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Evaluating Treated Sewage Sludge as A Sustainable Fertilizer for Enhanced Tomato Growth

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Abstract

This study evaluates the use of treated sewage sludge as a sustainable fertilizer for enhancing tomato (Lycopersicon esculentum) growth, focusing on its impact on soil characteristics and plant performance. Conducted in Tirran, Isfahan, the research utilized three different mixtures of soil and dewatered sludge at 0%, 20%, and 40% weight ratios. Key soil properties were analyzed, including pH, electrical conductivity, organic carbon, total nitrogen, and available nutrients. Results indicated that the application of 20% and 40% sludge significantly increased organic carbon levels by 128% and 258%, respectively. Total nitrogen content also rose dramatically from 0.08 g/kg (control) to 1.82 g/kg with 40% sludge. The phosphorus concentration soared from 13 mg/kg to 3400 mg/kg with the addition of sludge, indicating its potential as a nutrient source. Notably, tomato plants cultivated in 40% sludge yielded an average of 27 fruits per plant and a total fresh fruit weight of 880 g, compared to just 3 fruits and 50 g in the control group. Statistical analysis revealed significant differences ($p<0.05$) in growth parameters, including plant height and stem diameter, with maximum values recorded at 80 cm and 22 mm, respectively, in the 40% sludge treatment. The study concludes that treated sewage sludge can effectively enhance tomato growth and improve soil fertility, presenting an environmentally sustainable approach to agricultural practices. However, careful monitoring of heavy metal content is vital to ensure safety and compliance with agricultural standards.

Introduction

Wastewater generated from various urban activities cannot be directly discharged into the environment as they contain various organic and mineral pollutants. Consequently, prior to their release into the natural environment, they must undergo a purification process that generates residual sludge. The production of sludge increases with the development of wastewater treatment plants. A major challenge is to find a solution for the economical disposal of these residues while complying with environmental protection and public health constraints [1].

Dewatered sludge can be incinerated, buried in sanitary landfills or used in agricultural lands to make use of its value as soil conditioner or plant fertilizers. Sludge disposal could affect the environment as it could contain harmful components like pathogenic organisms, organic compounds, heavy metals, and excess phosphorus and Nitrogen. Depending on the method of disposal, these effects can be immediate or time-delayed and non-linear [2]. Agricultural valorization of residual sludge can be considered the most suitable recycling method for rebalancing biogeochemical cycles, environmental protection, and significant economic benefits. It aims to conserve natural resources and prevent any waste of organic matter through incineration or land filling [3].

Integrating sewage sludge into agricultural practices not only aids waste management but also fosters ecological balance and sustainability, ultimately benefiting future generations [4]. Sludge from wastewater treatment plants has potential fertilizing properties and can be used to enrich agricultural soils due to its nitrogen, phosphorus, and organic matter content [5].

Sewage sludge contains fertilizing elements and can serve as an energy source. Over the past few decades, this sludge has transitioned from being considered waste to valuable products [1]. At a global level, the possibility of using biosolids (stabilized sewage sludge) as fertilizer has been evaluated on several crops such as tomatoes, wheat, corn, and sugar cane. The results indicate that some biosolids can be used to improve soil structure, reduce the use of chemical fertilizers, optimize costs, and increase crop yields [6]. Mtshali, et al. investigate the potential of sewage sludge from seven wastewater treatment plants in Swaziland for agricultural applications. The sewage sludge was found to be rich in nutrients essential for plant growth, particularly nitrogen and phosphorus, with high levels of organic matter [7].

Sahraoui et al. highlight the dual benefit of using sewage sludge: it serves as a cost-effective fertilizer while addressing disposal challenges associated with wastewater treatment. This practice can reduce reliance on chemical fertilizers and improve soil fertility, particularly in degraded lands [8]. Usman et al discuss sludge (or biosolids) is rich in organic matter and essential nutrients such as nitrogen, phosphorus, and potassium, making it a valuable resource for enhancing soil fertility and crop yield in agricultural practices, particularly in arid and semi-arid regions [9]. The study by Mtshali, et al. shows the application of sludge show to enhance soil properties, such as increasing cation exchange capacity, improving moisture retention, and promoting better plant growth [7].

The study by Njomou Chimi et al., Cameroon, concludes that hydroponically growing tomatoes with treated sewage reduces reliance on chemical fertilizers and optimizes water use, making it a promising alternative in urban agriculture amidst increasing population pressures and environmental challenges [10].

In contrast, the accumulation of heavy metals such as lead (Pb), Cadmium (Cd), and Zinc (Zn) can lead to phytotoxicity, inhibiting plant growth and reducing yields. High concentrations of these metals can interfere with nutrient uptake and cause physiological stress in plants. Suanon et al., investigate the use of treated sludge as a fertilizer in agricultural soil in Benin, West Africa, focusing on the potential risks associated with heavy metal contamination. The study highlights that while sewage sludge is rich in organic matter and nutrients like nitrogen and phosphorus, it also contains significant levels of heavy metals such as Cadmium (Cd), Cobalt (Co), Copper (Cu), Zinc (Zn), Nickel (Ni), Chromium (Cr), Lead (Pb), Iron (Fe), and Manganese (Mn), which pose environmental risks [11]. The results of Mtshali, et al study indicate that heavy metal concentrations were generally within acceptable limits, suggesting low toxicity risks for agricultural use [1].

Janaszek et al. emphasize the environmental risks associated with sewage sludge, notably the presence of heavy metals. Their findings indicate that sewage sludge that does not meet conventional criteria based on total metal content may still have a low risk in the agricultural sector, because the mobility of heavy metals is also a critical issue in assessing their potential impacts [12]. Milojevic et al. highlight that the increasing presence of microplastics in sewage sludge poses a significant risk to soil ecosystems. They argue for stricter regulations regarding the quality of sludge before its application in agriculture, particularly concerning microplastics and other contaminants.

Slekove et al. investigate the presence and dissemination of Antibiotic-Resistant Pseudomonas Aeruginosa (AR-PA) from hospitals to the environment through wastewater. The authors conclude that AR-PA strains are prevalent in the wastewater network, with risks of environmental contamination from treated water and sludge used as fertilizer [13]. Reddy, et al. indicate that tomato seeds (Lycopersicon Esculentum) with vermicomposted sludge, especially those mixed with P. hysterophorus, had a higher germination rate (80%) compared to plain sludge (45%). The biomass of seeds also increased significantly in vermicomposted samples [14].

Reddy, et al. study concluded that utilizing weeds like P. hysterophorus and E. crassipes as additives in the vermicomposting of sewage sludge not only improves the nutrient quality of the sludge but also makes it safe for agricultural use by eliminating pathogens [14] The article by Giannakis et al. examine the sludge to improve tomato plant growth and resistance to the soil-borne fungus Fusarium oxysporum f. sp. radicis-lycopersici (Forl). The research highlighted that the severity of disease caused by Forl varied based on the soil type; outdoor plants grown in sandy soil mixed with biosolid exhibited higher disease tolerance compared to those in clay soil [15].

Castellanos-Rozo et al. discuss the potential of using sludge as a fertilizer for the cultivation tomatoes (Solanum lycopersicum L.) in Colombia. The study compared the fertilizing effects of sludge produced in Sotaquirá's wastewater treatment plant with traditional fertilizers (ABIMGRA and Naturcomplet®-G). Results indicated that dehydrated biosolids significantly enhanced plant growth compared to alkaline biosolids, with similar dry mass to traditional fertilizers [15].

Although the use of sewage sludge to improve soil fertility has been proposed as an environmentally friendly and economical solution for small communities, currently in many parts of the world, including less developed areas of Iran, the sludge produced by wastewater treatment plants is used in agriculture without any processing or adherence to health standards.

The subject of this work is a simple and inexpensive physical method for processing sludge and its direct use in agriculture. Besides, currently due to the unauthorized use of this sludge significant damage is being caused to the environment, and it also poses high health risks. In this research, tomato (Lycopersicon esculentum) is used to evaluate the effect of sewage sludge on plant growth. Furthermore, application of sludge to soil is expected to increase the cation exchange capacity of loamy silt soils which have poor cation binding capacity. It is known that organic matter behaves partially as an amphoteric substance with the negative charge attracting cations and hence increasing the cation exchange capacity of sludge.

Materials and methods

Study area

This study has been carried out in Tirran town in Isfahan province. Tirran is recognized as a hub for greenhouse cultivation and the economic production of vegetable, fruit, and flower products, with over 90% of the output exported to countries bordering the Persian Gulf and Russia. The agricultural products of the Tirran include a variety of crops that thrive due to the region's favorable climate and soil conditions.

This research was conducted at the Water and Wastewater Research Center in Isfahan, affiliated with the Energy Research Institute in 2024. The wastewater treatment plant of Tirran is located at 32°38'21.88"N, 51°11'12.20"E with 1768 meters above sea level. In the region, annual average temperature is approximately 15 to 17 degrees Celsius, while the temperature is around -5 to 35 degrees Celsius through the year. Moreover, the annual Average precipitation of Tirran in about 250 to 350 millimeters, and relative humidity typically varies between 30 to 50 percent throughout the year.

The wastewater treatment plant currently employs as an A^2O biological process with an average flow of 864 m^3/d. This process includes primary sedimentation, biological treatment (anaerobic, anoxic, and aerobic tanks), and secondary settling. Produced sludge is then treated in drying lagoons. A portion of sludge from secondary settling returns to the beginning of the biological system. Excess sludge is sent to thickening to reduce water content, and then sludge is dewatered in the drying bed. Through the treatment, coagulants are not used. In Figure 1 the flow diagram of the Tirran wastewater treatment plant is presented.

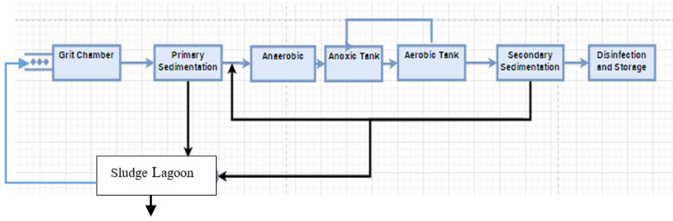

Figure 1: Schematic diagram of WWTP Flow diagram.

Sludge preparation

To mitigate the risks associated with using sewage sludge as fertilizer, several measures (based on the U.S. Environmental Protection Agency (EPA) regulations and guidelines for the use of biosolids in agricultural practices (the 40 CFR Part 503)) can be implemented which are listed in Table 1.

Table 1: Regulatory definition of processes to significantly reduce pathogens (PSRP).

Aerobic digestion	Biosolids are agitated with air or oxygen to maintain aerobic conditions for a MCRT and temperature between 40 d at 20°C and 60 d at 15°C.
Air drying	Biosolids are dried on sand beds or on paved or unpaved basins for a minimum of 3 months. During 2 of the 3 mo, the ambient average daily temperature exceeds 0°C.
Anaerobic digestion	Biosolids are treated in the absence of air between an MCRT of 15 d at temperatures of 35 to 55°C and an MCRT of 60 d at a temperature of 20°C.
Composting	Using either within-vessel, static aerated pile, or windrow composting, the temperature of the biosolids is raised to 40°C or higher for 5 d. For 4 h during the 5-d period, the temperature in the compost pile should exceed 55°C.
Lime stabilization	Sufficient lime is added to raise the pH of the biosolids to pH 12 and maintained for 2 h of contact.

*EPA

In this study, the dried sludge was first crushed and then exposed to direct sunlight for 180 days in an outdoor area (outside the boundaries of the wastewater treatment plant). In the subsequent stage, the sludge was turned monthly from June to November (6 months), while ambient average daily temperature exceeded 0 centigrade. Employing advanced treatment method of air drying according to the U.S. Environmental Protection Agency (EPA), can reduce pathogens and stabilize heavy metals in sludge, making it safer for agricultural use and as a result the produce sludge is categorized as Class B sludge. At the end, the fertilizer was passed through a sieve with a mesh size of 2 millimeters. The process of preparing sludge is shown in Figure 2.

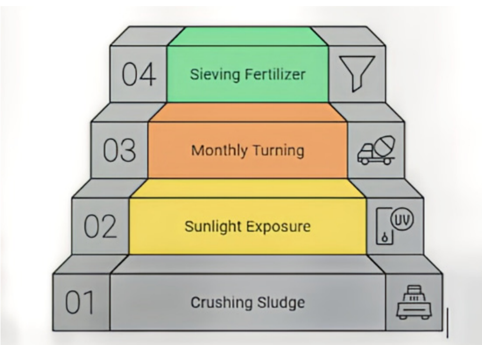

Figure 2: Sludge Preparation Steps.

Furthermore, there was no precipitation throughout sludge processing. According to EPA Standard, air drying reduces pathogens and the prepared sludge can meet the criteria for use in agriculture.

The article by Ngoc Khoi et al combined sludge with a bulking agent (cedar chips) and heated air at 50°C. Analysis showed that the Total Organic Carbon (TOC) and Total Nitrogen (T-N) levels met organic biofertilizer standards, although phosphorus content was slightly below the minimum required level but heavy metals and toxic substances were within acceptable limits [16].

Soil preparation

To ensure the absence of organic materials or coliforms, the soil used was extracted from a depth of 30-60 centimeters from desert lands of natural resources located on the outskirts of Tirran city. According to local evidence and research, no agricultural, residential, or industrial activities have taken place there, and no biological or chemical fertilizers has been added to it. This soil was transported to the research site after passing through a standard sieve number 4 with a mesh size of 4.75 millimeters to serve as the substrate used in the study. Then, air-dried soil samples were mixed with different percentages of sieved dry sludge.

Tomato cultivation

The experiment was carried out in a pot at greenhouse. In this study, plastic pots with a height of 40 cm and a diameter of 30 cm, with an approximate capacity of 3.5 kg of soil, were used. Before filling the pots with soil treatments, a layer of coarse gravel was placed at the bottom of each pot as drainage, and the pots were filled with the prepared soil. Preparation of tomato seedlings seeds of tomato (Lycopersicon esculentum var. Falcato F1) were surface sterilized with 2% (w/v) sodium hypochlorite for 10 min and then germinated.

Figure 3: Phots of experiment. **(A)** Sieving Soil; **(B)** Tomato Cultivation.

In the beginning, 12 pots were cultivated, then one pot that showed less growth or had dried out was removed after one month from each series. Thus, 9 pots, including three series, were kept for further research while the number of pots was 12 at the beginning of the experiments. In Table 2 experiment design scenario and in Table 3 characterization of soil in each experiment are presented.

Table 2: Experiments Design Scenario.

Experiment	Number of Pot (Sample 1,2 and 3)	Weight ratio of sludge to soil (%)
Test 0 (Soil)	3	0
Test 1	3	20
Test 2	3	40

During the growth period in the greenhouse, weeding was done manually, and no fertilizers or other chemical substances were used. The pots were irrigated with municipal drinking water, every three days during the first 30 days after transplanting, and then approximately every four to five days, up to the soil's field capacity, which was determined by weighing the pots. Soil acidity was measured with a pH meter, electrical conductivity with a conductivity meter, percentage of organic carbon by Walkley and Black method, total nitrogen using a Kjeldahl apparatus, available potassium by flame photometry, heavy metals with soil extraction by DTPA, heavy metals using atomic absorption (model B1100 Elmer Perkin) [17,18].

Table 3: Characterization of Soil in each Experiment.

Feature	Unit	Soil	Sludge	Test 1	Test 2
pH	-	7.68	6.4	6.7	6.5
Electrical conductivity	ds/m	1.7	2.12	1.83	1.87
Soil texture	-	Lomi silt	-	-	-
Moisture	%	1.1	0.2	7.5	8.8
Nutrient					
Organic carbon	ppm	3.11	21.7	7.1	11.2
Total nitrogen	ppm	0.08	4.28	1.1	1.82
Soluble phosphorus	ppm	13.09	3400	710	1345
Soluble potassium	ppm	210.13	1700	495	798
Soluble iron	ppm	7.62	60	17.5	29.5
Soluble manganese	ppm	8.81	115	31	50.5
Heavy Metal					
Soluble zinc	ppm	2.31	0.87	1.9	1.8
Soluble copper	ppm	3.02	0.13	2.5	1.9
Lead	ppm	0.79	1.1	0.85	0.81
Cadmium	ppm	0.08	0.26	0.12	0.14

Throughout the plant growth period and simultaneously with the harvest, the growth characteristics of the plants, including, the total number of fruits, total fresh fruit weight, number of branches, main stem diameter, and plant height. Tomato harvesting began 60 days after planting and continued for 30 days.

Table 4: Growth Characteristics of Tomato.

Experiment		Total number of fruits	Total fresh fruit weight (g)	Number of branches	Main stem diameter (mm)	Plant height (cm)
Test 0	Pot 1	5	110	4	7	19
Test 0	Pot 2	3	50	4	8	24
Test 0	Pot 3	0	0	5	7	14
Test 1	Pot 1	17	550	13	13	71
Test 1	Pot 2	15	685	18	13	68
Test 1	Pot 3	20	510	17	18	80
Test 2	Pot 1	21	686	15	18	69
Test 2	Pot 2	27	880	18	16	43
Test 2	Pot 3	19	690	27	22	95

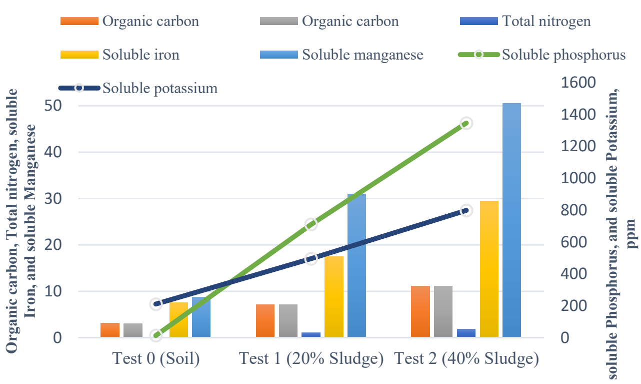

Figure 4: Characterization of Soil in each Experiment.

Table 5: Statistical Analysis of different soil in the experiment (One-Way ANOVA).

Parameter	Compare meaningful difference		
	Changing Soil to Sludge 20%	Changing Soil to Sludge 40%	Changing Sludge 20% to Sludge 40%
pH	0.171	0.112	0.729
Electrical conductivity	0.418	0.309	0.804
Organic carbon	0.001a	0.0003 a	0.006 a
Total nitrogen	0.00009 a	0.0001 a	0.004 a
Soluble phosphorus	0.00007 a	0.0001 a	0.002 a
Soluble potassium	0.001 a	0.0002 a	0.005 a
Soluble iron	0.001 a	0.0002 a	0.004 a
Soluble manganese	0.00028 a	0.0001 a	0.005 a
Soluble zinc	0.076	0.039 a	0.544
Soluble copper	0.083	0.006 a	0.030 a
Lead	0.421	0.775	0.587
Cadmium	0.009 a	0.003 a	0.133

At the end of the experiment, the results were statistically analyzed using SPSS software. After determining the significance of the parameters.

Results and discussion

The results of the analysis of sludge samples collected from the Tirran wastewater treatment plants are presented in Table 3 and in Figure 4 by performing one-way ANOVA in SPSS. The statistical analysis of these data is also presented in the Table 5.

Soil characteristics

pH: The research highlights the significance of pH in determining the bioavailability of metals in soil, especially those in labile forms. Applying sludge to soils with low pH (below 5) can further lower pH levels, which is not advisable unless the sludge is stabilized with lime. Ideally, crops thrive in soil with a pH between 6 and 7, where nutrients are most accessible. In this study, adding sludge decreased soil pH from 6.78 to 6.7 and 6.5 with 20% and 40% sludge, respectively. However, these changes were not statistically significant at the 95% confidence level, suggesting minimal impact on soil pH.

The pH of sewage sludge varies but generally falls within slightly acidic to neutral ranges, depending on treatment and additives [19]. Maintaining a soil pH above 6.5 for sludge-amended soils is often recommended [20]. The median pH of the sludge samples in this study was 6.4, indicating that further stabilization is unnecessary for soils that are not excessively acidic or alkaline.

Comparatively, a study by Mtshali et al. found that sludge samples typically ranged between 6 and 7, suggesting they are suitable for agricultural use without additional stabilization [7]. Additionally, Iticescu et al. discuss utilizing sewage sludge as a soil amendment in Romania, recommending calcite and dolomite to maintain pH and mitigate heavy metal mobility while enhancing nutrient availability [21]. These findings collectively emphasize the importance of careful pH management in sludge applications to maximize nutrient availability and minimize environmental risks.

EC: The study found that adding 20% and 40% sludge to the soil did not significantly alter its Electrical Conductivity (EC) at the 95% confidence level. This suggests that the sludge did not greatly influence the soil's hydraulic properties. The increase in soil EC with sludge application is primarily attributed to the high salt content in the sludge, which can also hinder plant growth [7]. In this research, the EC levels in tests 1 and 2 rose due to the sludge's higher EC compared to that of the soil.

Organic carbon

The organic carbon content in the sludge samples is 21.7 mg/l, while soil measures only 3.11 mg/l. The sludge, which was not anaerobically digested and had undergone air drying, shows promising potential when added to the soil. Incorporating sludge at 20% and 40% weight ratios significantly boosts the soil's organic carbon levels. In a related study, Nabil Charchar et al. explored the impact of sewage sludge on the growth and biochemical traits of the Rio Grande tomato cultivar. Their pot experiments tested sludge at concentrations of 25%, 50%, and 75%, compared to a control without sludge. Results indicated that sewage sludge had a notably higher total nitrogen content (20.58 mg/kg) than agricultural soil (2.09 mg/kg), although it had lower phosphorus and organic matter levels [22]. Similarly, Sahraoui et al. found that applying sewage sludge enhanced the physico-chemical properties of soil, especially increased organic content [8]. These findings align with other research highlighting sewage sludge's benefits as a soil amendment, demonstrating its potential to enrich soil nutrient profiles and improve plant growth.

Nitrogen and phosphor: Adding sludge to soil at 20% and 40% weight ratios significantly boosts nitrogen levels. The nitrogen content ranged from 0.08 grams per kilogram at the lowest to 1.82 grams per kilogram with 40% sludge. This indicates that incorporating sludge enhances soil nitrogen substantially. On the other hand, only a small fraction of total nitrogen is readily accessible to plants after applying sewage sludge. Over time, through mineralization, nitrogen is converted into forms that plants can use [23]. While sludge offers essential nutrients, excessive nitrogen or phosphorus can create nutrient imbalances detrimental to plant growth [7]. These results are in accordance with other studies, such as Smith et al. (2020), which highlighted the importance of balanced nutrient application for optimal plant health.

In this study, the phosphorus concentration in sludge is much greater than that in soil, with sludge containing roughly 3,400 grams per kilogram compared to about 13 grams per kilogram in soil. When sludge is mixed into the soil at a 20% ratio, the phosphorus concentration rises by approximately 540 times, and at a 40% sludge ratio, it increases to around 10,270 times. This highlights the opportunity to use the phosphorus found in sludge as a fertilizer for growing plants. Furthermore, the addition of sludge to soil at both 20% and 40% by weight significantly enhances the phosphorus levels in the soil. The phosphorous content in sludge is in average of 3400 mg/l. Phosphorus availability partly depends on the extent of treatment the sludge underwent. Phosphorous is an essential nutrient needed for plant growth and is required in large quantities by plants while it is relatively immobile in soils [7].

Potassium, iron, and manganese

Adding sludge to the soil at 20% and 40% weight ratios significantly boost potassium levels, with the potassium content increasing from a low of 210 grams per kilogram to 495 grams in the 20% sludge and 798 grams in the 40% sludge. This increase is due to sludge containing potassium concentrations approximately eight times higher than that of soil. Similarly, iron levels also rose dramatically with sludge addition. The lowest recorded iron concentration was 7.62 grams per kilogram, while the 40% sludge enhanced it to 29.5 grams per kilogram. This shows that incorporating sludge can notably improve iron content in soil. Moreover, sludge enhances magnesium levels, which is crucial for plant health alongside nitrogen, phosphorus, and potassium. It's important to note that micronutrients like manganese can be deficient in some soils, particularly when the pH exceeds 6.2, limiting its uptake in alkaline conditions [7].

Heavy metal

This study examined heavy metals in sewage sludge to assess its potential toxicity for agricultural use. Heavy metals like cadmium and lead are highly toxic to humans and animals but less so to plants. The sludge showed lower levels of zinc and copper, while cadmium and lead were found at higher averages compared to soil samples. Notably, adding sewage sludge reduced soil zinc content. Initially, zinc was at 2.31 grams per kilogram, dropping to 1.9 grams after adding 20% sludge and further to 1.8 grams with 40% sludge. However, these changes were not statistically significant at the 95% confidence level. Copper levels also decreased with sludge addition, but only the reduction with 40% sludge was statistically significant. Lead levels in soil dropped from 3.02 grams per kilogram to 2.5 grams after 20% sludge and further to 1.9 grams with 40% sludge, but these changes were not statistically significant. Moreover, cadmium levels increased with the addition of sludge, particularly significant at the 20% level in the first test. Importantly, all heavy metal concentrations remained below the EPA's permissible limits (e.g., lead at 2.8 ppm and cadmium at 1.4 ppm). While zinc, nickel, and copper can be harmful to plants at high concentrations, they were generally low in sludge, posing little risk for agricultural applications. However, elevated heavy metal levels can negatively impact soil biology and fertility.

Suanon et al. (2016) found heavy metal concentrations in sludge exceeding agricultural limits, with mobile forms of metals like cadmium and lead posing a risk for soil contamination [11]. Similarly, Ouadah et al. (2022) noted that heavy metal concentrations in sludge mixtures remained below European regulatory thresholds, indicating a lower risk of accumulation and contamination. These contrasting results highlight the importance of monitoring heavy metal levels in sludge before its application in agriculture [8].

Microbiological analysis of tomatoes

Microbiological testing was conducted on the tomatoes to determine if they were contaminated with pathogenic bacteria originating from the spread sludge. As sludge is excavated from the sludge lagoon of wastewater treatment in the warm season, the microbiological can be outnumbered than sludge in the cold season. The values of microbiological tests are presented in Table 6.

Coliform bacteria, total coliforms in soil, and parasite eggs: Table 6 reveals that soil samples have the highest levels of fecal coliforms and total coliforms, measuring 583 and 240 MPN per 100 mL, respectively. This is twice higher than soil mixed with 20% sludge. Although adding sludge up to 40% increases coliform counts, a 40% sludge mixture results in a total coliform level of 435 per 100 mL, about 25% lower than that of the pure soil. Notably, the egg count for parasites in both soil and sludge mixtures was nearly zero. In comparison, Reddy et al. found that vermicomposted materials with E. crassipes and P. hysterophorus had nearly double the total microbial count compared to plain sludge, yet no E. coli was detected, indicating a reduction in pathogens [14]. Similarly, Amorós et al. studied pathogenic protozoa in sewage sludge from various Spanish wastewater treatment plants, discovering that 86.6% of raw sludge samples contained Cryptosporidium oocysts and Giardia cysts, with stabilization processes failing to consistently eliminate these pathogens [24]. Conversely, Hadji et al. noted that tomatoes grown in sludge-treated soil showed no pathogenic bacteria, suggesting that properly treated sewage sludge can be safely used in agriculture [25].

Table 6: Statistical Analysis of different soil in the experiment.

Parameter	Unit	Test 0	Test 1	Test 2
Fecal Coliform	MPN/100 mL	240	115	185
Total Coliform	MPN/100 mL	583	289	435
Parasite Eggs	MPN/100 mL	0	0	0

Effect on tomato growth

Tomato growth in this research is shown in Figure 5.

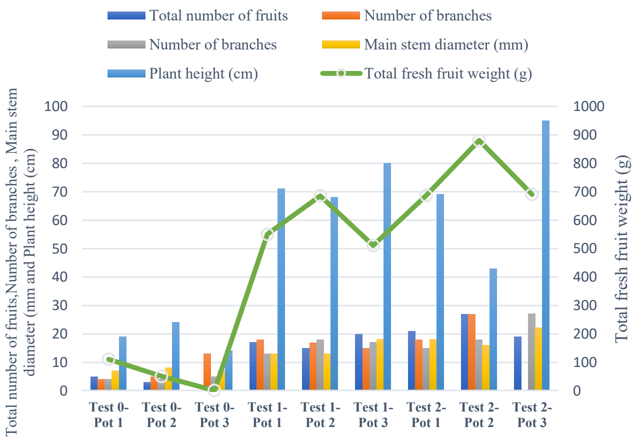

Figure 5: The Tomato Growth Indicator in Soil, 20% and 40% Sludge.

Fruit numbers and weight: According to the results, tomatoes treated with 40% sludge produced the highest quantity of tomatoes (19 to 27 fruits), while plants in the control soil recorded 0 to 5 fruits per plant. Nicolas et al 203 indicate that the application of fecal sludge biochar significantly increased the yield of tomato plants. When combined with fertilizer, the yield was 298% greater than the control soil, while biochar alone increased yield by 1060 [26].

The fruits harvested at the end of the experiment have different weights. It was observed 752 g/fruit for the sludge with 40% sludge, and 581.6 for 20% sludge, and 53.3 g/fruit for the control group of soil.

Branch number and main stem diameter

The number of branches is a good indicator of proper watering and mineral nutrition and biomass production by the plant. The highest number of branches is recorded for plants in the 40% sludge, with an average of 20 branches per plant. For plants in the control soil, a lower number of branches is recorded with an average of 4.3 branches per plant. Besides, the thickest diameter of main stem branches is recorded for plants grown in the 20% sludge, with an average of 73 mm diameter. For plants in the control soil, a lower number of branches is recorded with an average of 19 mm. Sahraoui et al represent that tomato plants grown in the 40% sludge mixture exhibited the best growth, with wider stem diameters compared to other mixtures and the control group. Tomatoes grown in this mixture exhibited superior biometric measurements with a maximum stem diameter of 6 cm while the control group (0% sludge) showed a stem diameter of 2.30 cm [8].

Plant height

The results show (Figure 5) that tomatoes grown in soil with 40% sludge reached an average height of 22 cm, while those in control soil only grew to about 8 cm. Velli et al. found that adding biochar from sewage sludge significantly improved soil quality and boosted plant growth, particularly increasing the dry weight of stems, leaves, and roots [27]. Similarly, Douaer et al. reported that tomato plants grown with a soil-sludge mixture achieved a maximum height of 97 cm [28]. Sahraoui et al. also noted that tomatoes in a 40% sludge mix displayed optimal growth, reaching heights of 78.5 cm and producing an average of 32 leaves, compared to other mixtures and the control group [8]. Additionally, Hadji et al. indicated that sewage sludge application significantly enhanced tomato growth, with the tallest plants measuring 97 cm, outperforming both control and mineral fertilizers [25]. Moreover, the study by Sahroui et al. found that a 40% sludge mixture resulted in a maximum height of the tomato by 78.50 cm while the figure for the control group (0% sludge) was 36.20 cm [8].

While increasing sludge content to 50% improved soil nutrient levels, it is crucial to compare this with Janson's nutrient solution, which contains a broader range of nutrients. The study concluded that combining sludge with a nutrient solution is an effective strategy for supporting tomato growth and yield, while also offering an environmentally friendly way to manage waste sludge.

Conclusion

This study underscores the potential of utilizing treated sewage sludge as a sustainable and effective fertilizer for enhancing tomato (Lycopersicon esculentum) growth. Through a straightforward and cost-effective physical processing method, the treated sludge demonstrated significant improvements in soil properties and nutrient availability, leading to remarkable increases in tomato yield. The application of 20% and 40% sludge not only enriched the soil with essential nutrients, such as nitrogen, phosphorus, and potassium but also contributed to an overall improvement in soil structure and fertility.

The findings reveal those higher concentrations of sludge correlate with enhanced plant metrics, including total fruit production, plant height, and stem diameter, highlighting the importance of sludge as a nutrient-dense organic amendment. Notably, the study alleviates concerns regarding heavy metal accumulation in the soil, as the levels observed remained within acceptable limits, ensuring the safety of agricultural practices that incorporate treated sewage sludge.

Moreover, this research advocates for the integration of treated sewage sludge in agricultural systems, particularly in less developed regions, where it offers an economically viable alternative to chemical fertilizers. However, it is essential to continue monitoring heavy metal concentrations and microbial levels to maintain safety standards and protect environmental health. The development of local sludge processing facilities is recommended to facilitate the safe and beneficial use of sewage sludge, promoting sustainable agricultural practices that can meet the challenges of food production in a growing global population.

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