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Comparative evaluation of treated sewage sludge and chemical fertilizers on soil quality and agricultural productivity

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ABSTRACT

In the context of sustainable and circular agriculture, this study assesses the comparative impact of soil amendment with treated sewage sludge and chemical fertilizers on soil quality and fertility. Three agricultural plots of equal size were monitored: a control plot, a plot amended with sludge from a wastewater treatment plant, and a third plot amended with chemical fertilizers. A physicochemical and bacteriological characterization of the sludge was carried out over six months, followed by a 12-month soil analysis campaign based on ISO standards. The parameters evaluated included organic matter, total nitrogen, phosphorus, potassium, C/N ratio, electrical conductivity, pH, water retention, microbial biomass, and crop yield. The results show that the treated sludge significantly improves organic matter content (+133%), water retention (+20%), and crop yield (+62%) compared to the control plot, while offering performance comparable to or even superior to that of chemical fertilizers. In the long term, sludge improves soil structure and fertility, although electrical conductivity increases slightly. This study demonstrates the potential of treated sludge as a sustainable input for circular agriculture. These findings highlight the potential of biosolids for sustainable agriculture in semi-arid regions.

Keywords: sustainable agriculture, chemical fertilizers, sewage sludge, fertilization, soil quality.

INTRODUCTION

The acceleration of the adaptation of conventional and unconventional wastewater treatment plants is widely used in different countries to treat raw wastewater for reuse in the agricultural sector, with the aim of preserving and protecting the environment against immigration and the disappearance of all aquatic species. Wastewater treatment plants are not limited to improving the quality of treated water, but also lead to an increase in the production of residual sludge containing pathogens. It is therefore mandatory to eliminate harmful elements in order to reduce health and environmental risks, improve beneficial use characteristics, and ensure value recovery and sustainability in the agricultural sector (Chen et al., 2021, Karimi et al., 2024, Marchuk et al., 2023).

Solid and semi-solid matter from wastewater treatment plants has also become a major challenge worldwide. Öztürk's study on the use of sewage sludge in agriculture showed that land treated with sludge had increased concentrations of nitrogen, phosphorus, and potassium in the soil depending on the amount of sludge applied, which encourages the reuse of this material in agriculture (Öztürk et al., 2020).

In the same context, the study conducted by Delibacak showed that the use of treated sludge from wastewater treatment plants is a low-cost and effective alternative to methods such as chemical fertilizers. However, this study highlighted the disadvantages of this alternative application, as it poses serious threats, including the presence of pathogens, heavy metals, and organic pollutants that hinder agricultural production. From an environmental perspective, it is necessary to reuse sludge in order to recycle valuable plant nutrients (nitrogen, phosphorus, and potassium), but each country is required to comply with regulations and standards regarding the use of sewage sludge as a fundamental solution for the use of this material in the agricultural sector (Delibacak et al., 2020).

In Morocco, agriculture plays an essential role in the Moroccan economy. In 2023, it accounted for 11.1% of Morocco's GDP, with an added value of 12.6% in 2023. The agricultural sector employs almost 40% of the working population, which means that this sector plays an important role in the development of the Moroccan economy, with an emphasis on rural development and food security linked to the agricultural sector. In terms of increasing production in this sector, Morocco uses a significant amount of chemical fertilizers to ensure agricultural production and protect plants from disease. However, the cost of these expensive fertilizers has a significant impact on the quality of the finished product and the cost of goods, which necessitates the use of alternative products for soil improvement, such as sewage sludge, which contains a significant amount of organic matter, major nutrients (nitrogen, phosphorus, and potassium). Increasing the water retention capacity of soils helps protect the water table while optimizing the use of water for agricultural irrigation. However, climate change and declining rainfall are forcing the use of sewage sludge, which increases water retention for plants in order to protect water resources and reduce water waste (Ouraich et al., 2018).

According to the FAO report on the management and agricultural use of sewage sludge in Morocco, the installation rate of wastewater treatment plants increased from 7% in 2006 to 58% in 2024, significantly increasing the volume of solid and semi-solid matter from wastewater treatment plants. Sewage sludge is rich in soil fertilizers that increase agricultural production, such as organic matter, mineral matter, C/N ratio, phosphorus, potash, and nitrogen. Our study is a comprehensive overview of the relationship between sludge and agricultural production (FAO., 2024).

In addition, few studies in Morocco have focused on soil fertilization and agricultural yield on three plots (one control, one amended with sewage sludge, and one amended with chemical fertilizers) by analyzing soil fertility parameters (OM, N, P, K, C/N, EC, pH), biological parameters (microbiota, pathogens), and agronomic parameters (agricultural yield and water retention), provide a general idea of the three main terms: soil, fertility, and agricultural production. Taking the example of the study conducted by Abdelmajid, which focused on the effects of sludge amendment rates on the concentrations of major soil nutrients, the relationship between these rates and soil fertility was highlighted. The results showed that the use of sewage sludge improves agricultural production but introduces heavy metals such as Zn, Cu, Pb, Ni, and Cd. The results showed that the second soil performs better in terms of agricultural production, fertility, and soil quality while avoiding the risk of soil contamination by pathogens such as micro bacteria and heavy metals. Compared to Abdelmajid's study, our study is a more comprehensive and holistic approach with favorable results on soil fertility (Achkir et al., 2022).

Even at the international level, studies remain limited in this area when it comes to analyzing the various parameters of the quality and fertility of different types of agricultural land. Take, for example, Martyna Buta's study on the use of treated sewage sludge in agriculture as a soil amendment to improve soil quality and enrich it with organic matter in order to fertilize agricultural land. This research analyzes emerging contaminants present in treated sewage sludge, chemical contaminants, and genetic determinants of resistance to these compounds. Another study conducted by William Ramos da Silva on the effects of sewage sludge stabilization processes on soil fertility, mineral composition, and corn grain yield in successive crops is based on the evaluation of two forms of stabilization (TSS) on shoot biomass, yield, and nutrient concentration in soil and plants in three successive corn crops. The results of this study show that chemical stability (CSS) and compost stability (TSS) can be achieved by adding calcium oxide and co-composting with plant residues, respectively. These studies remain limited as they focus on few parameters analyzed on a single type of soil or crop. Our study provides an integrated and holistic assessment, analyzing key soil parameters, fertility, and agricultural production across three different types of plots. (da Silva et al., 2021, Rigby et al., 2016, Buta et al., 2021).

Our study is based on a comparison of three soils, each covering an area of one hectare: natural soil without added fertilizer (control), soil tested with added sewage sludge, and a third plot with chemical fertilizers. This comparison is based on various physical, chemical, and biological parameters such as organic matter, main nutrient content (nitrogen, phosphorus, potassium), carbon/nitrogen ratio (C/N), water retention, pathogenic bacteria, cation exchange capacity, electrical conductivity, and agricultural yield of the three plots.

The results of this study show that the plot using sewage sludge remains more effective in terms of yield and soil fertilization than the other plots.

METHODOLOGY

Characterization of soil parameters

It is essential to analyze the control soil before adding chemical fertilizers or sewage sludge in order to characterize the parameters essential to soil fertility. Table 1 illustrates the different values of the parameters for the control soil. The parameters analyzed are organic matter, nitrogen content, phosphorus concentration, potassium, carbon-nitrogen ratio, cation exchange capacity, electrical conductivity, hydrogen potential, water retention, pathogens, and crop yield.

Sludge characterization

The recovery and reuse of sewage sludge require the characterization of its physical, chemical, and bacteriological parameters to identify the sludge before it is used on agricultural land.

As part of this study, sludge from wastewater treatment plant was monitored for a period of six months in order to better characterize it before beginning trials on agricultural soils. Various parameters were analyzed, including organic matter (OM), total nitrogen (TN), total phosphorus (TP), potassium (K), carbon/nitrogen ratio (C/N), hydrogen potential (pH), electrical conductivity (EC), copper (Cu), zinc (Zn), pathogens, and moisture.

These parameters provide an indication of soil fertility and agricultural land quality after the addition of this treated sludge (Table 2).

Description of the plots studied

To study the impact of elements added to the soil on fertilization and agricultural yield, three agricultural plots were dedicated to this comparative study on monitoring key parameters in the agricultural sector. One plot served as a control, another was characterized by the addition of sewage sludge, and the third by the addition of chemical fertilizers.

Figure 1 illustrates the three plots: (a) control plot, (b) addition of purifying sludge and (c) addition of chemical fertilizers.

Sampling used

The study of fertilization on the three selected plots (control plot, plot with added sewage sludge, and plot with chemical fertilizers) is based on various biological and physicochemical parameters, as well as on the agricultural yield of each plot with the C/N ratio. The analyses were carried out over a period of one year, covering the four seasons of the year to highlight seasonal climatic conditions. Samples were taken twenty days per month for one year (240 days of observation), with each analysis being repeated three

Table 1. Analysis of parameters for control soil

Parameters	Control
*MO (%)	1.2
*TN (mg/kg)	450
*TP (mg/kg)	130
*K (mg/kg)	220
C/N	12
*CEC (mg/kg)	10
pH	7.1
EC (dS/Cm)	0.85
Water retention (%)	35
Pathogens (UFC/g)	Faible
Yield (kg/ha)	2100

Note: *MO – organic matter; *TN – nitrogen levels, *TP – phosphorus levels; *K – potassium; *CEC – cation exchange capacity; *EC – electric conductivity.

Table 2. Physico-chemical and bacteriological characterization of sewage sludge

Parameters	Valeurs
*MO (%)	2.16
*TN (mg/kg)	783
*TP (mg/kg)	395
*K (mg/kg)	488
C/N	10.61
pH	7.23
EC (dS/Cm)	2.4
Cu (mg/kg)	48.83
Zn (mg/kg)	125.33
Pathogens (UFC/g)	$1.5 \cdot 10^3$

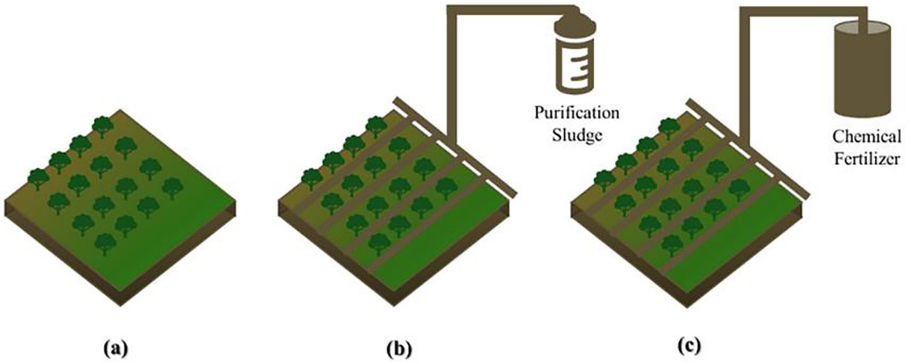

Figure 1. Agricultural surface: (a) control, (b) sewage sludge and (c) chemical fertilizers

times to ensure the quality and performance of the analyses within the laboratory.

Soil samples were taken from the three plots at a uniform depth of 0 to 20 cm; this depth being chosen because most microbial activity and nutrient exchange take place between the soil and the plant roots. The samples were taken using a soil corer to avoid any contamination of the soil and thus any errors in the results for the various parameters. The samples were then stored in airtight bags to ensure proper storage conditions, and the bags were labeled for easy identification during laboratory analysis.

The plots studied are subject to a semi-arid climate, as they are in Morocco, characterized by an average temperature of 20 °C with rainfall varying between 350 and 450 mm/year and an average humidity of 85%, as the plots are in the Ghareb Kenitra region of Morocco.

Analytical methods

Physicochemical and biological analyses

Sampling and analysis of these soil parameters are carried out using standardized methods; organic matter, total nitrogen, total phosphorus, and potassium are analyzed in accordance with ISO 10694, ISO 11261, ISO 11263, and ISO 11260 standards. In addition, cation exchange capacity, hydrogen potential, electrical conductivity, water retention and pathogenic bacteria are analyzed in accordance with the following standards: ISO 23470, ISO 10390, ISO 11265, NF 13041, and ISO 4833-1, respectively (Jouquet et al., 2016).

Analytical equations

- Organic matter (ISO 11465 :1993)

$$OM\ (\%) = \frac{M_{105} - M_{550}}{M_{105}} \times 100 \quad (1)$$

where: M_{105} – mass of sample dried at 105 °C; M_{550} – mass of ash after ignition at 550 °C.

- Organic carbon (ISO 23400 :2021)

$$C_{org} = \frac{OM\ (\%)}{1.724} \quad (2)$$

where: OM – organic matter; 1.724 – conversion factor (Van bemmelen factor).

- Carbon to nitrogen ration (ISO 23400 :2021)

$$\frac{C}{N} = \frac{C_{org}}{N_{tot}} \quad (3)$$

where: C_{org} – organic matter (%); N_{Tot} – total nitrogen (%).

- Crop yield (ISO 23400 :2021)

$$Y = \frac{W_p}{A} \quad (4)$$

where: W_p – weight of harvested product (kg); A – cultivated area (m^2 or ha).

- Formula (for pathogenic bacteria) (ISO 15213-2 :2023)

$$\frac{N_{colonies} \times F_{dilution}}{m_{sample}} \quad (5)$$

where: $N_{colonies}$ – number of colonies counted on a selective medium specific for the pathogen; $F_{dilution}$ – dilution factor used during plating; M_{sample} – mass of the inoculated sample (g).

Statistical analysis

The multivariate statistical method applied to the samples aims to analyze the effect of irrigation on two plots, one irrigated with well water and the other with treated water, as well as its environmental impact on the soil. This study is based on the use of various statistical tests, including ANOVA, descriptive statistics, radar charts, and scatter plots.

RESULTS AND DISCUSSION

The addition of elements to agricultural land, such as chemical fertilizers or sewage sludge, alters the physical, chemical, and bacteriological properties of the soil. In order to study the impact

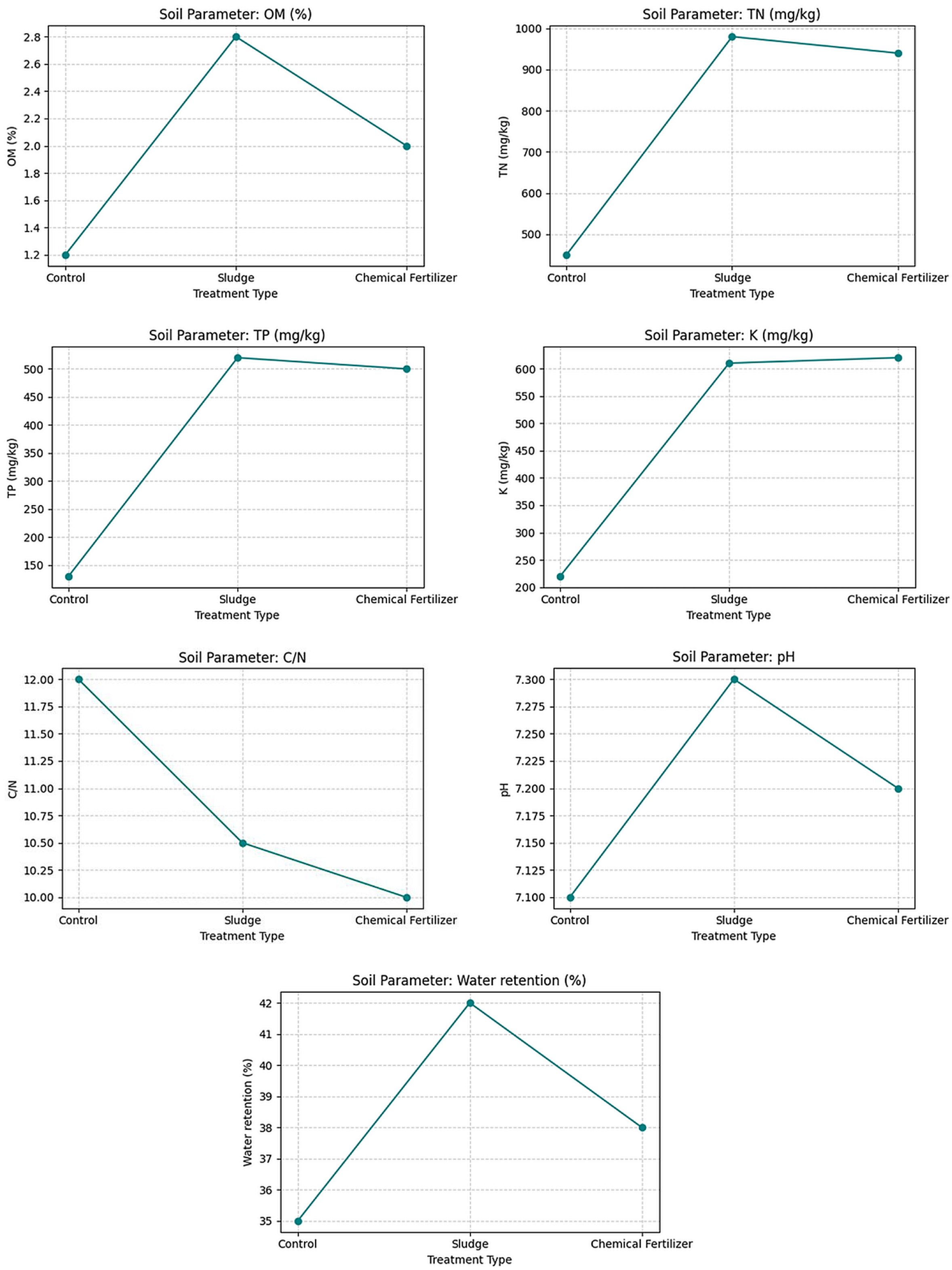

Figure 2. Descriptive analysis of 3 agricultural plots

of these elements on the soil, analyses are carried out to ensure soil hygiene and quality.

Various parameters were analyzed, including organic matter, total nitrogen, total phosphorus, potassium, C/N ratio, hydrogen potential, water retention, pathogens, and yield. These analyses were performed on three types of soil: a control soil, soil amended with sewage sludge, and soil amended with chemical fertilizers.

To complete this study, statistical analyses were performed to thoroughly analyze the impact of these added elements on agricultural yield and soil fertilization on the three agricultural lands.

Figure 2 illustrates the test by descriptive analysis of the various farmlands according to physico-chemical and bacteriological parameters.

The organic matter content of soil treated with sludge is higher (2.8%) than that of soil treated with chemical fertilizers (2%), with a difference of 133% between sludge and the control, showing that soil treated with sludge will be rich in organic carbon, thereby improving fertilization, soil quality, and water retention. In addition, soil amended with sewage sludge contains 980 mg/kg of TN, compared to 940 mg/kg for soil amended with chemical fertilizers. This means that soil amended with sludge promotes and improves plant development.

The total phosphorus content for soil amended with sewage sludge is 520 mg/kg, compared to 500 mg/kg for soil amended with chemical fertilizers, which means that soil amended with sludge promotes root growth and flowering. The potassium content also varied between 610 mg/kg for soil enriched with sewage sludge and 620 mg/kg for soil enriched with chemical fertilizers. These values are higher than those for the control soil (220 mg/kg). With a difference of 177% between the sludge-enriched soil and the control soil, sludge provides a balanced supply of trace elements.

The C/N ratio is almost identical for both soils amended with chemical fertilizers and sludge, which means that there is sufficient nitrogen for the plants without blocking their pores with excess carbon. The water retention value also increased between the control soil and the soil treated with sludge (35% vs. 42%), which means that the plants became more resistant to drought and able to retain a significant amount of irrigation water.

Based on the characterization of all these physicochemical and bacteriological parameters for the three soils, agricultural yield is high for soil amended with sewage sludge from the wastewater treatment plant. This interpretation is confirmed by the agricultural yield of 3,400 kg/ha, compared to that of the control soil of 2,100 kg/ha.

Comparing these results with other studies in literature, we find that they confirm Hassan's approach, which is based on the effectiveness of organic fertilizers from wastewater treatment plants on plants. The results of this study show that soil amendment with these sludges remains sustainable and effective in terms of soil quality, fertilization, and agricultural production, while limiting the risk of contamination by harmful elements such as pathogens and heavy metals. In summary, fertilizers based on sewage sludge have a positive impact on plant growth, productivity, and development (Hassan et al., 2025).

However, to improve the impact of sewage sludge and chemical fertilizers on the soil, it is necessary to monitor other key parameters such as conductivity and salinity, microbiota, and nitrates for the three agricultural plots.

Few studies analyze soil quality from various angles, but our approach is comprehensive and complete, taking into account the different properties of the three plots: physical properties (water retention, moisture), chemical properties (pH, EC, PT, K, Cu, Zn), organic (OM, TN, C/N), bacteriological and microbiological (beneficial bacteria and microbiota), and agronomic.

Figure 3 illustrates the evolution of soil electrical conductivity for the three plots studied. Soil amended with sludge has significantly higher conductivity, with values ranging from approximately 730 to 890 µS/cm. This increase can be explained by the significant contribution of mineral salts and dissolved elements contained in the sludge, particularly sodium, potassium, calcium, and magnesium ions. In comparison, these results are consistent with Sara Hechmi's study on the impact of urban sludge on the physicochemical parameters of soil, particularly the EC parameter, where values reached 4000 µS/cm. However, the EC in our study does not exceed 890 µS/cm, which means that the sludge from the Ibn Tofail treatment plant is of good quality in terms of conductivity, making it sustainable and contributing to water quality (Hechmi et al., 2020).

Electrical conductivity and hydrogen potential provide a general idea of soil salinity and chemical balance. Similarly, the amendment of agricultural plots with sewage sludge modifies the concentration of soluble salt and nutrients, which influences soil quality and fertility. The pH and EC results of this study are compared with recent studies in literature under various scientific contexts. Table 3 shows a comparison between the EC and pH values from our study and others in literature (Uddin et al., 2025, Shan et al., 2021, junior et al., 2023).

By comparing our results with others in literature, our study is a 12-month follow-up on three different plots to study and analyze the impact of the amendment on various physical, chemical, organic, and agronomic parameters. The results show that the sewage sludge amendment has positive effects on fertility, quality, productivity, and agricultural yield. Other studies show unfavorable EC and pH results for agricultural plots, with these values remaining below critical thresholds for certain crops. (Uddin et al., 2025, Shan et al., 2021, junior et al., 2023).

To also assess the impact of the amendment on soil quality and fertility, rigorous analyses of the microbiota and nitrate levels were conducted on the three plots over a 12-month period. These two indicators influence soil microbial dynamics through heterotrophic biomass and beneficial populations, while also modifying nitrogen and carbon cycles.

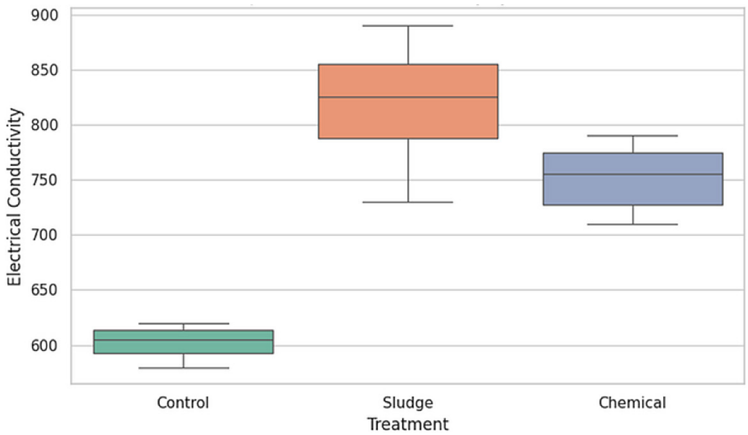

Figure 3. Boxplot of EC by treatment

Table 3. Comparison of the effects of sewage sludge amendment on soil EC and pH in various recent studies

Study	Amendment type	Soil (type/climate)	Observed EC (μS/cm)	Observed pH
This study	Sewage sludge (tonnage/ dose)	Loam-clay / semi-arid climate	730–890	7.30
Uddin et al., 2025	Sewage sludge in arid soils	Desert/semi-arid environment	Variable depending on the dose (1.4–3.0 dS/m)	7.5–8.2
Shan et al., 2021	Amendment in % organic carbon (0–2.5%)	Soil affected by salinity/water conditions	2.3–4.4 dS/Cm	7.4–7.8
Junior et al., 2023	Biochar (2%) from sludge	Highly acidic soil	< 2700	5.8–6.5

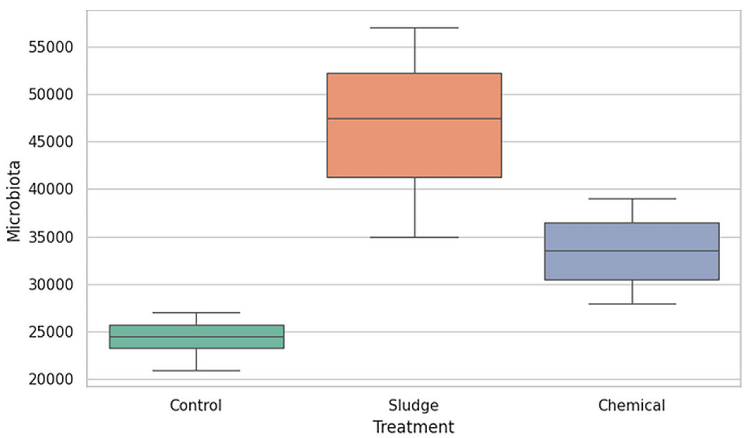

Figure 4. Boxplot of microbiota by treatment

Figure 4 shows the effect of different soil microbiota density values. The results show a clear superiority of the sludge-based treatment, which achieves a microbial abundance of up to 56,000 CFU/g. This high proliferation is explained by the richness of sludge in biodegradable organic matter, nutrients, and beneficial microorganisms that stimulate biological activity in the soil. In contrast, soil amended with chemical fertilizers, although slightly improving microbial abundance (up to approximately 39,000 CFU/g), remains well below the effect observed with sludge. Control and reference soils retain a relatively low microbial biomass, around 25,000 CFU/g, reflecting an inactive edaphic ecosystem. These observations highlight the agronomic and ecological value of sludge in restoring or maintaining soil microbial biodiversity, a key indicator of soil fertility and health.

Figure 5 shows the variation in nitrate levels for the three soils. The results show that soil amended with chemical fertilizers has a high nitrate concentration, above 100 mg/kg, with significant variation. This reflects the rapidly assimilable mineral nature of the nitrogen contained in chemical fertilizers. Soil amended with sewage sludge also generates an increase in nitrates, although more moderate (between 40 and 79 mg/kg). This form of organic nitrogen is released more gradually into the soil, which promotes better assimilation by plants and limits losses through leaching. The control soil has the lowest levels, around 50 mg/kg, which corresponds to natural background levels. These results confirm that sludge can be a sustainable source of nitrogen, offering a compromise between agronomic performance and environmental protection, unlike chemical inputs which, although very effective, can pose risks of nitrate pollution. To better interpret these nitrate and microbiota results for the plots studied, a comparative study was conducted between this study and other recent studies in the literature that focus on the effect of these two indicators on soil quality and fertility. Table 4 illustrates this comparison to better place the observations in the current scientific context (Silva et al., 2023, Yue et al., 2022, Serwecińska et al., 2024).

As mentioned in the previous sections, our study focuses on a comparative study between amended soil and control soil over a period of 12 months. The microbiota and nitrate values are favorable for soil amended with sewage sludge. Comparing these results with Serwecińska, this study highlights the presence of a microbiological risk with an enrichment of certain bacterial communities. Another study by Silva also shows that nitrate increases with better plant nutrition and that sludge residues maintain nitrogen availability during subsequent periods. Finally, Yue's study highlighted a diversity of nitrifying communities that varied according to the types of treatment used in this study, with a greater complexity of the network with organic matter. In addition, the nitrification rate is increased by the release of nitrate in proportion to the nitrogen applied. Comparing our results with previous studies, this study shows a more marked improvement

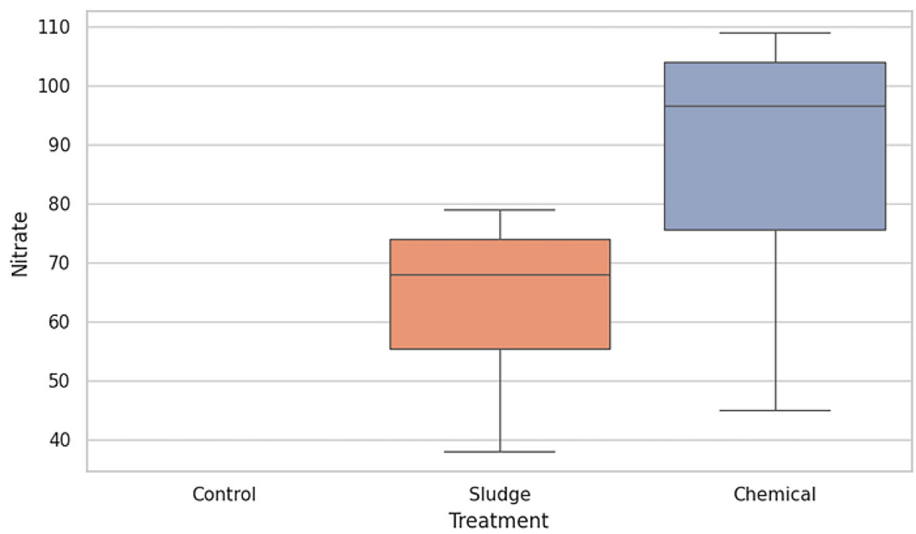

Figure 5. Boxplot of nitrate by treatment

Table 4. Comparison of microbiota and nitrate density in this study and in literature

Study	Type of amendment	Soil/Climate	Microbiota (diversity, structure, density)	Observable NO_3^-
This study	Sewage sludge	Loamy clay / semi-arid (Morocco)	35,000–56,000 CFU/g	40–79 mg/kg
Serwecińska et al. (2024)	Sewage sludge	Various agricultural soils (Poland)	Changes in microbiota structure; increase in Proteobacteria, ARGs	not focused on specific nitrates, but microbial activity related to N
Silva et al. (2023)	Composted sludge in crop rotation	No-Till, tropical soils (Brazil)	Positive effect on microbial biomass & plant N metabolism	Increased NO_3^-, good nitrate reductase activity, improved plant nutrition
Yue et al. (2022)	Organic + mineral fertilizers	Temperate climate / various soils	Diversity of nitrifying communities altered depending on treatment; greater network complexity with organic matter	Increased nitrification rate; nitrates released in proportion to N applied

in microbial density, which promotes the high agronomic potential of the biosolids applied from the wastewater treatment plant and used in this study under the climatic conditions in Morocco. In order to correctly interpret these results in the agronomic context for the various parameters analyzed in relation to soil quality and fertility, rigorous monitoring of these parameters was carried out over a long period of one year to study the long-term composition of the soil.

Figure 6 and Figure 7 illustrate two statistical models: Radar Chart and Scatter Plot, for a global and visual comparison of the normalized distribution of parameters and their impact on long-term soil quality. Figures 6 and 7 show the evolution of various parameters in relation to the three plots studied. For organic matter,

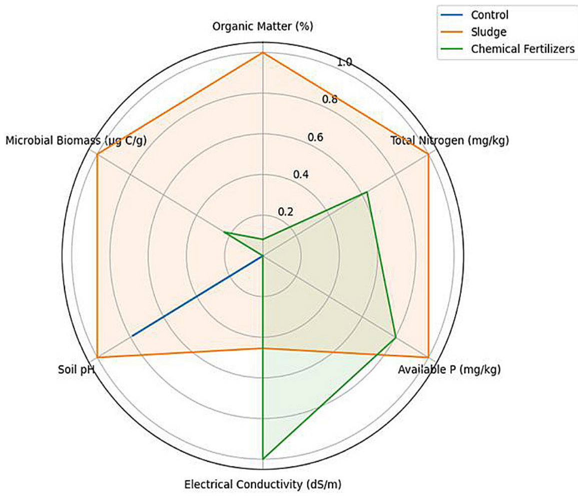

Figure 6. Long-term comparison of soil fertility indicators

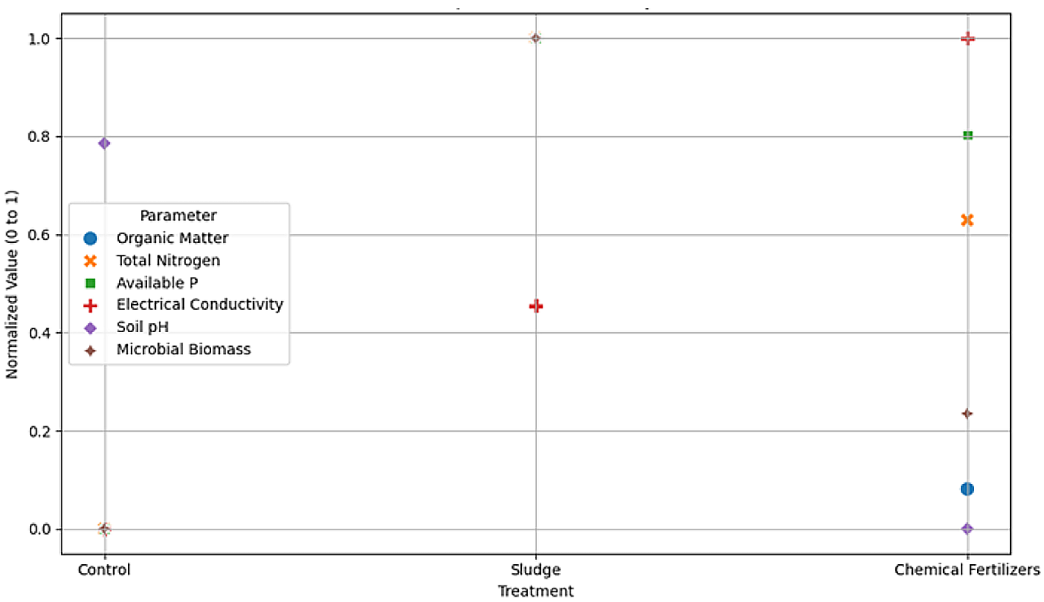

Figure 7. Normalized comparison of soil fertility parameters

Table 5. Analysis of variance (ANOVA)

Parameters	Statistical test	Control soil	Sewage sludge	Chemical fertilizers	P-value	Significance
pH	1-factor ANOVA	7.52 ± 0.11	7.62 ± 0.08	7.57 ± 0.10	0.042	$p < 0.05$
EC (μS/cm)	ANOVA + Tukey	710 ± 25	860 ± 30	780 ± 22	0.015	$p < 0.05$
NO_3^- (mg/kg)	1-factor ANOVA	18.2 ± 1.5	27.4 ± 2.3	23.1 ± 1.9	0.008	Significant
Microbiota (UFC/g sol sec)	ANOVA + Tukey	25 000 ± 2 300	56 000 ± 3 000	35 000 ± 2 700	0.001	Very significant

there was a significant increase in this parameter in the soil amended with sludge, indicating an improvement in soil structure and water retention. For total nitrogen and available phosphorus, there was a more marked accumulation in the soil amended with sludge, demonstrating a progressive and lasting effect. Electrical conductivity is improved in soils amended with chemical fertilizers, which leads to a risk of long-term salinization. Finally, soil microbial biomass was found to be higher in soils treated with sludge, confirming the positive effects on fertilization, biological activity, and soil biodiversity.

According to the results analyzed concerning the long-term impact of these parameters on agricultural land, the amendment based on treated sewage sludge showed a gradual but lasting effect on soil fertility, thanks to an increase in organic matter, improved availability of nitrogen and phosphorus, and stimulation of microbial activity. However, vigilance is required with regard to the long-term accumulation of certain trace elements, such as zinc.

In conclusion, sewage sludge from the Ibn Tofail wastewater treatment plant remains a sustainable solution for soil fertility, as evidenced by nutrient parameter values (N, P, and K) that meet agricultural standards, as well as improved water retention and agricultural yields. These positive effects of sewage sludge on agricultural soils contribute to and promote the circular economy for sustainable agriculture, which is part of sustainable development.

Finally, to better interpret the results and evaluate the significance of the various tests and parameter analyses for the three plots, a one-way ANOVA and ANOVA + Tukey test was applied to the data on hydrogen potential, nitrate, microbial density, and electrical conductivity. Table 5 shows the mean values, standard deviations, and significant levels for each of these parameters.

The ANOVA test for the results of the analyses of the various parameters according to the three plots shows significant differences. The hydrogen potential is slightly but significantly higher for the plot amended with sewage sludge from the wastewater treatment plant, with a value of (7.62 ± 0.08) compared to the control (7.52 ± 0.11). However, the value of these parameters for the third plot amended with chemical fertilizers (7.57 ± 0.10) has a p-value of 0.042 ($p < 0.05$), which indicates a moderate effect of the amendments on soil acidity. Electrical conductivity was higher for plots amended with sewage sludge, with a p-value of 0.015, reflecting an increased supply of water-soluble salts. The same applies to nitrate, with a high value for biosolids (27.4 ± 2.3 mg/kg) compared to 23.1 ± 1.9 mg/kg for soil amended with chemical fertilizers. These results show that biosolids provide better nitrogen availability for crops and plants. Finally, statistical analysis of microbial density is essential for a comprehensive and complete analysis of this comparison between the three plots in terms of microbial contamination. In this regard, the microbial population is strongly stimulated and detected in soil amended with sewage sludge, with an average value of 56,000 CFU/g, whereas for chemical fertilizers, the average value is 35,000 CFU/g with a value of $p = 0.001$, which indicates the positive effect of organic amendments (biosolids) on microbial activity.

Agricultural plots amended with sewage sludge improve soil quality and fertility as well as agricultural yield and productivity, particularly through microbiological activity and high nitrate content. EC and pH values are also favorable for this type of soil, which means that amendment with biosolids contributes to sustainable agriculture while promoting the implementation of the circular economy.

CONCLUSIONS

Land treated with sewage sludge, as demonstrated by this study, offers significant environmental benefits, particularly in terms of soil quality and fertilization. The results show that the use of sewage sludge from the Ibn Tofail wastewater treatment plant meets all the required standards for key soil physicochemical parameters, including organic matter, C/N ratio, pH, electrical conductivity, water retention, and total nitrogen, phosphorus, and potassium concentrations. These parameters are essential for ensuring sustainable agricultural practices that promote soil quality. In addition, the use of sustainable materials helps improve soil fertilization by enriching it with nutrients and organic matter, two elements essential to maintaining long-term soil fertility. The results of this study confirm that sewage sludge is a viable alternative to conventional water sources, such as chemical fertilizers, which are increasingly in demand due to their long-term harmful impact. This highlights the potential of sustainable sludge amendment as an effective strategy for improving organic waste management, preserving soil productivity, and promoting environmental sustainability. Future work should focus on long-term trace metal accumulation and greenhouse gas balance to ensure the sustainability of biosolids use.

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