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RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

The Effect of Dewatered Sludges Obtained from Different Stabilization Systems on the Development of Strawberry Plant

Farklı Stabilizasyon Sistemlerinden Elde Edilen Susuzlaştırılmış Çamurların Çilek Bitkisinin Gelişimine Etkisi

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Abstract

This study investigates the comparative efficacy of dewatered wastewater sludges derived from conventional treatment system followed by anaerobic digestion and extended aeration processes as organic fertilizers for strawberry (*Fragaria × ananassa*) cultivation. Conducted over a six-week duration in a controlled greenhouse environment, the research evaluated the vegetative and morphological development of 'Quinault' strawberry seedlings grown in sandy loam soil. The experimental design utilized a blank control group alongside five distinct mass-by-mass application rates: 1/5, 1/10, 1/20, 1/25, and 1/50.

Initial results identified a clear phytotoxic threshold, as high-dosage treatments (1/5, 1/10, and 1/20) resulted in plant mortality. Conversely, optimized lower ratios significantly enhanced plant vigor. The most substantial development was recorded in the 1/50 ratio group utilizing anaerobically digested sludge, which exhibited a 244.4% increase in plant body length and a 162% increase in root length compared to initial measurements. Statistical analysis confirmed significant correlations ($p<0.05$) between stabilized biosolid application and improved morphological indicators. Elemental analysis revealed that anaerobic residuals possessed superior organic matter and nitrogen profiles, providing a more stable nutrient flux than the extended aeration system.

The findings conclude that stabilized urban sludge is a high-efficiency organic fertilizer when applied at optimized ratios. This approach supports circular economy goals by converting wastewater residuals into valuable agricultural resources while prioritizing food safety and environmental health. However, it is emphasized that these fertilizers cannot be safely utilized without rigorous verification that they are free of heavy metal contamination.

Keywords: Strawberry, stable sludge, fertilizer, dewatered sludge, optimized sludge ratio

Öz

Bu çalışma, geleneksel arıtma sistemini takiben anaerobik çürütme ve uzun havalandırmalı aktif çamur proseslerinden elde edilen susuzlaştırılmış atıksu çamurlarının, çilek (*Fragaria × ananassa*) yetiştiriciliğinde organik gübre olarak kullanımındaki etkinliğini karşılaştırarak incelemektedir. Kontrollü bir sera ortamında altı haftalık bir süre boyunca yürütülen araştırma, kumlu tınlı toprakta yetiştirilen 'Quinault' çilek fidelerinin vejetatif ve morfolojik gelişimini değerlendirmiştir. Deneysel tasarımda, bir kontrol grubunun yanı sıra kütlece beş farklı uygulama oranı (1/5, 1/10, 1/20, 1/25 ve 1/50) kullanılmıştır.

İlk sonuçlar net bir fitotoksik eşik belirlemiştir; yüksek dozlu uygulamalar (1/5, 1/10 ve 1/20) bitki ölümleriyle sonuçlanmıştır. Buna karşılık, optimize edilmiş daha düşük oranlar bitki canlılığını önemli ölçüde artırmıştır. En belirgin gelişim, başlangıç ölçümlerine kıyasla bitki boyunda %244,4 ve kök uzunluğunda %162 artış gösteren, anaerobik olarak çürütülmüş çamurun kullanıldığı 1/50 oranındaki grupta kaydedilmiştir. İstatistiksel analizler, stabilize edilmiş biyolojik çamur uygulaması ile iyileşen morfolojik göstergeler arasında anlamlı korelasyonlar ($p<0.05$) olduğunu doğrulamıştır. Elementel analizler, anaerobik kalıntıların üstün organik madde ve azot profillerine sahip olduğunu ve uzun havalandırmalı sisteme göre daha stabil bir besin akışı sağladığını ortaya koymuştur.

Bulgular, stabilize kentsel çamurun optimize edilmiş oranlarda uygulandığında yüksek verimli bir organik gübre olduğu sonucuna varmaktadır. Bu yaklaşım, atıksu kaynaklı stabil çamurları değerli tarımsal kaynaklara dönüştürerek gıda güvenliğini ve çevre sağlığını önceliklendirirken döngüsel ekonomi hedeflerini desteklemektedir. Ancak, bu gübrelerin ağır metal kontaminasyonu içermediğine dair titiz bir doğrulama yapılmadan güvenli bir şekilde kullanılamayacağı da vurgulanmaktadır.

Anahtar kelimeler: Çilek, stabil çamur, gübre, susuzlaştırılmış çamur, optimize edilmiş çamur oranı

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I.INTRODUCTION

The generation of sludge by wastewater treatment plants is experiencing a steady upward trend, necessitated by rapid demographic growth and the intensification of industrial activities. However, according to the latest TURKSTAT (2025) figures, current municipal production levels are approximately 353,000 tons of dry matter annually, reflecting both the increasing scale of treatment infrastructure and the ongoing challenge of sustainable byproduct management [1]. Furthermore, the growing diversity of chemical substances in wastewater complicates the removal process, significantly increasing the operational costs of sludge disposal [2]. In response, the European Union advocates for the ecological management of these residuals [3]. One of the most promising avenues for the recovery and reuse of treated sludge is its application in plant breeding and soil enrichment.

Treated sludge is primarily composed of organic solids and high concentrations of nitrogen and phosphorus, supplemented by essential minerals such as calcium, potassium, magnesium, sodium, iron, manganese, and zinc [4]. However, this matrix may also harbor hazardous components, including toxic inorganic and organic chemicals, high salinity, and various pathogens—such as viruses and bacteria—that present significant health risks. A substantial portion of the nitrogen in treated sludge exists in proteinaceous forms; consequently, the actual nitrogen utilization rate by plants typically ranges from 10% to 30%, a variability dictated by both plant species and specific soil characteristics [5].

Sludge dewatering facilitates the recovery of renewable substances and produces a concentrated sludge by significantly reducing its total volume. This volume reduction allows for more efficient handling, transportation, and storage, ultimately enhancing waste management efficiency and reducing operational costs. Following the dewatering process, the dry solid content typically ranges between 15 - 45% [6]. To achieve this, several technologies are commonly employed, including centrifuges (decanters), belt filter presses, geomembranes, screw presses, and drying beds [7].

Following appropriate treatment, wastewater sludge is converted into a nutrient-rich material referred to as biosolids, which are suitable for agricultural application [8]. Extensive research indicates that biosolids provide essential nutrients for plant growth and significantly enhance soil productivity. For instance, Akat and Altunlu demonstrated that biosolids application positively influenced the growth, yield, and floral quality of *Limonium sinuatum* by mitigating the adverse effects of high salinity [9]. Furthermore, in a study involving maize (corn), increasing application rates of treated sludge were found to improve both fresh and dry biomass yields, while simultaneously elevating the root concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) [10].

Despite the clear agronomic benefits of biosolids, their application in agriculture is governed by strict regulations due to potential environmental contamination. Raw sludge is inherently unstable and contains high levels of pathogens, which can lead to offensive odors, aesthetic discoloration, and significant hygiene concerns. Consequently, the stabilization of sludge is a legal prerequisite for agricultural application to ensure the protection of public health. Furthermore, the concentration of heavy metals within plant tissues must be strictly monitored. Given that heavy metals persist and accumulate in the soil, their translocation into the food chain and the surrounding aquatic ecosystems must be mitigated. This is achieved by suspending sludge applications as concentrations approach the maximum permissible limits established by current legislation [11].

Extended aeration is a specialized activated sludge process that utilizes aerobic conditions to facilitate the biodegradation of organic waste. This system is favored for its operational simplicity, low odor profile, and reduced sludge production. A defining characteristic of extended aeration is its high solids retention time typically ranging from 20 to 40 days compared to conventional systems, which operate with a significantly higher food-to-microorganism (F/M) ratio [12]. While extended aeration yields a highly mineralized product characterized by nitrified nitrogen (NO_3-N), anaerobic digestion offers a contrasting profile—richer in ammonium and organic nitrogen—for agricultural application [12; 8]. Anaerobic processes generally preserve higher levels of organic carbon and produce a digestate rich in ammonium-nitrogen (NH_4-N), providing more immediate nutrient bioavailability at the expense of the higher structural stability found in aerobically treated sludge [13; 14].

The evolution of biosolids research from the mid-2010s to the present underscores a significant transition from general soil enrichment toward crop-specific optimization and sustainable agricultural integration. Earlier studies established that dewatered and stabilized sludge not only provides essential macronutrients but also enhances the soil's physical architecture, including water-holding capacity and porosity [15; 16]. This period also saw foundational advancements in fruit and ornamental production, where the slow-release organic nitrogen found in stabilized organic residuals improved the growth and physiological status of horticultural crops [17]. Furthermore, studies on organic amendments have demonstrated that these materials can serve as a robust, renewable substrate for nursery seedlings, effectively replacing a significant portion of traditional peat moss while maintaining or enhancing plant quality indices [18; 19]. Building upon these findings, recent research has demonstrated that properly stabilized biosolids can significantly elevate biomass and grain yield in cereals and leafy vegetables [20; 21]. Furthermore, the application of these organic amendments has been shown to improve soil nutrient retention, thereby mitigating the nutrient leaching typically associated with highly soluble synthetic fertilizers [22; 23]. Furthermore, contemporary investigations into horticultural and cereal crops have highlighted the role of stabilized organic amendments in promoting complex root architecture by increasing root surface area and length density [24]. Additionally, the application of treated sludge-derived biochar has been shown to enhance physiological resistance to environmental stressors, such as water-deficit stress, by modulating morphological traits and strengthening the plant's antioxidant defense system [25; 26]. Collectively, treated sludge, when managed as a stabilized resource, offers a versatile and balanced nutrient profile capable of meeting the diverse morphological and physiological requirements of modern agricultural systems [27].

Building on the established consensus of biosolid efficacy, the present study investigates the comparative efficacy of dewatered sludge, derived from both conventional treatments followed by anaerobic digestion and extended aeration processes, as an organic fertilizer for strawberry (*Fragaria × ananassa*) cultivation. The research evaluates how the distinct solids retention times and mineralization levels inherent to each treatment process influence the vegetative and morphological development of the plants. To facilitate this assessment, the experimental design utilized a blank control group receiving no sludge alongside five distinct application rates—1/5, 1/10, 1/20, 1/25, and 1/50—calculated on a mass-by-mass basis. The study monitors several key growth indicators to compare the performance of the two sludge types, specifically measuring plant body length, root length, leaf length, and the number of petioles.

Statistical analyses were performed using SPSS Statistics for Windows (Version 29.0.1.0). To identify significant differences between the treatment applications, the data were analyzed using Paired-Samples Correlations and Paired-Samples T-Tests. All statistical evaluations were conducted at a 5% significance level (two-sided), ensuring a robust assessment of how these stabilized biosolids meet the nutritional requirements of strawberries during their critical development stages.

II. MATERIALS AND METHODS

2.1 Plant Material and Growth Conditions

The research was conducted within the greenhouse facilities of the Marmara University Natural Plants and Aquaculture Research and Application Center. The experimental plant material consisted of the everbearing strawberry species (*Fragaria x ananassa)* 'Quinault', which was selected for its characteristic growth height of 20–25 cm and its preference for organically rich, well-drained sandy loam soils. To ensure successful adaptation to the greenhouse environment and varying soil conditions, seventh-flowering seedlings were utilized. Throughout the two-month research period, the morphological development of the plants—including root, stem, and leaf lengths—was systematically monitored alongside fruit production.

2.2 Experimental Design and Treatment Preparation

The study was conducted over a six-week duration, allowing for a comprehensive assessment of the vegetative growth and morphological adaptation of the strawberry plants to the stabilized biosolid amendments. Throughout the six-week period, the plants were monitored for consistent development across all evaluated parameters. Data collection focused on the transition from initial establishment to active vegetative growth, ensuring that the morphological indicators—plant body length, root length, leaf length, and petiole count—reflected the sustained nutrient release from the stabilized sludge rather than a transient response.

The cultivation environment was prepared using dewatered sludge (25% dry solids) obtained from two different Biological Wastewater Treatment Plants. First one utilizes extended aeration systems which stabilize the sludge aerobically and there is no primary sedimentation. The second wastewater treatment plant stabilizes the sludge anaerobically. Dewatering was completed by centrifuges in both wastewater treatments. To assess the comparative efficacy of different stabilization processes, including conventional treatment followed by anaerobic digestion and extended aeration, the sludge was applied to the pots in five distinct mass-by-mass ratios: 1/5, 1/10, 1/20, 1/25, and 1/50. A total of five rectangular pots were employed, with 2 kilograms of fertilizer-free sandy loam soil added to each to isolate the specific effects of the sludge amendments. Precision balances were used to ensure accurate gravimetric measurement of the soil-sludge mixtures. The experimental setup included a blank control group containing only unamended soil to establish a baseline for natural plant growth.

2.3 Cultivation and Maintenance

Seedlings were housed in 10-liter pots with a depth of 15 centimeters to prevent root compression, featuring drainage holes at the base to ensure optimal aeration and prevent root rot. Irrigation was performed at three-day intervals using a 100-milliliter beaker to deliver a total of 500 milliliters of water per pot. To prevent thermal shock, the irrigation water was maintained at the same temperature as the controlled greenhouse environment.

2.4 Morphological and Soil Analysis Procedures

Morphological measurements were conducted to evaluate the impact of the dewatered sludge on plant vigor and reproductive success. These assessments included the total body length measured from the soil surface, the length of the petioles to determine leaf development, and the root length to assess nutrient accessibility and soil health. Additionally, leaf length was measured to estimate photosynthetic capacity, and the total number of fruits was recorded to evaluate productivity and reproductive success. All physical and chemical analyses conducted to determine the effects of the dewatered sludge on soil properties were carried out in the accredited laboratories of the Istanbul Metropolitan Municipality, Department of Environmental Protection and Control, which is accredited by TÜRKAK. The following standard methods were utilized during the analysis process:

Saturation Mud and Water Holding Capacity: The TS 8333 standard was employed to evaluate the water-holding dynamics of the soil.

Soil Texture: The proportions of clay, silt, and sand were determined using the TS 8341.

Carbonate Content: Lime content, which significantly influences soil pH levels and nutrient availability, was assessed according to the TS EN ISO 10693 standard.

Nutrient Content and Cation Exchange Capacity: Precise measurements for exchangeable cations (Ca, Mg, K, Na) were performed using a combination of the TS 8341 Ammonium Acetate Method and TS EN ISO 22036 ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry) techniques.

Organic Matter: The organic matter content of the soil was determined in accordance with TS 8336 and the procedures outlined in the Tüzüner laboratory handbook [28].

2.5 Statistical Analysis

Statistical processing was performed using SPSS Statistics for Windows (Version 29.0.1.0). Differences between the various treatment applications were evaluated using Paired-Samples Correlations and Paired-Samples T-Tests at a 5% two-sided significance level. The correlation coefficients were interpreted as weak (0.01–0.29), medium (0.3–0.7), or strong (0.7–0.99), with a *p*-value of less than 0.05 indicating statistically significant differences between the experimental groups.

III. RESULTS AND DISCUSSIONS

The initial experimental phase established a clear phytotoxic threshold for biosolid application, as the high-dosage treatments (1/5, 1/10, and 1/20 (w/w)) from both wastewater sources resulted in severe plant "burning" and subsequent mortality. These failures are attributed to the excessive accumulation of salts and ammonia-nitrogen, which induced osmotic stress and exceeded the physiological tolerance of the strawberry plants.

Consequently, the research focus was refined to analyze the morphological development across five viable treatment groups: the blank control media (S0), the 1/25 (S1) and 1/50 (S2) dosages derived from conventional treatment followed by anaerobic digestion, and the 1/25 (S3) and 1/50 (S4) dosages obtained from the extended aeration system. By shifting the analysis to these optimized mass-based ratios, it became possible to observe the specific influence of sludge stabilization methods on vegetative vigor without the interference of acute toxicity.

Data obtained from the accredited Istanbul Metropolitan Municipality laboratory indicated that even at these lower ratios, the soil-sludge mixtures maintained significantly higher organic matter, available phosphorus, and potassium levels than the blank control.

3.1 Plant Morphological Analyses

3.1.1 Plant Body Length

The morphological response of the strawberry plants, specifically regarding plant body length, under different application rates of various urban sewage sludge types is detailed in Figure 1.

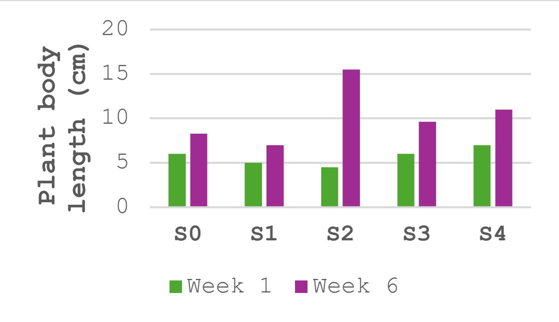

Figure 1. Plant body lengths after Week 1 and Week 6.

The statistical analysis of these measurements revealed a moderately strong correlation between the application of various wastewater treatment sludges and the resulting vegetative growth, a relationship that was maintained from the initial establishment through the conclusion of the study. This correlation was found to be statistically significant (p<0.05), indicating that the morphological response of the plants to the specific nutrient profiles of the stabilized biosolids is both predictable and systematic.

Plant body length measurements of increasing doses of different urban sewage sludge applied to strawberry plants at the end of the 1st week and the 6th week are illustrated in Figure 1. Examining Figure 1, the statistical analysis showed a moderately strong correlation between the effects of different wastewater treatment sludges at various rates on plant body length at the end of the 1st and 6th weeks, which was found to be statistically significant (p<0.05). Notably, the S2 treatment (1/50 mass ratio from conventional treatment followed by anaerobic digestion) demonstrated the most substantial growth trajectory, with the plant body length increasing from 4.5 cm at the end of the first week to 15.5 cm by the sixth week. This represents a remarkable 244.4% increase in vertical development over the six-week experimental period.

The significant 244.4% increase in plant body length observed in the S2 group underscores the potential of stabilized biosolids to serve as an effective nutrient source when applied within the physiological tolerance limits of the species. According to Singh and Agrawal (2008), sewage sludge amendments significantly enhance plant height and biomass by improving soil porosity and providing a steady release of macronutrients; however, they emphasize that the dosage must be carefully managed to avoid heavy metal or salt-induced inhibition [29]. The failure of the higher dosages (1/5, 1/10, and 1/20) in this study corroborates the findings of Kamboj (2020), who noted that excessive biosolid application can lead to high electrical conductivity (EC) in the root zone, causing osmotic stress and subsequent leaf necrosis in sensitive horticultural crops like strawberries [30].

3.1.2 Plant Root Length

Plant root length measurements for different urban sewage sludge applied to strawberry plants at the end of the 1st week and the 6th week are illustrated in Figure 2. Statistical analysis of these measurements indicates a moderately strong correlation between the application of various wastewater treatment sludges and root elongation, which was found to be statistically significant (p<0.05).

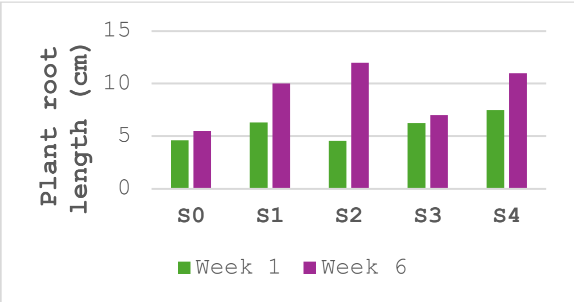

Figure 2. Plant root lengths after Week 1 and Week 6.

Among the viable treatments, the anaerobic digestion group demonstrated significant progress; the S1 treatment (1/25 ratio) grew from 6.3 cm to 10 cm, while the S2 treatment (1/50 ratio) exhibited the most substantial growth trajectory, expanding from 4.58 cm to 12 cm. This represents a 162% increase in root development for the S2 group, confirming that the 1/50 ratio provided a highly favorable environment for below-ground expansion over the 6-week period. The extended aeration treatments, S3 (1/25) and S4 (1/50), also showed stable and consistent expansion of the root architecture compared to the blank control media (S0).

The significant root elongation observed across the S1–S4 treatments underscores the efficacy of stabilized biosolids in enhancing the physical and chemical properties of the rhizosphere. According to

Latare et al., sewage sludge amendments improve soil porosity and water-holding capacity, which directly supports deeper root penetration and more efficient nutrient acquisition in sandy loam soils [15].

The superior performance of the S2 treatment suggests that the 1/50 ratio provided an optimal concentration of mineralized nutrients while remaining below the osmotic stress thresholds that hindered the higher dosage groups. This aligns with the observations of Kamboj, who noted that excessive biosolid application typically leads to a surge in electrical conductivity (EC) that inhibits root tip elongation [30].

The consistent development in both the anaerobic digestion (S1, S2) and extended aeration (S3, S4) applications highlights the role of organic matter as a slow-release nutrient source. As noted by Singh and Agrawal, organic amendments provide a steady flux of macronutrients, particularly phosphorus, which is critical for early root establishment and long-term vegetative vigor [29].

3.1.3 Plant Leaf Length

Plant leaf length measurements of increasing doses of different urban sewage sludge applied to strawberry plants at the end of the 1st week and the 6th week are given in Figure 3. Examining Figure 3, the statistical analysis shows a strong positive correlation ($r > 0.70$) between the effect of different wastewater treatment sludges at various rates on plant leaf length at the end of the 1st and 6th weeks, which was found to be statistically significant ($p<0.05$).

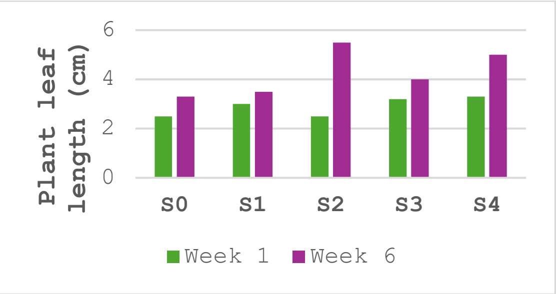

Figure 3. Plant leaf lengths after Week 1 and Week 6.

Similar to the trends observed in plant body length, the S2 treatment (1/50 anaerobic digestion) and the S4 treatment (1/50 extended aeration) demonstrated superior leaf expansion compared to the higher dosage variants. The strong correlation suggests that the initial nutrient availability in these stabilized amendments directly dictated the photosynthetic surface area development throughout the 6-week period. While the 1/25 ratios (S1 and S3) provided substantial growth compared to the S0 control, the leaf length values in the 1/50 treatments indicated a more optimized physiological response, avoiding the marginal chlorosis potential associated with higher mineral loads.

The strong positive correlation between sludge application and leaf length expansion highlights the importance of nitrogen and phosphorus availability in the development of the strawberry's photosynthetic apparatus. According to Singh and Agrawal, the addition of sewage sludge to soil significantly improves the leaf area index and chlorophyll content, which are critical for biomass accumulation [29]. The significant increase in leaf length in the S1–S4 groups relative to the control suggests that the biosolids provided a consistent supply of micronutrients that enhanced the vegetative vigor of the *Fragaria* × *ananassa* plants. Furthermore, Méndez et al. suggest that anaerobically digested sludge (as seen in S1 and S2) can often provide a more stable nitrogen release than aerobically treated sludge, which may explain the robust expansion of leaf length observed by the 6th week [31]. By optimizing the dosage to 1/50, the S2 treatment maximized the benefit of the organic amendment, providing enough nutrients to support a significant increase in leaf length without the risk of osmotic stress.

3.1.4 Number of Plant Petioles

The number of plant petioles observed for the various urban sewage sludge treatments at the end of the 1st and 6th weeks is presented in Figure 4. Statistical analysis shows a significant correlation between the application of stabilized biosolids and the proliferation of petioles over the six-week study period ($p<0.05$).

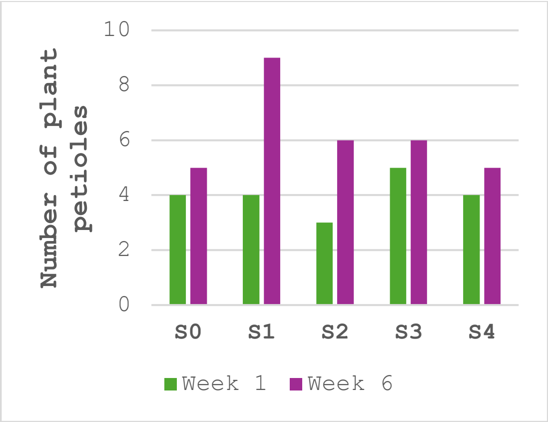

Figure 4. Number of plant petioles after Week 1 and Week 6.

The data indicate that the S2 (1/50 anaerobic digestion) and S4 (1/50 extended aeration) groups maintained a steady production of new petioles, reflecting robust crown development. In contrast to the high-dosage groups (1/5, 1/10, 1/20) which failed to develop due to acute phytotoxicity, the lower-ratio amendments provided a nutrient-rich environment that supported vegetative branching. By the 6th week, the increase in petiole numbers across the S1–S4 treatments relative to the S0 control suggests that the mineralized nutrients provided by the wastewater treatment residuals significantly enhanced the architectural complexity of the strawberry plants.

Delibacak and Ongun emphasized that the use of stabilized sewage sludge can significantly increase the leaf and petiole count in strawberries by enhancing the availability of exchangeable cations [32]. The result of our 6-week study supports the conclusion that both anaerobic digestion and extended aeration stabilization methods produce a viable agricultural amendment that promotes structural development. The consistent emergence of new petioles by the final week highlights the transition from initial establishment to a high-vigor vegetative state, setting a strong foundation for the reproductive phase of the plant.

3.2 Effect of Sludge on Soil

Some chemical properties determined as a result of the analyses made on the soil sample used in the experiment are given in Table 1. The results indicate that the experimental soil is classified as SL (Sandy Loam) and has a neutral pH.

Table 1. Properties of the soil used in study.

<table>
<tr><th colspan="2">Soil Properties</th><th>Unit</th><th>Amount</th></tr>
<tr><td colspan="2">Saturation</td><td>%</td><td>134</td></tr>
<tr><td colspan="2">pH</td><td></td><td>7.20</td></tr>
<tr><td colspan="2">EC</td><td>µS/cm</td><td>2670</td></tr>
<tr><td colspan="2">Salt</td><td>%</td><td>0.22</td></tr>
<tr><td colspan="2">Sand Ratio</td><td>%</td><td>59.68</td></tr>
<tr><td colspan="2">Silt Ratio</td><td>%</td><td>25.16</td></tr>
<tr><td colspan="2">Clay Ratio</td><td>%</td><td>15.16</td></tr>
<tr><td colspan="2">Lime</td><td>%</td><td>7.47</td></tr>
<tr><td colspan="2">Organic Matter</td><td>%</td><td>14.03</td></tr>
<tr><td rowspan="5">Useful</td><td>Phosphorus</td><td>P_2O_5 kg/da</td><td>59.25</td></tr>
<tr><td>Potassium</td><td>K_2O kg/da</td><td>452.20</td></tr>
<tr><td>Calcium</td><td>mg/kg</td><td>9375</td></tr>
<tr><td>Magnesium</td><td>mg/kg</td><td>720.60</td></tr>
<tr><td>Sodium</td><td>mg/kg</td><td>343.20</td></tr>
</table>

Table 2. Elemental analysis of the sludges

Parameter	Conventional treatment followed by anaerobic digestion	Extended aeration
Carbon (C) %	30.0% – 35.0%	28.0% – 33.0%
Nitrogen (N) %	4.0% – 5.5%	4.0% – 5.0%
Phosphorus (P) %	2.5% – 3.5%	2.8% – 4.0%
Organic Matter (VSS %)	65% – 75%	60% – 70%
Average C/N/P Ratio	**10.8 : 1.6 : 1**	**9.0 : 1.3 : 1**

The elemental analysis calculation of the dewatered sludges is given in Table 2. A critical comparison of the biochemical profiles of the biosolids reveals that the sludge from a conventional treatment followed by anaerobic digestion offers a slightly more robust nutrient framework for horticultural application than the sludge from an extended aeration system. Specifically, the anaerobic residuals demonstrated a higher organic matter content (VSS 65%–75%) and a superior nitrogen concentration (4.0%–5.5%), which likely facilitated the enhanced vertical and root development observed in the S1 and S2 treatments. The C:N:P ratio of 10.8:1.6:1 for the anaerobic sludge indicates a more carbon-rich matrix compared to the 9.0:1.3:1 ratio found in the extended aeration sludge. This suggests that the anaerobic digestion process yields a more stable organic structure that promotes a sustained, rather than rapid and potentially phytotoxic, nutrient release. While the extended aeration sludge featured a slightly higher phosphorus potential (up to 4.0%), the higher carbon-to-nitrogen balance in the anaerobic digestion sludge appeared more effective at buffering the sandy loam soil. This allowed the 1/50 ratio (S2) to achieve peak growth performance. The lower nitrogen and organic matter percentages in the extended aeration samples (S3 and S4) likely explain their more modest, albeit significant, morphological results. Consequently, for the cultivation of *Fragaria × ananassa*, the sludge from a conventional treatment followed by anaerobic digestion at a 1/50 mass ratio provides the most optimized balance of structural stability and nutrient availability.

The variations in strawberry development and the observed phytotoxicity in higher dosages cannot be solely attributed to the structural differences between anaerobic digestion and extended aeration stabilization methods. Instead, several physicochemical parameters inherent in the sludge matrix act as concomitant factors. Firstly, the high electrical conductivity (EC) of the sludges likely induced osmotic stress, a critical factor for salt-sensitive species like strawberry [29; 32]. This likely led to physiological drought in the root zone at 1/5 and 1/10 ratios, preventing efficient water uptake. Secondly, the rapid mineralization of organic nitrogen in high-dosage applications can release free ammonia (NH_3) or cause excess ammonium (NH_4^+) accumulation, which exceeds the physiological tolerance of strawberry root tissues [26; 29]. Lastly, the shifts in rhizosphere pH and the high organic matter content of the sludges influence the soil's buffering capacity and nutrient bioavailability [26; 27]. The superior performance of the 1/50 anaerobic sludge ratio indicates that at lower concentrations, these parameters remain within the plant's tolerance limits, allowing for a synchronized nutrient release that meets the morphological requirements of 'Quinault' seedlings [30] without inducing the inhibitory effects seen in higher ratios.

IV. CONCLUSION

The investigation into the morphological response of *Fragaria × ananassa* to urban biosolid amendments confirms that stabilized sewage sludge serves as a high-efficiency organic fertilizer when applied at optimized ratios. The research successfully identified a clear phytotoxic threshold, where high-dosage applications (1/5, 1/10, and 1/20) induced acute osmotic stress and ammonia toxicity, highlighting the critical role of the sludge's chemical matrix, such as high electrical conductivity and rapid nitrogen mineralization alongside the stabilization method. Conversely, lower mass-based ratios (1/25 and 1/50) facilitated significant vegetative vigor.

The most remarkable development occurred within the S2 treatment group (1/50 ratio from conventional treatment followed by anaerobic digestion), which exhibited a 244.4% increase in plant body length (from 4.5 cm to 15.5 cm) and a 162% increase in root length (from 4.58 cm to 12 cm) over the six-week study period. These results, supported by a strong statistical correlation ($p < 0.05$), demonstrate that the anaerobic digestion process yields a more stable, nutrient-dense matrix compared to extended aeration. The higher organic matter content (VSS 65%–75%) and superior nitrogen profile (4.0%–5.5%) inherent to the anaerobic residuals provided a sustained nutrient flux that matched the physiological requirements of the strawberry plants.

While the morphological results highlight the efficacy of biosolid amendments, the primary and most concerning constraint regarding their use as fertilizer remains the potential presence of heavy metals. To ensure the long-term safety of the soil-plant system and protect the final consumer, it is imperative that such sludges are strictly verified to be free of heavy metal contamination. The potential for the accumulation of elements like lead, cadmium, and nickel remains a critical concern. Rigorous and continuous toxicological screening is essential to ensure that the nutrient benefits of the 1/50 ratio are not offset by the introduction of hazardous inorganic pollutants into the food chain.

In summary, the utilization of stabilized urban sludges at optimized ratios represents a sustainable strategy for horticultural production, provided that safety protocols are strictly enforced. By converting wastewater residuals into a high-value agricultural resource while prioritizing the elimination of heavy metal risks, this approach supports circular economy goals and reduces reliance on synthetic fertilizers. This research provides a robust framework for balancing maximum vegetative yield with essential environmental and toxicological safeguards in strawberry cultivation.

The characteristics of organic fertilizers used in agricultural production and their effects on the soil-plant system involve complex processes. While this study highlights the potential of wastewater sludge, it emphasizes the need for further comprehensive research focusing on heavy metal transport and food safety to ensure the reliability of such wastes in agricultural products. The transition of waste into a resource can only evolve into a sustainable circular economy model through such rigorous scientific validation.

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