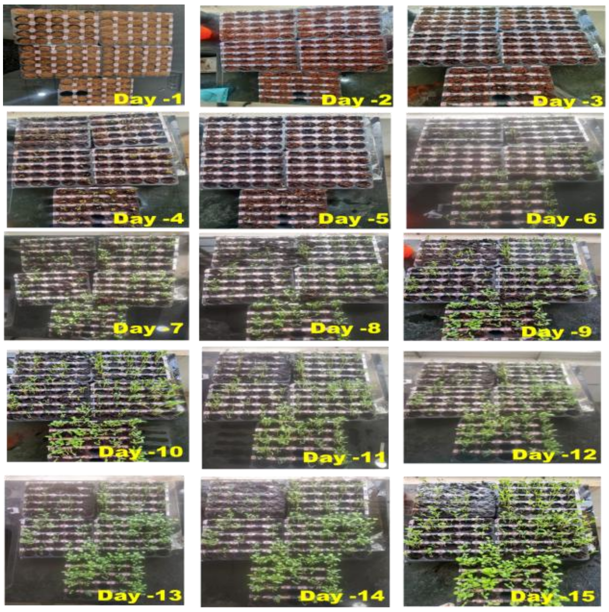


Figure 1. Effect of various tea waste on the growth performance of fenugreek germination and seeding growth.

2.4 Soil Analysis

2.4.1 Moisture Content

Soil moisture content was determined by weighing 10 g of soil, drying it in a hot air oven, and recording the weight at regular intervals until a constant weight was achieved. The moisture content was calculated as:

$$\text{Moisture Content (\%)} = \frac{(\text{Initial Weight} - \text{Final Weight})}{\text{Weight of Sample}} \text{ X } 100$$

2.4.2 Soil Density

Bulk density was measured by transferring a known mass of soil into a graduated cylinder and determining its volume. The density was calculated using the following formula:

$$\text{Density } \left(\frac{\text{g}}{\text{mL}}\right) = \frac{\text{Mass}}{\text{Volume}}$$

2.4.3 Water Holding Capacity

To determine the water holding capacity, 3 g of soil was placed on filter paper within a measuring cylinder. A total of 50 mL of water was added, and the volume retained was recorded using:

$$\text{Water Holding Capacity } = \frac{\text{Volume of Water retained (mL)}}{\text{Volume of water added (mL)}}$$

$$\text{Volume of the water retained (mL)} = \text{Volume of the water added(mL)} - \text{Volume of the water passed (mL)}$$

2.4.4 Porosity

Soil porosity was assessed by saturating a known volume of soil with deionized water and measuring the volume required for saturation. Porosity was calculated as:

$$\text{Porosity (\%)} = \frac{\text{Volume of the water added(void volume)}}{\text{Total volume of the soil}} \text{ X } 100$$

2.5 Germination Analysis

Fenugreek (*Trigonella foenum-graecum*) seeds (procured from Sri Karan Narendra Agriculture University, Jobner, Jaipur, India) were used to evaluate the effects of organic amendments on germination and early growth. Seeds were surface sterilized using 0.1% sodium hypochlorite for 2 minutes, followed by thorough rinsing with distilled water. The sterilized seeds were sown in soil mixtures containing different concentrations (3%, 5%, 8%, and 10%) of tea and brewery waste. Uniform environmental conditions were maintained throughout the experiment.

The germination percentage was recorded daily for 10 days, with germination defined as radicle emergence (≥2 mm). The final germination percentage (FGP) was calculated as:

$$\text{Final Germination percentage (FGP) (\%)} = \frac{\text{Number of Germinated seeds}}{\text{Total Number of seeds sown}} \text{ X } 100$$

Seedling growth parameters, including shoot length, root length, and leaf count were measured. Shoot and root lengths were recorded using a digital Vernier calliper. Root morphology was categorized into primary and secondary roots to evaluate developmental patterns influenced by the amendments. Measurements were performed on 25 randomly selected seedlings per treatment, and statistical analyses were conducted to determine the impact of the amendments on plant growth.

2.6 Chlorophyll and Carotenoid Analysis

Chlorophyll and carotenoid contents were quantified to assess the physiological response of fenugreek plants to organic amendments. Fresh leaf samples (20 mg) were collected, washed with distilled water, and subjected to pigment extraction.

2.7 Pigment Extraction

Pigment extraction was conducted following a modified Lichtenthaler (1987)protocol. Fresh leaves were homogenized in 10 mL of 80% acetone using a sonicator at 25% efficiency for 3 min under dark and cold conditions to minimize pigment degradation. The extract was stirred at 800 rpm for 2 min and centrifuged at 6000 rpm for 6 min at 4°C [12]. The supernatant containing chlorophyll and carotenoids was collected for spectrophotometric analysis. The absorbance of the samples was recorded at 470 nm, 652 nm, and 665 nm using a UV-Vis spectrophotometer (Shimadzu UV-1800, Japan). Pigment concentrations were calculated using Lichtenthaler's equations:

$$\text{Chlorophyll} - \text{a}\left(\frac{\mu\text{g}}{\text{mL}}\right) = (16.72 \times A665) - (9.16 \times A652)$$

$$\text{Chlorophyll} - \text{b}\left(\frac{\mu\text{g}}{\text{mL}}\right) = (34.09 \times A652) - (15.28 \times A665)$$

$$\text{Total Carotenoids}\left(\frac{\mu\text{g}}{\text{mL}}\right) = \frac{(1000 \times A470 - 1.63 \times \text{Chl} - \text{a} - 104.96 \times \text{Chl} - \text{b})}{221}$$

2.8 Statistical Analysis

All the values presented are mean ± S.D. of five replicates (n=5).

3. Results and Discussions

India is one of the leading tea producers globally, and this large-scale production generates of substantial quantities of tea spent waste. This study aimed to evaluate the potential of different types of tea waste such as green tea, tea dust, and tea granules as well as tea spent derived from various stages of tea processing (after adding the sugar and after adding the sugar and milk), as organic amendments to enhance the growth and biomass production of *Trigonella foenum-graecum*(fenugreek).

The experiment was carried out under monitored pot conditions. Environmental parameters, including ambient temperature and relative humidity, were monitored throughout the study period and are presented in Figure 2. The recorded temperature ranged between 28°C and 32°C, while the relative humidity varied from 60% to 48%. No significant fluctuations in either temperature or humidity were observed during the experimental duration, ensuring consistent environmental conditions for plant growth.

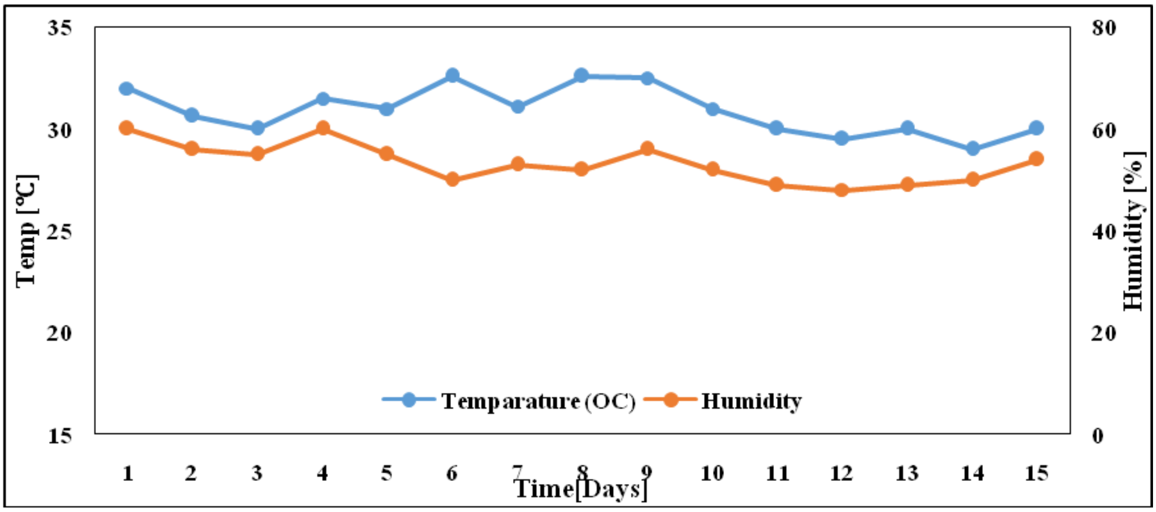


Figure 2. Temperature and humidity of the experimental room for maintaining fenugreek seeds.

3.1 Soil characteristics

As presented in Table 1, different compositions of tea spent waste such as green tea (GT), tea dust (TD), and tea granules (TG)were amended to individual sapling pots to evaluate their influence on soil properties and plant growth. Following the amendment, changes in soil characteristics were assessed. The results are illustrated in Figure 3.

A significant enhancement in soil moisture content was observed across all tea spent-amended groups when compared to the untreated control. Among the treatments, the tea granules (TG) group exhibited the highest soil moisture retention, followed by the green tea (GT) group. In the GT group, the moisture content increased proportionally with the percentage of green tea waste incorporated, suggesting a positive correlation between the GT amendment level and moisture content. Conversely, the lowest moisture content was recorded in the tea dust sugar (TDS) group. However, a dose-dependent increase in moisture content was noted in the TD, TGS (tea granules sugar), and TDMS (tea dust mixed sugar) groups, indicating that higher concentrations of tea spent may compensate for the otherwise low moisture retention properties of finer tea particles such as dust.

The improvement in moisture retention can be attributed to the organic matter content and fibrous nature of tea spent waste, particularly in coarser fractions like granules, which contribute to better soil structure and porosity. Previous studies have shown that the incorporation of organic amendments can improve the soil's moisture content by enhancing its aggregate stability and increasing pore space [8][13]. This, in turn, benefits plant growth by maintaining adequate moisture levels in the rhizosphere, particularly under conditions of limited irrigation. On the other hand, the comparatively lower moisture retention in the TDS group could be due to its fine particle size and higher sugar content, which may have influenced the microbial activity and temporarily altered the osmotic balance in the soil.

The density of the soil following amendment with various tea spent waste variants was analyzed and is presented in Figure 3b. Among all treatment groups, the highest soil density was recorded in the tea granules mixed with sugar (TGMS) group, whereas the lowest density was observed in the tea dust (TD) group. Across the TD, tea dust sugar (TDS), tea dust mixed sugar (TDMS), green tea sugar (GTS), and tea granules sugar (TGS) groups, no statistically significant dose-dependent variations in soil density were detected.

The observed differences in soil density can be attributed to the physical structure and particle size of the tea spent material. Coarser particles, such as those found in tea granules, tend to compact more densely in the soil matrix, particularly when combined with sugar residues that may act as binding agents, leading to the higher bulk density seen in the TGMS group. In contrast, finer particles such as tea dust contribute less to compaction and aeration resistance, thereby reducing the density. From an agronomic perspective, soil density is a critical indicator of soil structure and porosity, both of which directly influence root penetration, water infiltration, and aeration [14]. Soils with high bulk density may hinder root elongation and limit oxygen availability to plant roots, negatively impact plant growth and microbial activity[15].

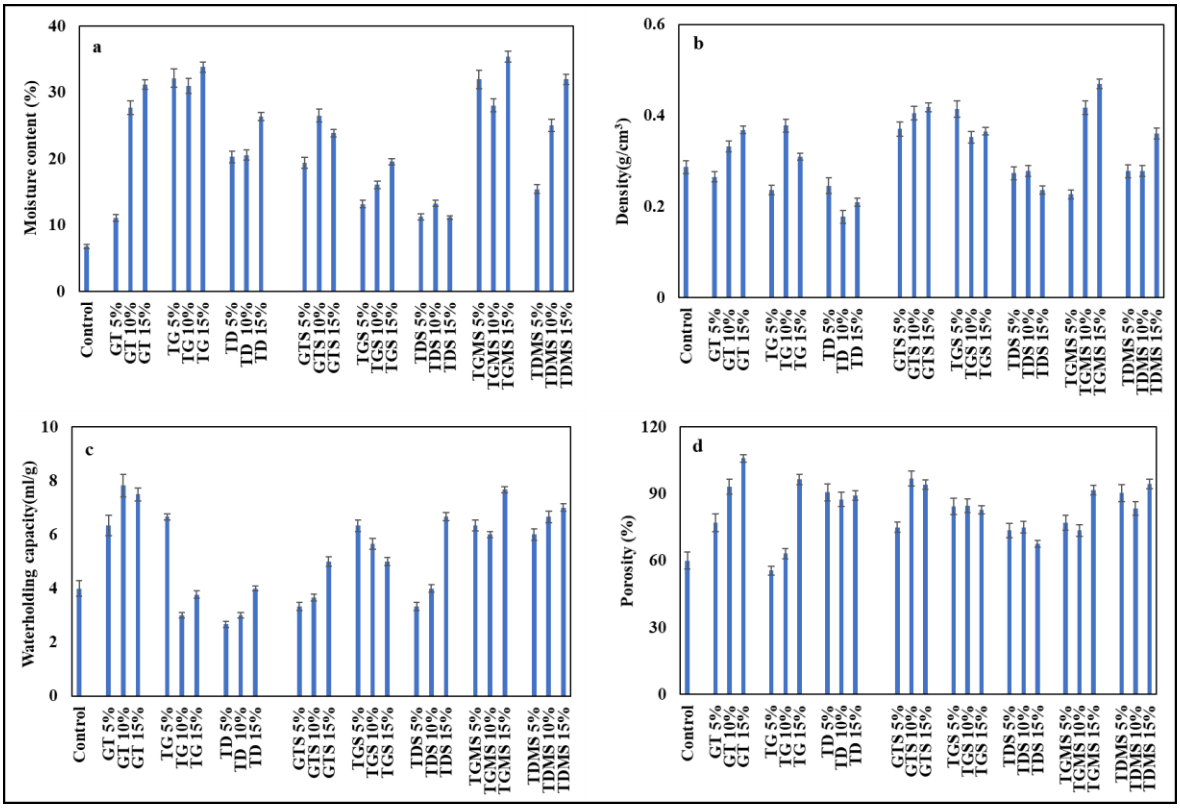


Figure 3. Soil characteristics with amendment of tea spent as organic fertilizer. a. Moisture, b. Density, c. Water holding capacity, and d. Porosity. All the values are mean ± SD of three replicates analysed. Green Tea (GT), Tea Granules (TG), Tea dust (TD), Green Tea + Sugar (GTS), Tea Granules + Sugar (TGS), Tea Dust +sugar (TDS), Tea Granules + Milk +Sugar (TGMS), Tea Dust + milk + Sugar (TDMS).

The water holding capacity (WHC) of soils amended with various tea spent waste variants is presented in Figure 3c. All treatment groups demonstrated a higher water-holding capacity (WHC) compared to the control, suggesting a beneficial impact of tea spent waste on the soil's moisture retention properties. Among all groups, the highest WHC was recorded in the green tea (GT) and tea granules mixed with sugar (TGMS) treatments. A dose-dependent increase in WHC was observed in the tea dust (TD), green tea sugar (GTS), tea dust sugar (TDS), and tea dust mixed with milk and sugar (TDMS) groups. In contrast, a dose-dependent decrease in WHC was noted in the tea granules (TG) and tea granules sugar (TGS) groups, indicating that higher concentrations of coarse tea granule waste may not proportionally contribute to improved water retention. The observed enhancement in WHC, particularly in the GT and TGMS groups, can be attributed to the high organic matter and fibrous content of green tea and sugar-rich residues, which improve soil porosity and microaggregate formation [16].The organic amendments, including polyphenol-rich tea waste, are known to enhance soil structure and increase capillary water retention, thereby promoting sustained moisture availability in the root zone [8][13][17].In the case of TDMS, the inclusion of milk and sugar residues likely contributed additional organic colloids and soluble carbohydrates, which may act as natural soil conditioners, thereby enhancing WHC by increasing the soil's cation exchange capacity and microbial biomass activity [18]. However, excessive accumulation of organic residues such as milk proteins and sugars may also lead to microbial imbalances or hydrophobicity if not properly mineralized. The dose-dependent decrease observed in TG and TGS groups could be due to the coarser particle size and lower surface area of the granules, which may increase macro-porosity and facilitate faster water drainage, thereby limiting moisture retention capacity. Enhanced WHC is agronomically advantageous, particularly in semi-arid and water-scarce conditions, as it supports prolonged soil moisture availability, reduces irrigation frequency, and improves nutrient solubility and uptake. These results highlight the potential of tea spent waste, especially variants rich in fine particles and organic content, such as GT and TDMS, to act as sustainable soil conditioners for improving moisture dynamics in agricultural soils.

The soil porosity data for all treatment groups are presented in Figure 3d. An increase in porosity was observed across all tea spent waste-amended groups compared to the unamended control, indicating the positive influence of organic amendments on soil structural properties. The highest porosity values were recorded in the green tea (GT), green tea sugar (GTS), tea dust mixed with milk and sugar (TDMS), tea dust (TD), and tea granules mixed with milk and sugar TGMS) treatments. An apparent dose-dependent increase in porosity was observed in the GT, tea granules (TG), and TGMS groups, suggesting that increasing concentrations of these specific variants enhanced the soil's pore space. However, no significant changes in porosity were noted across different concentrations within the TD, tea dust sugar (TDS), and TDMS groups, indicating a saturation effect or limited structural contribution from these finer-textured residues.

The increased porosity in the GT and TG-based groups is likely due to the coarser, fibrous nature of these amendments, which contribute to better soil aggregation and the formation of macropores. This structural modification can facilitate improved root penetration, aeration, and water infiltration [19][20]. Green tea, in particular, may enhance soil microbial activity due to its high content of polyphenols and organic matter, which indirectly promotes soil porosity by improving the formation of stable aggregates [21].In contrast, the absence of significant porosity improvement in the TD, TDS, and TDMS groups may be attributed to the finer particle size and potentially higher levels of soluble organic matter from milk and sugar. These components might clog soil pores at higher doses or create compacted microstructures, thus diminishing their contribution to overall porosity enhancement. Improved soil porosity is highly beneficial in agriculture as it facilitates better gas exchange, root respiration, and microbial proliferation while reducing the risk of compaction and surface crusting. However, excessively high porosity, particularly with very coarse amendments, may lead to reduced water retention and faster nutrient leaching if not balanced with finer matrix materials.

3.2 Plant growth characteristics

3.2.1 Seed Germination

The germination percentage of *Trigonella foenum-graecum*(fenugreek) seeds under various tea spent waste treatments is presented in Figure 4. The results indicate that, except the tea dust (TD) group, all experimental treatments resulted in a higher germination percentage compared to the untreated control. The highest germination was observed in the green tea (GT) group, followed by the tea granules (TG), tea dust with sugar (TDS), tea granules mixed with sugar (TGMS), tea dust mixed with milk and sugar (TDMS), and green tea with sugar (GTS) groups respectively. Notably, although the TD group exhibited the lowest germination percentage among all treatments, its performance improved significantly upon the addition of sugar (TDS) or a combination of milk and sugar (TDMS), suggesting a mitigating effect of these additives. A dose-dependent increase in germination percentage was observed in the GT, TG, TDMS, and TDS treatment groups, indicating that optimal concentrations of these amendments can enhance seedling emergence. The positive influence of GT and TG amendments may be attributed to the relatively high organic content and favourable nutrient profiles in these residues, which can improve soil microbial activity and enzymatic processes critical for seed germination [22][23].

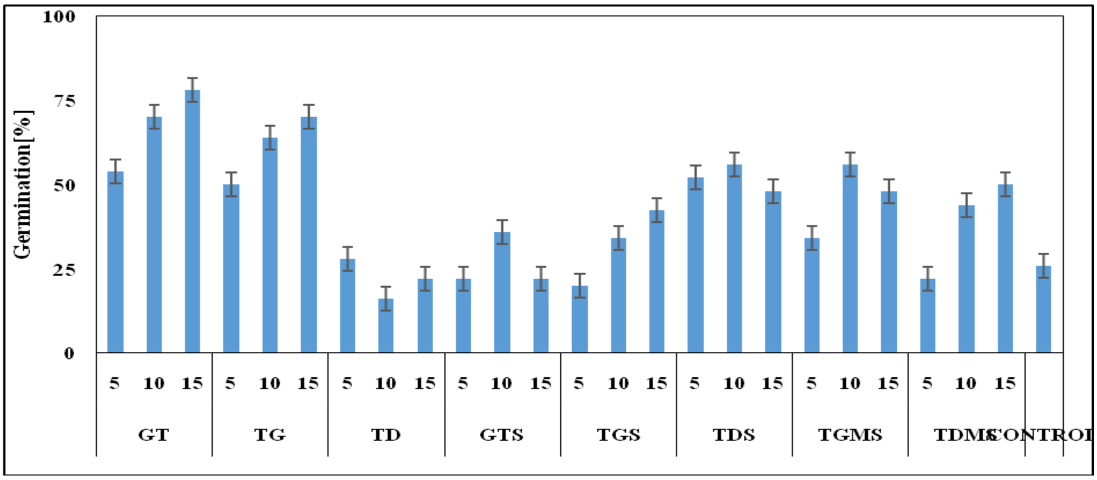
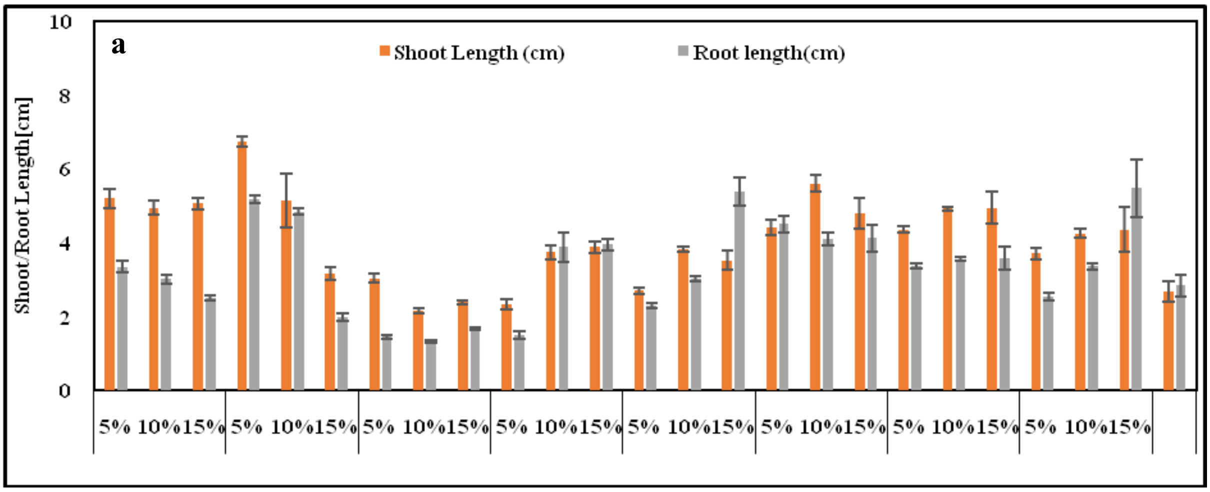


Figure 4. Germination percentage of experimental plants. Green Tea (GT), Tea Granules (TG), Tea dust (TD), Green Tea + Sugar (GTS), Tea Granules + Sugar (TGS), Tea Dust +sugar (TDS), Tea Granules + Milk +Sugar (TGMS), Tea Dust + milk + Sugar (TDMS).

Green tea residues, in particular, are known to contain antioxidant compounds such as catechins and theanine, which have been reported to modulate soil microbial communities and support early root development by alleviating oxidative stress during germination [24][25]. Meanwhile, the low performance of the TD group could be due to its finer particulate size and possible presence of residual polyphenols in inhibitory concentrations, which are known to exert allelopathic effects that suppress seed germination [26]. The improved germination in TDS and TDMS treatments may be due to the addition of sugars and milk proteins, which can serve as readily available carbon and nitrogen sources for soil microbes, thereby enhancing microbial metabolism and creating a more favourable microenvironment for germination. Enhanced seed germination is a critical agronomic trait, particularly in sustainable agriculture systems where rapid establishment of crops can reduce weed pressure, optimize resource use, and improve yield potential. Therefore, the use of selected tea spent waste variants mainly green tea and sugar-enriched formulations demonstrates significant promise in promoting early seedling vigour in fenugreek cultivation.

3.2.2 Root length and Shoot length

The shoot and root lengths of *Trigonella foenum-graecum*(fenugreek) seedlings measured during the course of the experiment are presented in Figure 5a. Overall, all treatment groups exhibited increased shoot and root growth compared to the control, with the notable exception of the tea dust (TD) group, which consistently showed the lowest values for both parameters. The maximum shoot and root length was recorded in the 5% tea granules (TG) group, indicating a positive effect of low-concentration TG amendment on early plant development. However, a concentration-dependent decline in both shoot and root lengths was observed with increasing TG content beyond 5%, suggesting potential negative effects at higher doses, possibly due to increased accumulation of phytotoxic compounds or alterations in soil structure that may hinder root expansion[27]



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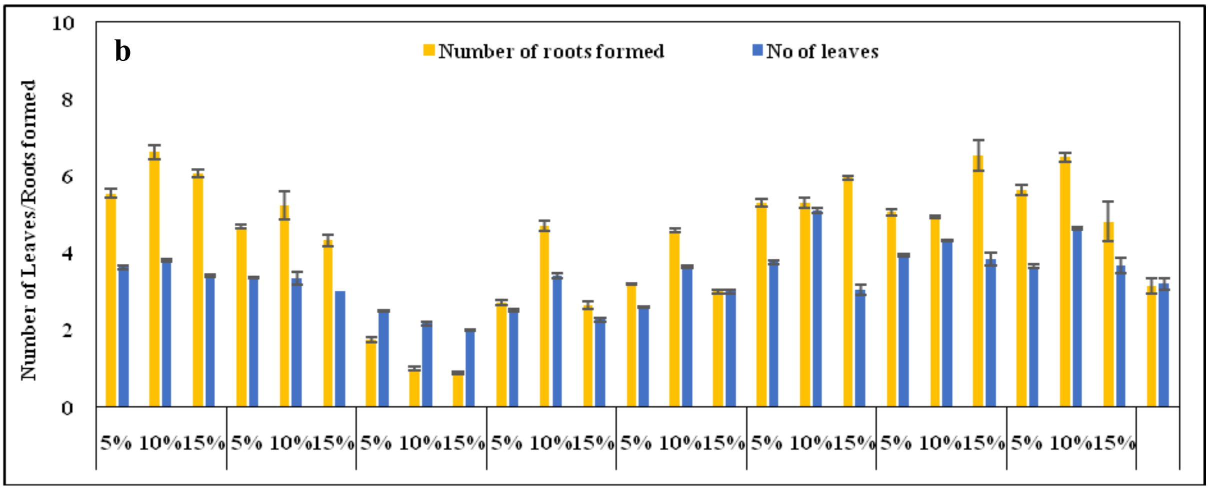

Figure 5.a. Root and shoot length of the experimental samples and b. Number of leaves and roots of the experimental samples. Green Tea (GT), Tea Granules (TG), Tea dust (TD), Green Tea + Sugar (GTS), Tea Granules + Sugar (TGS), Tea Dust +sugar (TDS), Tea Granules + Milk +Sugar [TGMS), Tea Dust + milk + Sugar [TDMS).

In the green tea (GT) treatment group, shoot length remained relatively consistent across all concentrations (5–15%), although a slight decline was noted at higher doses. Conversely, the green tea with sugar (GTS) and tea granules with sugar (TGS) treatment groups demonstrated a dose-dependent increase in both shoot and root length, implying that the presence of sugar enhances the beneficial effects of tea residues. This enhancement is likely due to improved microbial activity stimulated by the addition of easily metabolisable sugars, which can support root elongation and nutrient uptake [28].The TD group consistently exhibited the lowest shoot and root lengths, reinforcing previous observations of its limited agronomic benefit. However, when sugar was incorporated (TDS group), a significant improvement in both shoot and root length was noted, underscoring the potential of carbon-rich amendments to mitigate the adverse effects of tea dust. In the TGMS (tea granules with milk and sugar) group, no significant differences in root or shoot length were observed across varying concentrations, indicating a neutral response likely due to the complex composition of milk proteins and fats, which may slow microbial decomposition and nutrient release. In contrast, the tea dust with milk and sugar (TDMS) group exhibited a concentration-dependent increase in root length, suggesting that the combination of organic additives may facilitate the gradual release of nutrients, thereby supporting subterranean growth. These findings highlight the potential of tea spent residues especially when amended with sugar as effective organic soil conditioners that can improve root and shoot development. Enhanced root length contributes to greater soil exploration and water uptake, while increased shoot length reflects robust vegetative growth: both are critical for achieving higher biomass and yield under sustainable cultivation practices. However, optimization of concentration is essential to avoid potential phytotoxicity at higher levels of amendment [27].

The number of leaves and number of roots formed were also measured and the results are presented in Figure 5b. These results indicate that all experimental groups have showed an increase in number of roots and leaves compared to the control, except in TD group. The

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highest number of leave formed in GT group followed by TG, however the lowest number of leaves and roots formed in the TD group. The number of roots and leaves formed were gradually decreased in the TD group with increase in concentration. In the case of GTS, the number of roots and leaves formed were less than that of GTgroup; however, a higher number was observed at a 10% concentration. The similar trend was observed in TGS. In the case of TDS there is a substantial increase in the number of roots and shoots formed was observed compared to the TD group. TGMS and TDMS groups also showed higher number of leaves compared to the remaining all groups, however in roots there is no significant difference was observed.

The number of leaves and roots developed in *Trigonella foenum-graecum* seedlings under various tea spent amendments is depicted in Figure 5b. The data indicate that all treatment groups, with the exception of tea dust (TD), showed a significant increase in both leaf and root numbers compared to the control group, highlighting the potential of tea spent residues as soil amendments that promote early plant development. Among all treatments, the green tea (GT) group recorded the highest number of leaves, followed by the tea granules (TG) group. These results suggest that GT residues, rich in polyphenols and mineral content, may create a favourable rhizosphere environment for shoot development and leaf emergence[Iannucci et al., 2013). The TD group not only demonstrated the lowest number of leaves and roots but also exhibited a dose-dependent decline, possibly due to the presence of inhibitory compounds or insufficient nutrient content retained in tea dust, which might negatively impact root initiation and foliar growth. In the green tea with sugar (GTS) and tea granules with sugar (TGS) groups, although the number of leaves and roots formed was lower than the GT group, a peak response was observed at 10% concentration, indicating an optimal threshold for nutrient availability and microbial stimulation. These findings are consistent with the theory that moderate sugar supplementation enhances microbial activity and nutrient cycling, which in turn facilitates organogenesis [29]. Notably, the tea dust with sugar (TDS) group exhibited a substantial increase in both root and leaf formation compared to the unamended TD group. This improvement is likely due to the addition of sugar serving as a carbon source that compensates for the low nutrient profile of tea dust and stimulates beneficial microbial consortia that enhance plant root architecture [30][31].

Furthermore, the TGMS (tea granules with milk and sugar) and TDMS (tea dust with milk and sugar) groups showed a consistently higher number of leaves compared to most other treatments, although no significant variation was observed in root numbers across concentrations. The increased leaf count in these groups could be attributed to the additional organic matter provided by milk components, which may support shoot biomass production. However, the lack of significant improvement in root number suggests that nutrient release might be slower or less bioavailable in these complex mixtures [32]. These results reinforce the potential of selectively utilizing tea spent variants, particularly green tea and granules, either alone or in combination with sugar, to enhance root and shoot development. An increased number of leaves correlates with higher photosynthetic capacity, while a robust root system supports nutrient and water uptakeboth of which are critical for sustainable crop performance and yield[33][34].

3.2.3 Chlorophyll and carotenoids

The chlorophyll-a (Chl-a) and chlorophyll-b (Chl-b) contents of *Trigonella foenum-graecum* plants subjected to different tea spent waste treatments are illustrated in Figure 6. A significant increase in Chl-a concentration was observed across all treated groups when compared to the control, indicating enhanced photosynthetic potential. In contrast, Chl-b levels remained statistically unchanged in most treatment groups, except in the green tea with sugar (GTS) group, where a notable increase was recorded. Among the treatments, the tea granules (TG) group exhibited the highest Chl-a content, followed by the GTS group. An apparent dose-dependent increase in both Chl-a and Chl-b levels was evident in the TG group, suggesting that increasing concentrations of tea granule residues may progressively improve photosynthetic pigment synthesis. Conversely, the green tea (GT) treatment group did not show significant changes in either Chl-a or Chl-b content across varying concentrations, indicating a plateau effect or limited impact at the applied doses. The lowest concentrations of

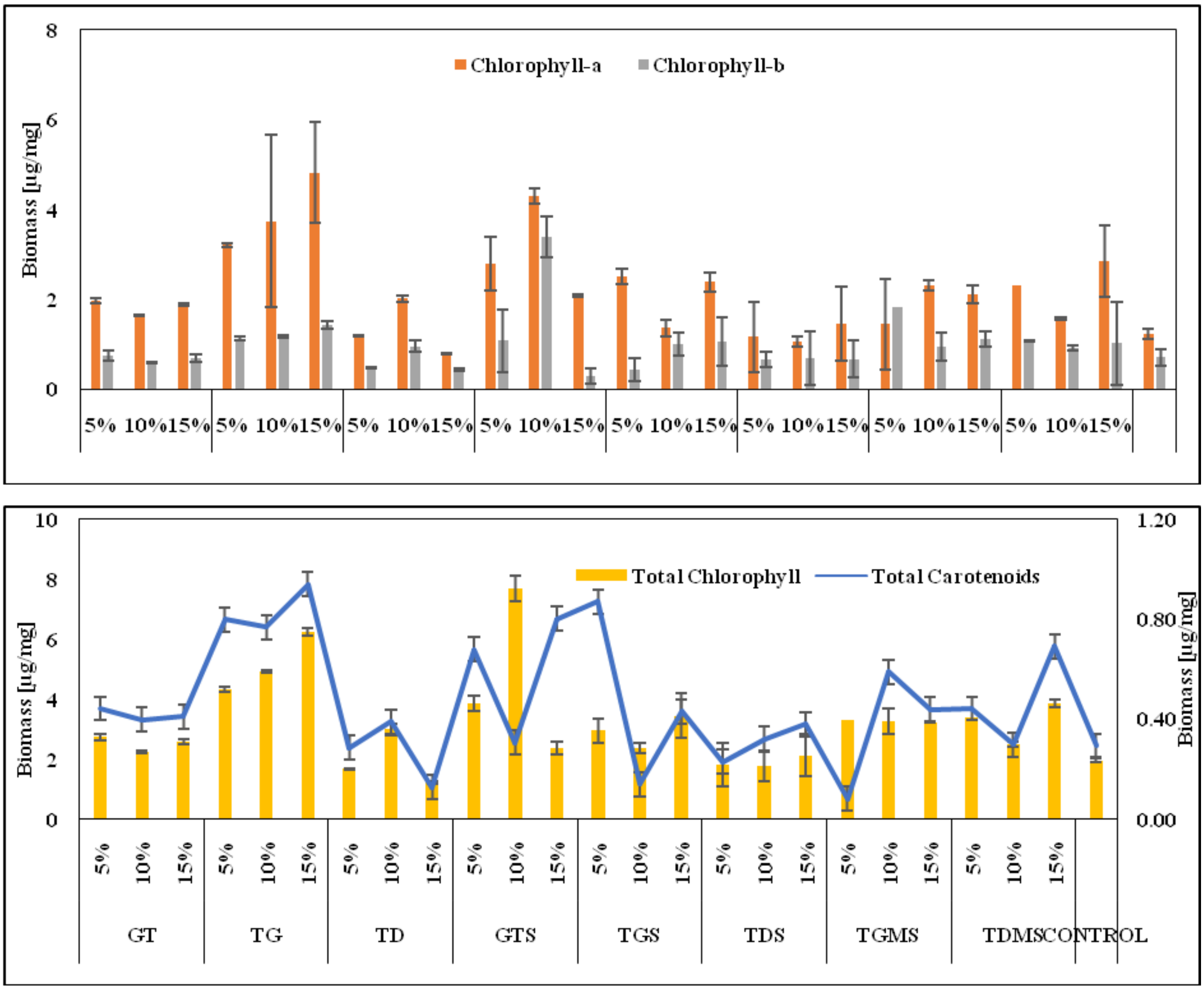

Figure 6.a. Chlorophyll-a and Chlorophyll-b content of the experimental plants and b. Total chlorophyll and total carotenoid content of the experimental plants. Green Tea (GT), Tea Granules (TG), Tea dust (TD), Green Tea + Sugar (GTS), Tea Granules + Sugar (TGS), Tea

Dust +sugar (TDS), Tea Granules + Milk +Sugar (TGMS), Tea Dust + milk + Sugar (TDMS).

both Chl-a and Chl-b were recorded in the tea dust (TD) group, potentially due to the presence of residual inhibitory compounds or poor nutrient contribution. Interestingly, the GTS group at 10% amendment showed the highest Chl-b content among all treatments, which could be attributed to the synergistic effect of sugar addition enhancing nutrient bioavailability and microbial activity in the rhizosphere. Sugars can also act as osmo-protectants and signalling molecules that indirectly regulate chlorophyll biosynthesis pathways(Singh et al., 2015). Increased chlorophyll content, especially Chl-a, is directly associated with enhanced photosynthetic efficiency and improved biomass accumulation [12]. The results of this study suggest that specific variants of tea spent waste, particularly TG and GTS have a positive influence on the photosynthetic machinery of fenugreek plants, thereby offering a sustainable and nutrient-rich organic amendment for improved crop performance. On the other hand, lower pigment content in the TD group may indicate limited agronomic value or possible phytotoxic effects, as previously noted in studies on polyphenol-rich organic residues [35].The total chlorophyll and carotenoid contents of *Trigonella foenum-graecum* plants grown in soil amended with various tea spent waste variants are illustrated in Figure 6b. The total chlorophyll content followed a trend similar to that of chlorophyll-a and -b, with higher values observed in most treated groups compared to the control. This reinforces the positive influence of specific tea waste variants on the plant's photosynthetic pigment profile.

Regarding carotenoids, a significant increase in content was observed in all treatment groups, except for the tea dust (TD) group, where the lowest carotenoid levels were recorded. Notably, the tea granules (TG) group exhibited the highest carotenoid concentration, followed closely by the green tea with sugar (GTS) group. A dose-dependent increase in carotenoid content was evident in the TG group, suggesting a cumulative stimulatory effect of the tea granules on the synthesis or accumulation of these pigments. Interestingly, no significant variation in carotenoid content was observed with increasing concentrations of green tea (GT) and tea dust with sugar (TDS), indicating a possible threshold effect or limited bioavailability of beneficial compounds. Moreover, in the tea granules with sugar (TGS) group, a dose-dependent decline in carotenoid content was observed, suggesting potential antagonistic interactions between tea components and sugar at higher concentrations, possibly due to osmotic stress or altered soil microbial dynamics. Carotenoids play a crucial role in protecting plants from oxidative stress and facilitating light harvesting for photosynthesis [36][37]. Elevated carotenoid levels are generally indicative of enhanced plant stress tolerance and overall vigour. The observed enhancement in the TG and GTS groups implies that this specific tea spent variants may contribute not only to improved photosynthetic efficiency but also to increased resilience of plants under suboptimal growing conditions. Conversely, the low carotenoid content in the TD group could be attributed to the accumulation of polyphenols and caffeine residues, which are known to inhibit enzymatic activities and disrupt cellular processes in plants [38]. These results suggest that while certain types of tea waste can serve as effective biofertilizers, others may require pretreatment or blending to mitigate potential phytotoxic effects.

4. Conclusion

This comprehensive study evaluated the potential of various tea spent residues namely Green Tea (GT), Tea Granules (TG), and Tea Dust (TD), along with their variants prepared with sugar and milk (GTS, TGS, TDS, TGMS, TDMS)as sustainable inputs in agriculture through both chemical characterization and plant growth response assessments. The dual approach aimed to explore the feasibility of converting post-consumer tea waste into valuable bioresources in line with circular bioeconomy principles. The nutrient density underlines the potential of tea waste as a low-cost soil amendment, microbial substrate, or compost additive. The application of these residues to soil notably influenced physicochemical properties such as moisture retention, porosity, and water-holding capacity particularly in GT and TG amended groups. These enhancements are vital for plant health, especially in water-deficient or nutrient-poor soils. The growth trials using *Trigonella foenum-graecum*(fenugreek) revealed improved seed germination, biomass accumulation, chlorophyll content, and carotenoid levels in most treatments, with green tea and tea granules variants producing the most beneficial outcomes. These effects suggest enhanced photosynthetic efficiency, metabolic activity, and potential stress tolerance. However, raw Tea Dust (TD), especially at higher concentrations, negatively impacted plant performance, likely due to phytotoxic compounds such as caffeine and polyphenols. Variants with sugar or milk (TDS, TDMS) showed moderate improvements, indicating that processing can mitigate some inhibitory effects.

The findings collectively illustrate that tea-spent residues should not be dismissed as mere waste; rather, they are nutrient-dense, bioactive materials that possess significant potential for valorization. These residues can be transformed into effective soil enhancers, nutrient-rich microbial feedstocks, or even precursors for bio-based materials. Notably, the green tea (GT) and traditional tea (TG) variants emerged as the most promising in terms of their beneficial properties. However, it is crucial to emphasize that the optimization of application rates for these residues is paramount. Careful management is required to maximize the agronomic advantages while mitigating the risk of phytotoxicity, which could adversely affect plant health and soil quality. This study serves as a foundational reference point for prospective research efforts aimed at large-scale composting initiatives, practical plant trials, and the microbial valorization of tea waste. Ultimately, these findings offer a scalable and eco-friendly solution to the challenges of organic waste management, promoting sustainable farming practices that not only reduce agricultural waste but also enhance soil fertility and plant growth.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

CREDIT AUTHOR STATEMENT

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Data Availability Statement

The data that support the findings of this study will be made available on reasonable request from the corresponding author. The data are not publicly available due to privacy of ethical restrictions.

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