

Effects of Treated Wastewater Sludge Application on Soil Physico-Chemical Properties and Chickpea Growth

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Abstract:

The rising volume of sludge produced during wastewater treatment creates substantial environmental pressures, which could be reduced through its beneficial reuse in soil systems. A multi-season field study evaluated the effects of treated wastewater sludge on soil characteristics, microbial activity, yield, and grain quality of rainfed chickpea (*Cicer arietinum*). Characterization conducted before application revealed that sewage sludge from secondary (SS) and tertiary (TS) treatment plants fell within the Class B category, permitting limited agricultural reuse but prohibiting its application to land used for the cultivation of raw fruits and vegetables. Sludge application significantly increased chickpea biomass and grain quality, leading to grain yield improvements of 61–76 % relative to the control (46 g/m²), with yields of 74 g/m² and 81 g/m² under SS and TS treatments, respectively. During the initial season, grain protein peaked at 14.5% under the TS treatment. Microbial analyses revealed temporal variability, while SS application in the second season was associated with a potential increase in total coliform contamination. Our findings substantiate the positive contribution of treated sewage sludge to soil fertility and chick pea grain quality, supporting its strategic integration into sustainable agriculture. At the same time, they emphasize the necessity for ongoing surveillance of sludge composition and soil conditions to safeguard environmental integrity and public health.

Keywords: Sewage sludge, Soil fertility, Chickpea (*Cicer arietinum*), Microbial safety, Agronomic yield.

1. INTRODUCTION

Soils form the foundation of agricultural productivity but are increasingly recognized as a limited and vulnerable resource. Under intensive cultivation, maintaining soil fertility requires approaches that replenish nutrients and rebuild soil organic matter (SOM) without overreliance on mineral fertilizers [1]. Although chemical fertilizers remain a primary tool for sustaining crop yields and quality, their associated environmental impacts and dependence on finite resources, particularly phosphorus, raise critical concerns regarding the resilience and sustainability of modern agricultural systems [2]. Feeding a global population expected to reach nine billion by 2050 will require almost doubling current levels of food, feed, and biofuel production [3]. In response, rapid industrial growth has intensified agricultural reliance on fertilizers to maximize productivity. The indiscriminate deployment of fertilizers has increasingly been linked to adverse environmental outcomes, including soil salinity, heavy

metal contamination, nitrate leaching into aquatic environments, and eutrophication of surface waters, underscoring the importance of transitioning toward sustainable nutrient management frameworks [4]. Rising fertilizer costs and increasing supply instability reflect the finite nature of the resources required for their production. Given that phosphorus fertilizers rely on phosphate rock and that ammonia production depends on natural gas, both nonrenewable resources, the long-term sustainability of conventional fertilizer practices is jeopardized. Alternative fertilization strategies have been widely examined, with organic waste reuse receiving increasing attention. The application of organic wastes improves soil organic matter levels, enhances nutrient availability, and promotes favorable physico-chemical and microbial soil conditions [5]. Notably, sewage sludge, generated as an inherent byproduct of municipal wastewater treatment, has been widely recognized for its effective reuse in agriculture as a non-traditional organic amendment. The agronomic potential of sewage sludge stems from its elevated organic carbon content, significant levels of essential nutrients, especially nitrogen and phosphorus, and textural properties that allow nutrients to be released gradually [6]. Assessed the impact of sludge amendment on the growth and yield of durum chick pea (*Cicer arietinum*) in semi-arid regions. Results from the study confirmed that sewage sludge application positively influences soil fertility and durum chickpea performance, underscoring its role as a sustainable pathway for sludge reuse and enhanced agricultural productivity [7], [8]. In addition, organic fertilizers have proven effective in the remediation of heavy metal-contaminated soils by reducing contaminant bioavailability and minimizing groundwater contamination through adsorption and precipitation processes. The enrichment of soil organic matter through manure application enhances soil water-holding capacity while fostering the development of soil microbial communities [9]. The agronomic reuse of sewage sludge promises waste reduction and nutrient return, yet it also introduces risks: microorganisms and heavy metals derived from industrial and domestic inputs and runoff can accumulate in soils examples include lead, cadmium, and mercury thereby compromising soil quality and safety. Previous studies have shown that the application of saline sewage sludge can lead to soil salt accumulation, negatively influencing soil structure, plant development, and crop productivity [10], [11]. The presence of pathogens, pharmaceuticals, and organic contaminants in sewage sludge complicates disposal and reuse in agriculture; consequently, application must be regulated through context-sensitive, country-level guidelines that integrate local soil and climate characteristics, wastewater treatment capacity, and socio-economic considerations. Most sewage sludge generated by wastewater treatment plants in India is currently disposed of in landfills [12]. Due to the lack of sustainable disposal alternatives, sewage sludge produced at the Sathyabama University wastewater treatment plant is currently stored in nearby landfill areas. Meanwhile, empirical studies evaluating its effects on Indian soils and plant growth remain scarce. The reuse of treated sludge as an organic fertilizer replacement for selected crops, in compliance with established sludge-use and food safety regulations, represents a promising and context-appropriate solution for sludge disposal in India. Therefore, this study examined two sewage sludge types originating from secondary and tertiary wastewater treatment for potential application in the Sholinganallur agricultural field, Chennai, India. Comprehensive soil characterization (physical, chemical, and biological) was paired with

cultivation of soft chickpea (*Cicer arietinum*) to assess the impacts of treated sewage sludge on crop growth. The study's main objective was to evaluate how sludge amendments influence soil health as well as the yield and grain quality of rainfed chickpea under Indian semi-arid conditions. Specifically, the research objectives are to:

- a. Evaluate the agronomic benefits and potential environmental risks of sewage sludge use by characterizing its effects on soil physical, chemical, and microbial indicators.
- b. Assess the trade-offs between enhanced yield and grain quality versus food-safety and environmental concerns for rainfed chick pea following sludge application.

2. Materials and methods

2.1. Study area and Soil sampling

The field experiments were carried out at the Sholinganallur agricultural field, situated in the southeastern part of Chennai, Tamil Nadu, India. This area is characterized by a mixture of peri-urban agricultural activities and has a tropical semi-arid to sub-humid climate, with hot summers, moderate rainfall during the northeast monsoon, and mild winters. The soils are mainly sandy clay loam to clay loam, supporting seasonal cultivation of cereals, pulses, and vegetables. Chickpea (*Cicer arietinum*) was selected as the test crop due to its suitability for semi-arid conditions and its ability to enhance soil fertility through nitrogen fixation. A split-plot design with three replications ($n = 3$) was used to evaluate three treatments: (i) an unamended control, (ii) sewage sludge from a secondary treatment plant (SS), and (iii) sewage sludge from a tertiary treatment plant (TS). The TS sludge, obtained from combined secondary and tertiary processes, was air-dried and lime-stabilized before application, while the SS sludge was applied without further stabilization. After drying at the treatment plants, the sludges were transported to the experimental site. Subsamples were collected, homogenized by grinding, and passed through a 2 mm sieve to ensure uniformity for analysis. The experiments were conducted during the 2023 and 2024 cropping seasons. In line with agronomic recommendations, the sludge was applied once per season to newly prepared plots before sowing and incorporated into the topsoil layer (10–15 cm) using rotary tillage. At the start of each season, all plots received a starter application of 50 kg ha^{-1} of NPK fertilizer (18–46–0) to ensure uniform nutrient availability across treatments.



Experimental Layout of Chickpea (*Cicer arietinum*) Trials at Sholinganallur Agricultural Field

Figure 1 - Experimental Design for Rainfed Chick Pea Incorporating Control and Sludge-Amended Treatments Using Dried Secondary and Tertiary Wastewater Sludge

2.2 Description of Treatments and Agronomic Procedures

The experiment comprised 27 plots (4.5 m × 4.5 m) planted with *Cicer arietinum* during two consecutive growing seasons. Sowing dates were December 1, 2022, and November 21, 2023, while harvests occurred on July 1, 2023, and June 15, 2024. To comply with institutional crop rotation policies and reduce disease incidence, the study was relocated to a new field in the second season. A seeding rate of 200 kg ha⁻¹ was applied, corresponding to 20 kg per dunum, in line with standard practices in the Sholinganallur agricultural field. Sewage sludge was incorporated into the soil at a rate of 3000 kg ha⁻¹ following Indian guidelines. Supplemental groundwater irrigation was provided during the late dry period in each season. Climatic conditions differed between seasons, with higher mean temperatures recorded in the first season and greater cumulative rainfall in the second, most of which occurred between December and April.

2.2.1 Soil sampling

Multiple soil subsamples were collected from each replicate plot to a depth of 15 cm using a shovel and combined into a single representative composite sample. This depth corresponds to the cultivated soil layer and the main root zone. Sampling was carried out before the experiment to characterize initial soil conditions and again after crop harvest in each season to evaluate changes resulting from chick pea cultivation. To preserve soil integrity by limiting moisture-driven and microbial alterations, samples were dried at 40 °C and then sieved through a 2 mm mesh to remove coarse fractions and standardize particle size for laboratory analyses. Particle-size analysis was conducted using the Bouyoucos hydrometer approach, based on sedimentation principles in a sodium hexametaphosphate medium. Soil texture classification remained consistent between seasons and was identified as silty clay loam.

2.3 Sludge characterization

Soil chemical analyses adhered to the procedures outlined by Abdelrhman et al., 2021 [13]. Soil pH and electrical conductivity (EC) were determined in 1:2.5 soil–water suspensions using an HQ40d instrument equipped with a PHC 101 probe and a portable EU TECH conductivity meter. Organic carbon content was determined by the Walkley–Black method and converted to organic matter by multiplying by 1.72. The cation exchange capacity was measured by exchange with ammonium acetate and read by a BWB flame photometer. Heavy metals (Cd, Cr, Ni, Pb, Cu, Zn) were extracted with DTPA and quantified using a Shimadzu AA-6300 atomic absorption spectrophotometer. Phosphorus availability (PO₄³⁻-P) was assessed using the Olsen method and measured at 882 nm with an Optima SP-300 spectrophotometer. Exchangeable cations (K⁺, Na⁺, Ca²⁺, Mg²⁺) were extracted with 1N ammonium acetate. Potassium concentrations were obtained by flame photometry (BWB Technologies), whereas calcium and magnesium were analyzed by atomic absorption spectroscopy (Shimadzu AA-6300). For each type of sludge, three replicate samples were air-dried and then ashed at 600 °C for 6 hours. The ash was subjected to acid digestion using a diluted mixture of HNO₃ and HCl (1:3, v/v), and the resulting extracts were analyzed for total heavy metals and nutrient content following the same analytical procedures used for the soil samples. NH₄⁺-N concentrations

were measured via the APHA 4500-NH₃ phenate colorimetric method, and chemical data are reported as means accompanied by standard deviations.

2.4 Estimation of microbial properties

Raw sludge and control and sludge-amended soils (SS and TS) were assessed for microbiological quality by enumerating total viable microorganisms, fecal indicators, and selected pathogens, including coliforms, *E. coli*, *Salmonella* spp., *Pseudomonas aeruginosa*, *Enterococcus* spp., *Listeria monocytogenes*, *Bacillus* spp., sulfite-reducing bacteria, yeasts, and molds, using standardized methods at the Coimbatore Agricultural Research Institute, India. Microbial indicators and pathogens were enumerated using standard culture techniques: total viable counts by plate counting; coliforms via lactose fermentation at elevated temperatures; *E. coli* on selective agar; *Salmonella* spp. and *Listeria monocytogenes* through enrichment and selective plating; *P. aeruginosa* on cetrimide agar; enterococci on selective media; *Bacillus* spp. via spore cultivation; sulfite-reducing bacteria under anaerobic conditions; and yeasts and molds on selective fungal media.

2.5 Analysis of plant sampling

The locally prevalent chickpea species *Cicer arietinum* was sampled by collecting all plants from a 1 m² quadrat established in each plot row, providing nine observations per treatment across three replicates. Harvested shoots were cleaned with distilled water, oven-dried at 55°C for 72 h, and analyzed for dry weight. Measured agronomic traits comprised shoot height (cm), hay weight (g), spike density, and individual spike and grain weights (g), with mass measurements obtained using an analytical balance. Proximate analysis of grain (crude protein, crude fiber, ether extract, ash, and starch) was conducted on a dry-matter basis.

2.6 Statistical analysis

For each treatment, soil and plant analyses used independent triplicate samples. A one-way analysis of variance (ANOVA) was applied to determine differences among treatment means, with statistical significance defined at $P < 0.05$. Fisher's LSD test was subsequently used for pairwise comparisons at the same significance level. All analyses were carried out using Minitab 17 (Windows).

3 RESULTS AND DISCUSSION

3.1. Baseline Soil and Sewage Sludge Characterization Before Application

Comprehensive physicochemical and microbial assessments of SS and TS sewage sludges were conducted before the field claim (Table 1). Sludge behavior in soil is largely governed by pH and electrical conductivity (EC), which affect nutrient availability, adsorption, and soil structure. Observed pH values for both sludge types stayed consistently slightly acidic to neutral across the two growing seasons. SS exhibited pH values of 7.51 in the first season and 6.27 in the second, while TS recorded pH values of 6.81 and 7.47, respectively. These pH values are slightly lower than the typical neutral range of sewage sludge reported in the literature (7.0–8.5). Secondary-treated sludge maintained a consistently high EC of approximately 5.24 mS/cm across both seasons. In contrast, EC in the tertiary-treated sludge

varied substantially, increasing from 2.28 mS/cm in the 1st season and 5.24 mS/cm in the 2nd season. The macronutrient profiles of secondary (SS) and tertiary (TS) sewage sludges are summarized in Table 1, emphasizing their role as nutrient sources. A clear divergence in seasonal phosphorus dynamics was evident between treatments: phosphorus concentrations in TS improved from 1.28 g/kg in the first season to 5.08 g/kg in the second, whereas SS followed an inverse pattern, with higher phosphorus levels in the first season (3.98 g/kg) and substantially lower levels in the second (0.65 g/kg). During the first season, ammonia contents were similar for both sludge types; however, in the second season, TS exhibited nearly a tenfold increase compared to SS. Potassium levels were consistently higher in TS across the study period, whereas sodium accumulation was more pronounced in SS during the second season. Magnesium concentrations were stable (6.27–6.42 g/kg), while calcium remained higher in TS throughout. Organic matter was more abundant in SS, corroborating previous findings from the different agricultural fields, which reported sludge OM at 52.3% [14], [15]. Seasonal fluctuations and differences between sludge types largely reflect changes in wastewater quality and the release of poorly treated effluents from animal farms, slaughterhouses, hospitals, and food-processing operations. Indian sludge reuse guidelines categorize sludge based on heavy metal content into four classes: A (unrestricted), B and C (restricted), and D (unsuitable). As shown in Table 1, most heavy metals in both SS and TS fell below the allowable limits for agricultural application, with minor deviations in a few cases. While most metals in SS and TS remained within permissible limits, zinc and lead exceeded allowable levels in some cases. Accordingly, both sludges are designated Class B due to high zinc in SS throughout both seasons and elevated lead in TS in the second season. Materials classified as Class B may be applied safely to agricultural lands, provided the crops are not consumed raw, and are also suitable for use in forests, reclamation areas, landfills, and surface soils within wastewater treatment facilities. The evaluated sludges demonstrate suitable physico-chemical and heavy-metal properties for fertilization purposes, yet microbiological findings indicate potential risks that warrant careful management [16]. FAO threshold exceedances were observed: in season one, SS had elevated total viable counts, and both sludges showed excessive yeast and mold levels; in season two, SS exceeded limits for total and fecal coliforms as well as *Enterococcus* spp., and sulfite-reducing bacteria were above permissible limits in both SS and TS (Table 1). These results underscore the need for pathogen mitigation before agricultural application.

Table 1 - Analysis of Chemical and Microbiological Properties of Secondary and Tertiary Sludge Over Two Growing Seasons

Parameter	Permissible limits	SS – 1 st season	SS – 2 nd season	TS – 1 st season	TS – 2 nd season
Physico-chemical characteristics					
pH	–	7.51	6.27	6.81	7.47

Electrical Conductivity (mS/cm)	–	5.76	5.24	2.28	3.61
Ammonia (g/kg)	–	0.04	0.02	0.01	0.1
Phosphorous (g/kg)	–	3.98	0.65	1.28	5.08
Potassium (g/kg)	–	7.57	3.37	10.21	4.36
Sodium (g/kg)	–	-	1.32	-	0.65
Calcium (g/kg)	–	57.5	82.6	135.7	108.6
Magnesium (g/kg)	–	6.27	6.03	6.26	6.42
Moisture (%)	–	8.87	17.59	4.76	7.21
Ash (g)	–	6.12	0.89	8.47	1.18
OM (%)	–	65	72	55	69
Heavy Metals (mg/kg)					
Chromium (Cr)	250	66.2	44.2	77.5	56.7
Cadmium (Cd)	5	1.38	1.7	0.8	1.4
Lead (Pb)	150	77.6	94.1	125.4	163.2
Nickel (Ni)	125	35.8	45.4	32.4	54.1
Zinc (Zn)	700	1357.6	1348.4	521.42	519.8
Copper (Cu)	375	295.8	220.2	109.8	119.4

3.2 Impact of Sludge Treatments on Soil Physical Parameters

3.2.1 Temporal Variations in Soil pH and EC under Sludge Treatments

End-of-experiment results reveal that SS and TS amendments had no significant effect on soil pH in the first season. In the second season, however, both treatments induced a minor yet statistically significant pH increase relative to the control (Table 2). The rise in soil pH may result from the release of exchangeable cations during sludge mineralization, mimicking the effects of standard liming. This pattern was not observed in the first season, possibly due to lower cation content and cation exchange capacity in the soils [17]. Even though prior studies frequently note pH declines with sludge use, the alkaline nature of agricultural soils prevails, supported by the calcareous components present in sludge from sediment transport within wastewater [18]. Long-term studies are needed to confirm these observations. Electrical conductivity of soils amended with SS or TS did not differ significantly from the control. The first season showed a minor EC increase in SS-treated plots and a slight decrease in TS plots, with both variations falling below significance thresholds. Despite literature reports of EC increases after sludge application, our findings revealed only slight variations, with a single

sludge treatment producing values significantly lower than the control. Therefore, as suggested by Santos et al., 2025 [19], long-term monitoring is essential to fully understand the impact of sludge on soil EC.

Table 2 - Post-Harvest Chemical Characteristics of Soils Amended with SS and TS Across Two Growing Seasons

Parameter	Control – 1 st season	Control – 2 nd season	SS – 1 st season	SS – 2 nd season	TS – 1 st season	TS – 2 nd season
Physico-chemical characteristics						
pH	8.19	8.28	8.17	8.46	8.27	8.58
EC (mS/cm)	189	172	241	172	201	162
PO ₄ ³⁻ (kg/ha)	1829	2149	2137	2689	2347	3011
K ⁺ (mg/kg)	1137	431	1149	432	1231	501
Na ⁺ (mg/kg)	59.82	23.64	70.71	22.81	64.76	23.19
Ca ²⁺ (mg/kg)	1492	4971	4467	4936	3127	5106
Mg ²⁺ (mg/kg)	491	322	489	326	498	321
Soil moisture (%)	5.76	7.17	5.80	7.69	6.86	7.91
OC (%)	1.17	1.08	1.29	1.29	1.48	1.59
OM (%)	2.08	1.67	2.16	2.16	2.58	2.92
CEC (meq/100 g)	44	17	47	19	49	19
Heavy Metals (mg/kg)						
Cr	0.12	0.11	0.21	0.21	0.21	0.19
Cd	0.19	0.19	0.19	0.19	0.14	0.21
Pb	1.08	1.21	1.31	1.22	1.31	1.14
Ni	1.61	0.81	1.67	0.82	1.29	0.82
Zn	1.52	1.22	3.72	1.71	2.12	1.31
Cu	3.11	3.18	3.33	2.92	2.87	2.89

3.2.2 Changes in Soil Organic Matter and Moisture Due to Sludge Application

During the second season, soils treated with SS and TS showed a statistically significant increase in organic matter (OM) content in comparison to the untreated control plots. Although a similar positive trend was evident during the first season, the differences observed were not statistically significant. For example, Table 2 indicates that the OM content in TS-amended soils during the first season was 2.58%, slightly higher than the control, but without a significant difference. In the second season, however, the amendments produced a notable and statistically significant increase in OM, with SS-treated soils reaching 2.16% and TS-treated soils achieving 2.92%, compared to 1.67% in the control plots. The increase in soil organic matter observed here is consistent with Maggioli et al., 2022 [20], who found a linear and significant enhancement from 1.11% in the control to 1.93% in soils receiving the highest sludge amendment. This suggests that the application of both secondary and tertiary sewage sludge can substantially enhance soil organic matter and thereby improve fertility under semi-arid conditions. Consistent with the observations of Desjardins et al., 2025 [21], repeated applications of sewage sludge over time have been shown to enhance soil organic carbon (OC). Table 2 highlights that soils amended with TS exhibited a greater increase in OM than those treated with SS, which is attributed to the higher organic matter content of the TS sludge (Table 1). Through its effects on nutrient dynamics, soil structure, and moisture retention, organic matter significantly improves both the fertility and quality of soils. In addition, Kučera et al., 2026 [22] demonstrated that sludge amendments increase soil water retention. Higher OM also promotes improved soil aggregation and stability, which are essential for maintaining long-term soil health. These outcomes highlight the effectiveness of sludge amendments in rehabilitating degraded soils in India, and potentially in other arid and semi-arid regions where the inherent ability of soils to retain organic carbon is limited. Analysis of final soil moisture indicated that TS treatment significantly improved water retention in season one, and in season two, both SS and TS amendments increased soil moisture to 7.5% and 7.8%, respectively, compared with 7.1% in the control. The chick pea crop in this experiment was managed under rainfed conditions, and the enhanced soil water content is likely a result of organic matter accumulation. This positive effect is projected to elevate soil quality and reduce erosion risks over time, a pressing geo-environmental concern in India. While both sludge treatments enhanced soil moisture, evaluating possible drawbacks remains important. According to Agbna et al., 2025 [23], hydrogel polymers reduce the evaporation rate of water from the soil. While this can be advantageous for conserving moisture, it can also cause waterlogging, which may be detrimental to plants in humid regions or soils susceptible to poor drainage. Nevertheless, such negative outcomes are improbable in the semi-arid conditions of the agricultural field.

3.3 Effect of sludge amendments on soil chemical properties

CEC values in the first season were 44 meq/100 g (SS) and 47 meq/100 g (TS), compared with 49 meq/100 g in the control. In the second season, CEC decreased to 17 meq/100 g in unamended soils but rose to 19 and 20 meq/100 g with SS and TS amendments, respectively, with a significant increase observed for TS soils, in line with higher organic matter levels. These observations are consistent with reports by Abdelfattah et al., 2024 [24] and Ali et al.,

2024 [25], demonstrating that repeated sludge applications elevate CEC. The mechanism involves organic matter addition, which functions as a cation reservoir, enhances complexation with minerals and toxic anions, and improves their retention while limiting bioavailability. The incorporation of SS and TS sludges led to a significant rise in soil phosphorus during the second season relative to control soils, as shown in Table 2. Other macronutrients, including calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+), did not show substantial variations relative to the control, with exceptions observed for Ca^{2+} and Na^+ in SS-amended soils and Mg^{2+} in TS-amended soils during the first season, where levels were significantly higher. The study demonstrates that sewage sludge amendments can boost soil nutrient availability, including P, K, Na, Mg, and Ca, while maintaining concentrations below Indian recommended limits, thereby supporting sustainable soil management. Beyond acting as a nutrient source for crops, the application of sewage sludge supports soil structure, enhances fertility, and contributes to sustained soil productivity. These results align with previous studies reporting that sewage sludge effectively increases phosphorus (P) and nitrogen (N) levels in soils cultivated with crops. The application of organic amendments facilitates phosphorus availability in alkaline soils, where P is often immobilized. Seasonal mineralization of organic matter promotes the gradual conversion of P into forms readily taken up by crops. Moreover, with escalating fertilizer costs and dwindling global phosphorus resources, sewage sludge represents a promising method to recover phosphorus from waste streams and reintroduce it into agricultural systems, provided that both economic and environmental feasibility are considered.

3.4 Accumulation of metals in soils after application of sewage sludge

Elevated metal concentrations in soils represent a potential environmental hazard. The presence of high organic matter (OM) content in soils is crucial as it improves soil biodiversity, increases nutrient storage and accessibility, and facilitates the immobilization of metals through complexation. This immobilization reduces the risk of metals leaching into groundwater or surrounding areas. In this study, the majority of metals in the applied sewage sludge were below the maximum limits allowed for agricultural use (Table 1), with exceptions being Zn in SS and Pb in the second-season TS treatment, which exceeded Indian guidelines. Overall, despite these elevated metal levels in the sludge, the concentrations in the amended soils largely remained comparable to the control soils across both seasons, without significant differences. Slight increases in the concentrations of heavy metals such as Zn and Pb were observed following sludge amendments, though these differences were not statistically meaningful. These results imply that the addition of sewage sludge may marginally raise heavy metal levels in calcareous soils, particularly under conditions of high nutrient availability and organic matter. Amendment with SS and TS sludges led to lower levels of Cu, Ni, and Cd compared with control soils, consistent with prior findings by Hasan et al., 2025 [26] and Camps-Saguér et al., 2024 [27], which suggested metal leaching or plant assimilation as the underlying mechanisms. Repeated sewage sludge application can lead to an accumulation of heavy metals in soils over extended periods. Janaszek et al., 2023 [28] demonstrated that agricultural soils exhibited considerable heavy metal buildup after 50 years of consistent sludge use. Similarly, Liu et al.,

2025 [29] observed a marked increase in soil heavy metal concentrations as a result of long-term sludge application. While it is necessary to account for the short-term annual heavy metal load, evaluating the potential long-term impacts, anticipating future accumulation, and maintaining careful monitoring of sludge composition and soil metal levels are equally critical. According to the proposed Indian conditions and recommendations, sludge application rates can be calculated based on sludge chemical quality and the initial concentration of metals present in the soil. This guidance assists in determining safe application thresholds. Most studies to date have investigated heavy metal accumulation in soils and crops, reporting concentrations generally below critical thresholds. Yet, there is a contrasting viewpoint suggesting that such contamination may not meaningfully compromise soil quality in the long term. Although metals may initially accumulate in amended soils, subsequent processes such as weathering, leaching, microbial transformation, precipitation, and plant uptake can reduce their bioavailability and overall concentrations. These processes help reduce heavy metal concentrations and limit their bioavailability, thereby lessening the environmental risks they present. Consequently, soil pH, which strongly influences metal solubility and availability, should be carefully considered when evaluating sludge and other organic matter amendments applied to soils.

3.5 Microbial characterization of control and sludge-amended soils

Extensive research has demonstrated that sewage sludge application can stimulate soil biological activity, particularly by increasing microbial respiration and enzymatic processes. Despite these advantages, careful monitoring of microbial contamination remains a prerequisite for the safe agricultural reuse of sludge. Microbial analysis revealed that sewage sludge amendments did not significantly elevate contamination relative to control soils, except for thermotolerant coliforms in both SS and TS treatments during the first season and increased yeast and mold counts in SS soils in the second season. Thermotolerant coliform concentrations stayed within the regulated limits for soils in season one (Table 3). Notably, these soil microbial findings were not fully aligned with the sludge microbial data, as thermotolerant coliforms were present in amended soils despite their low abundance in the sludge itself. The second-season analysis revealed total coliform presence in control and SS-amended soils, with TS treatments remaining free of coliforms. According to Silva., 2025 [30], tertiary treatment, especially UV irradiation, efficiently reduces pathogens and residual nutrients, potentially explaining the enhanced microbial safety of TS-amended soils. However, the results may also indicate pre-existing soil contamination or inputs from external sources during the cropping season, as commonly observed in open-field systems. Organic amendments have been reported to boost beneficial microbial activity and improve soil microbial community structure. Gil-Martínez et al., 2025 [31]. The study emphasizes that the long-term implications of sewage sludge use in agriculture must be carefully assessed. Despite the absence of detectable total and thermotolerant coliforms in amended soils during the initial season, continuous pathogen monitoring is essential to evaluate potential cumulative risks. This is particularly relevant due to the heterogeneous composition of sewage sludge and the possibility of variations in its quality between seasons. In addition to sludge-related factors such as dose, origin, and

treatment, soil texture strongly influences soil biological activity and nutrient dynamics. Fine-textured soils are more capable of retaining nutrients, which can enhance microbial activity and bio-stimulation processes. Given that the soil in this experiment is clay-rich, such effects are likely to be pronounced. This observation is supported by Curci et al., 2020 [32], who reported increases in soil microbial biomass of up to 28%, particularly in clay loam soils. Sewage sludge application can provide short-term agronomic benefits, including improved microbial activity and nutrient cycling; however, the possible presence of human pathogens and their long-term effects on soil health necessitate careful management to avoid risks to crop safety and consumers.

Table 3 - End-of-Season Microbial Properties of Soils Treated with Secondary and Tertiary Sludge

Parameter	Control – 1 st season	Control – 2 nd season	SS-soil – 1 st season	SS-soil – 2 nd season	TS-soil – 1 st season	TS-soil – 2 nd season
Microbial Characteristics (CFU/g) of Soil						
Total viable count	129874	205179	35729	54829	97284	259046
Total coliforms	0.86	3489	0.92	4259	0.98	0.72
Thermotolerant coliforms	0.82	0.88	32.18	0.59	31.71	0.92
E. coli	0.76	0.72	0.87	0.89	0.92	0.87
Salmonella sp.	N/A	N/A	N/A	N/A	N/A	N/A
Pseudomonas aeruginosa	0.88	0.89	0.74	0.78	0.85	0.88
Enterococci sp.	2549	0.92	659	0.78	3597	0.69
Listeria monocytogenes	N/A	N/A	N/A	N/A	N/A	N/A
Bacillus spp.	19900	654	9562	9419	27196	1592
Sulfate-reducing bacteria	0.81	0.76	0.72	0.59	0.67	0.74
Yeast and molds	65.79	90.47	165.42	99.71	0.89	65.61

3.6 Biomass development, yield response, and grain composition in chick pea

Extensive research has indicated that sewage sludge amendment positively influences plant growth and enhances crop productivity. In many instances, productivity levels achieved

following sludge application were higher than those observed in properly fertilized control treatments. The grain yield and contents were summarized in Table 4 and Figure 2. During the first season, treatment effects on biomass and grain yield were not statistically significant (Fig. 2a), aligning with findings from Shanmugam et al., 2021 [33], which indicated that sewage sludge amendments did not affect chickpea performance. During the second season, plots receiving either SS or TS sludge showed a substantial increase in grain yield compared with the unamended control. On average, the increase in yield ranged from 61 to 76% for both sludge treatments relative to the control, indicating the positive influence of sludge application on crop productivity. Specifically, SS-treated plots yielded 74 g/m², while TS-treated plots reached 81 g/m², both values significantly higher than the 46 g/m² recorded in control plots, highlighting the significant agronomic benefits of sewage sludge in enhancing chick pea yield and supporting sustainable nutrient management. The differences observed between the two growing seasons are likely linked to higher precipitation levels during the second season, which enhanced grain development and enabled crops to utilize the additional nutrients supplied by sludge, whereas water scarcity limited chickpea growth potential in the first season. The observed increase may be attributed to soil enzymatic activity, which plays a key role in nutrient transformation processes and plant–microbial interactions. Enzyme activity is often regulated by soil organic matter (SOM), which facilitates various biochemical reactions that support plant development and productivity. The second-season results agreed with findings reported by Usru et al., 2025 [34], who documented a 45 % increase in rice–chick pea system yields following sewage sludge application. With respect to hay yield, amended soils exhibited significant increases in both plant height (Fig. 2b) and dry biomass (Fig. 2d) compared with the control during both growing seasons. In the first season, hay dry weight increased significantly to 145 g/m² in both SS- and TS-amended soils, compared with 93 g/m² in the control. Likewise, in the second season, hay weight was significantly higher in the TS treatment (162 g/m²) and numerically higher in the SS treatment (149.5 g/m²) than in the control soil (130 g/m²). The substantial increase in hay weight in SS- and TS-amended soils reflects improvements in organic matter content, soil moisture retention, and overall soil quality, leading to enhanced plant growth. Collectively, the findings confirm the positive effects of sewage sludge application on biomass production, hay yield, and plant height. Higher hay yields are particularly beneficial for farmers in this region, as hay can be used as animal feed, sold for additional income, or retained in the soil to further enhance organic matter content and soil quality. In terms of chick pea tiller number, significant differences among treatments were recorded in the first season, with SS producing 7.3 tillers and TS producing 8.1 tillers, both of which were higher than the control value of 4.8 tillers. Results from the second season indicated that control plots produced a higher number of tillers relative to soils amended with SS and TS (Fig. 2f), suggesting that seasonal factors such as delayed rainfall and limited macro- and micronutrient availability may have markedly affected chick pea tillering.

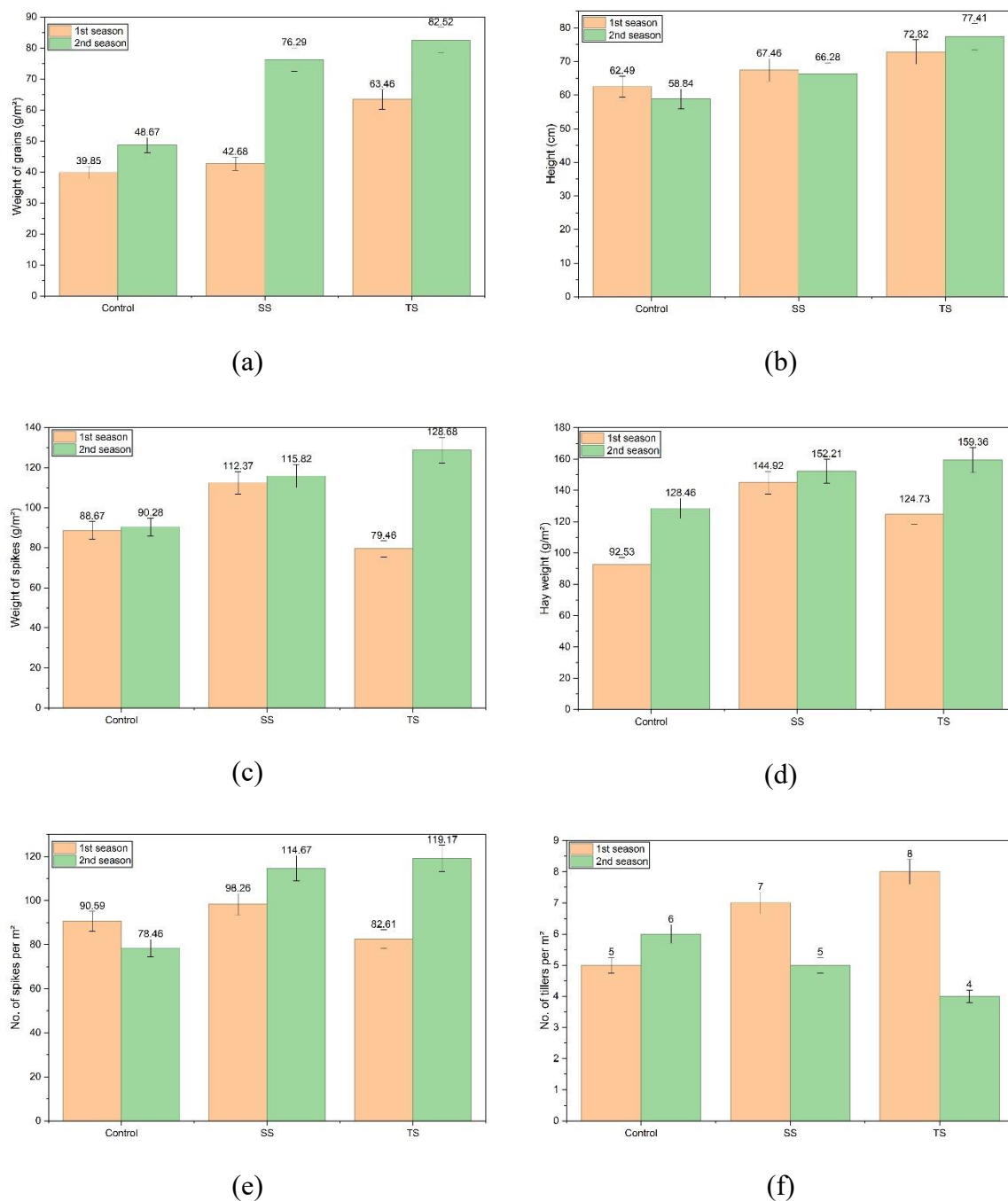


Figure 2 - Average Grain Weight, Plant Height, Spike Weight, Hay Yield, Spike Density, and Tiller Number Across Treatments (Figs. 2a–f).

Grain quality analysis in this study revealed that TS treatment increased crude protein content to 14.5% in the first season, while in the second season, both TS (10.8%) and SS (10.1%) treatments outperformed the control. Crude protein content increased by 1–11% across different treatments and seasons compared with the control, largely reflecting improved nutrient availability, especially in TS-amended soils and, to a lesser degree, in SS plots (Table 1). The pronounced increase in hay weight in SS- and TS-amended soils indicates that enhanced organic matter, improved soil moisture retention, and better overall soil quality under

sludge treatments collectively contributed to increased plant growth and productivity. Accordingly, sewage sludge application had a positive effect on biomass production, hay yield, and plant height in the experimental plots. In addition, TS-treated soils exhibited higher crude fiber content during the second season and lower grain fat levels than the control (Table 4), suggesting that sludge amendments can also influence chickpea grain quality. However, the magnitude of these effects varied seasonally. These findings are consistent with those of Li et al., 2025 [35], who reported enhanced chickpea growth and increased grain fat, ash, and protein contents following sludge application. A single sludge application per plot did not significantly alter the soil's nutrient status; however, it contributed to measurable improvements in the chickpea grain's nutritional composition.

Table 4 - Proximate Composition of Grains Grown in SS- and TS-Amended Soils Across Two Seasons

Parameter	Control – 1st season	Control – 2nd season	SS – 1st season	SS – 2nd season	TS – 1st season	TS – 2nd season
Moisture (%)	10.96	11.27	9.82	12.46	9.8	11.55
Protein (%)	14.02	10.06	13.95	9.97	13.89	9.74
Fat (%)	2.18	2.57	2.19	2.19	1.97	1.95
Crude fiber (%)	2.59	2.11	2.82	1.95	2.54	2.32
Ash (%)	1.48	1.51	1.76	1.42	1.93	1.51
Starch (%)	65.71	60.86	65.82	60.07	63.26	61.57

4 CONCLUSION

The marked increase in hay weight observed in both SS- and TS-amended soils suggests that improvements in organic matter content, soil moisture retention, and overall soil quality under sludge treatments collectively enhanced plant growth and productivity. Overall, these results demonstrate that sewage sludge application positively influenced biomass production, hay yield, and plant height across the experimental plots. Results from the Sholinganallur agricultural field, Chennai, revealed that a one-time sewage sludge amendment favorably influenced soil fertility, increasing organic matter and macronutrient content while avoiding heavy metal accumulation beyond permissible levels. The application of sewage sludge demonstrated notable agronomic benefits, yet microbiological analyses detected heightened levels of total coliforms, yeasts, and molds, stressing the need for vigilant management to prevent adverse environmental and health outcomes. Furthermore, TS treatment resulted in higher crude fiber content during the second season and lower grain fat content compared with the control (Table 4). These findings indicate that sewage sludge application can exert beneficial effects on chickpea grain quality, although the magnitude of these effects is influenced by seasonal variability. Consistent with the findings of Samara et al. (2017), sludge

amendments enhanced overall chickpea growth and productivity and increased grain fat, ash, and protein contents relative to unamended soils. Findings from this research underscore the critical need for comprehensive economic assessments coupled with strong governmental backing—through legislation, subsidies, and educational programs—to promote sustainable sewage sludge management. The development of sustainable sewage sludge management strategies has become a critical global priority, particularly in regions such as Chennai, where limited land availability and environmental constraints restrict conventional disposal options. Consequently, the agricultural reuse of sewage sludge as an organic soil amendment merits further investigation to evaluate its potential for enhancing soil fertility through the enrichment of organic matter, phosphorus, and essential nutrients that support crop growth, particularly chickpea.

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