Advanced and Sustainable Technologies
ASET
E-ISSN 2976-2294

Volume 5, No 2, September 2026 [320-330]

Influence of Water Treatment Sludge on the Growth of *Coleus amboinicus*

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Received 10 June 2026, Revised 20 July 2026, Accepted 5 August 2026

ABSTRACT

The accumulation of water treatment sludge (WTS) poses a significant environmental challenge, as traditional disposal methods, such as landfilling, are increasingly constrained by high costs and land scarcity. The objective of this preliminary study was to assess the potential and feasibility of utilizing WTS for plant cultivation, specifically by examining the growth of Coleus amboinicus across varying WTS amendment concentrations. The experimental design used four treatments: a control group (100% soil) and three amended groups with low, medium, and high WTS content, respectively. Plants were grown in pots under natural conditions for 54 days. Growth performance was quantified through weekly measurements of plant height and leaf size development. The results demonstrated a trend of improved plant vitality with increasing WTS content. Notably, the treatment with the highest WTS content showed the greatest growth in both height and leaf dimensions compared to the control and lower-concentration amendments. These findings suggest that water treatment sludge is viable for soil enhancement, offering a dual solution for waste management and aligning with SDG 12 while supporting SDG 15 through agricultural productivity and sustainable ecosystem management.

Keywords: *Coleus amboinicus,* Growth performance, Sludge management, Soil amendment, Sustainable agriculture, Sludge.

1. INTRODUCTION

The accelerating global sludge production from water treatment plants, as well as municipal and industrial sewage, has prompted a strategic transition from conventional disposal practices toward resource recovery within a circular economy framework. Most existing studies on sludge reuse have focused on wastewater treatment plant sludge because of its high organic matter content and rich supply of essential nutrients such as nitrogen and phosphorus, making it a suitable material for fertilizers and soil amendments [1, 2, 3, 4]. Despite these advantages, its widespread agricultural application remains limited due to concerns about potential contaminants, including pathogens, heavy metals, and persistent organic pollutants, which may pose risks to human health and the environment [5]. In comparison, considerably less attention has been given to water treatment plant (WTP) sludge. This material is often considered less valuable for agricultural purposes because it has lower nutrient concentrations and may retain residual chemical coagulants from the water treatment process [6, 7]. However, this lack of research presents an important opportunity for advancing sustainable waste management

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practices. Investigating safe and effective approaches for WTP sludge reuse could help unlock its potential as a valuable resource. For example, previous studies have suggested that blending WTP sludge with sewage sludge may improve the mixture's biodegradability and suitability as a soil conditioner [8], while others have demonstrated its potential for domestic wastewater treatment [9]. Therefore, expanding research in this area is essential for supporting circular economy initiatives, reducing landfill disposal, and transforming an underutilized industrial byproduct into a resource with environmental and economic value.

In this context, recent scholarship has increasingly focused on the valorization of sludge as a bioactive soil amendment, particularly for plant systems. This approach addresses two interrelated engineering challenges: the sustainable management of nutrient-rich waste streams and the rehabilitation of degraded land. A study by [10] reported that pelletized sewage sludge functions as a high-potency fertilizer, containing up to 5.7% nitrogen and 4.9% phosphorus, thereby significantly enhancing the physiological development of ornamental species such as *Tagetes erecta*. This nutrient potential is further optimized through composting processes. Studies by [11, 12] concur that co-composting sludge with agro-industrial residues stabilizes organic matter, leading to improvements in root morphology and photosynthetic performance in species such as *Calathea insignis*. Accordingly, sludge-based substrates are increasingly conceptualized not merely as waste derivatives but as engineered growing media capable of substituting conventional materials such as peat [13].

The influence of sludge-based amendments on plant morphology and growth performance has been extensively documented, with consistent evidence demonstrating enhanced phenotypic responses. Research by [14, 15] highlights the applicability of water treatment and dewatered municipal sludge in supporting native vegetation in nutrient-deficient environments, such as the Brazilian Cerrado and compacted clay soils. This underscores the functional role of sludge-derived nutrients in facilitating vegetation establishment and ecosystem recovery. Complementary findings from [16, 17] demonstrate that in containerized ornamental systems, plant quality, particularly for species such as Impatiens, can be significantly improved when substrate composition is carefully tailored to meet species-specific physical and chemical requirements.

Despite these advantages, the feasibility of sludge utilization is critically constrained by associated biochemical risks, particularly salinity and phytotoxicity at elevated application rates. For instance, salt accumulation is a primary limiting factor, as sludge proportions exceeding 30% (w/w) frequently cause severe growth inhibition [18]. Furthermore, phytotoxicity remains highly site-specific, governed predominantly by local soil characteristics and reuse conditions [19]. Their work highlights that contaminant bioavailability is not uniform but context-dependent, thereby necessitating site-specific engineering design to balance nutrient enrichment against potential toxicity risks.

A substantial body of literature also addresses the implications of heavy metal accumulation, particularly elements such as zinc (Zn), copper (Cu), and iron (Fe), within sludge-amended substrates. Although elevated metal concentrations are frequently reported, there is a broad consensus that *the* plant species *Coleus amboinicus* can serve as an effective buffer against associated risks. Many ornamental and wild plant species exhibit considerable tolerance to metal stress, often without observable phytotoxic symptoms despite measurable tissue accumulation [20, 21]. Notably, soil acidification can intensify metal bioavailability and toxicity, thereby identifying pH regulation as a critical management parameter [21]. In addition, species such as *Canna* and *Reutealis trisperma* have been identified as functional phytoremediation agents, utilizing sludge nutrient content to generate biomass capable of stabilizing or extracting contaminants from the soil matrix [14, 22].

Ultimately, the successful application of sludge-based soil mixtures is contingent upon the optimization of substrate composition. While some studies recommend maintaining sludge content below 20% to minimize salinity-related risks [18, 23], the literature collectively indicates that sludge-based substrates represent a viable, sustainable, and cost-effective alternative for *Coleus amboinicus* cultivation, with reported costs as low as \$0.98 per ton [10]. However, the long-term success of such applications depends on precision-based formulation strategies. Careful balancing of nutrient availability against thresholds for salinity and heavy-metal bioavailability is essential to transform sewage sludge from an environmental burden into a strategic resource for sustainable horticulture and landscape restoration.

Therefore, this study aims to investigate the potential of transforming WTS into a valuable resource by evaluating its suitability as a sustainable soil amendment. In line with the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land), this study contributes to sustainable waste management and land restoration through resource recovery. To achieve this objective, a preliminary study was conducted to evaluate the growth and development of *Coleus amboinicus* in WTS-amended soil.

2. MATERIAL AND METHODS

2.1 Materials

In this experiment, the dried sludge was collected from a local water treatment plant. The plant species utilized in this study was *Coleus amboinicus*. For soil characterization, the wet acid digestion Method 3050B was employed using 65% nitric acid (RCI Labscan), 30% hydrogen peroxide (Sigma) and 37% hydrochloric acid (QReC).

2.2 Chemical Properties Characterization

The chemical characterization of the sludge-soil was performed using the acid wet digestion technique (Method 3050B), following the methodology described in [24]. Approximately 1.0 g of dried sludge was accurately weighed into a digestion vessel, then 10 mL of 50% HNO_3 was added. The mixture was heated for 15 min at a temperature below the boiling point. Subsequently, 5 mL of concentrated HNO_3 was added, and the sample was further heated at 90°C for 30 min. After cooling, an additional 5 mL of concentrated HNO_3 was introduced, and the mixture was reheated at 90°C for another 30 min. This step was repeated with successive additions of concentrated HNO_3 until no further evolution of brown nitrogen oxide fumes was observed, indicating complete oxidation of the organic matter. A mixture consisting of 10 mL of 30% H_2O_2 and 2 mL of distilled water was then added slowly to the digest to complete the oxidation process. The solution was subsequently heated until its volume was reduced to approximately 5 mL. Thereafter, 10 mL of 37% HCl was added, and the digest was heated for an additional 15 min and then allowed to cool. The digested sample was then analyzed using ICP-OES (PerkinElmer Optima 8000) to determine the composition of potassium (K), calcium (Ca), aluminium (Al), chromium (Cr), zinc (Zn) and copper (Cu). Chemical characterization was restricted solely to the amended sludge-soil treatments (T1–T3) to monitor temporal elemental dynamics. Conversely, the unamended soil (T0) received no chemical testing and was utilized strictly as a phenotypic and morphological control.

2.3 Experimental Design

The sludge-soil mixtures were prepared by mixing sludge with soil in varying ratios, as shown in Table 1. The experimental design comprised three sludge-amended treatments (T1, T2, T3) and unamended soil (T0). Following preparation, the respective substrates were transferred into 9 cm × 12 cm polybags prior to the cultivation period.

Table 1: Composition and mixing ratios of sludge-soil treatment groups.

Treatment	Description	Sludge: Soil Ratio
T0	Soil only (control)	-
T1	Low sludge content	1:1
T2	Medium sludge content	2:1
T3	High sludge content	3:1

The *Coleus amboinicus* plants used in this study were sourced from existing cultivation using the stem-cutting method. Uniformly sized cuttings were selected, and surplus leaves were removed prior to planting. Each cutting was inserted into a 5 cm-deep hole at the center of the substrate mixture in each polybag, then watered until excess water drained to ensure uniform moisture. The plants were then positioned in an open area with adequate sunlight exposure and watered daily. No fertilizers were applied throughout the experimental period, which spanned from Day 1 to Day 54. Throughout the experimental period, the pH of the sludge-soil was monitored, and plant growth was assessed by measuring plant height increment and leaf width for each treatment group, following the method described by [25]. All the measurements were performed in triplicate.

3. RESULTS AND DISCUSSION

3.1 Chemical Properties

Characterizing the chemical properties of the sludge is fundamental to predicting its behavior and impact on agricultural productivity. These attributes, including pH and elemental profiles, critically govern soil fertility and nutrient availability. Therefore, this study evaluates these physicochemical parameters to systematically assess the specific effects of pH and elemental concentrations of K, Ca, Al, Cr, Zn and Cu on plant growth dynamics.

Over the 54-day monitoring period, the mean soil pH remained stable at 6.64 across all sludge–soil treatments. This slightly acidic to near-neutral pH falls within the range generally considered favorable for plant growth, as it promotes the availability of essential macro- and micronutrients while maintaining a balanced soil chemical environment. Soil pH between 6.0 and 7.0 has been widely reported to optimize nutrient availability, particularly for nitrogen, phosphorus, and potassium, thereby supporting plant development [26]. In addition, maintaining the pH above 5.5 reduces the solubility of potentially phytotoxic metals, including aluminum (Al^{3+}) and chromium, which become more mobile under strongly acidic conditions [26]. The consistent pH observed across all sludge-soil treatments indicates that WTS did not adversely affect soil acidity and likely contributed to maintaining a favorable soil environment for the growth of *Coleus amboinicus*.

The elemental composition in sludge-soil decreased over the cultivation period, reflecting a balance between plant nutrient assimilation and soil stabilization (Table 2). The decrease in K and Ca concentrations suggests that *Coleus amboinicus* absorbed these nutrients to support its growth and development. Concurrently, all treatment groups exhibited decreased concentrations of potentially phytotoxic elements, particularly Al and Cr, by Day 54. This reduction was consistent with the well-buffered, near-neutral pH conditions created by the WTS contents. Conversely, Zn and Cu remained at low, stable concentrations with only minor temporal fluctuations, indicating a low risk of trace-element toxicity throughout the experiment.

Table 2: Chemical composition of sludge-soil treatment groups on Day 1 and Day 54.

Chemical Composition	Treatment Soil	Day 1 (mg/L)	Day 54 (mg/L)
Potassium, K	T1	33.18	9.47
	T2	14.90	9.90
	T3	8.41	3.31
Calcium, Ca	T1	38.84	32.07
	T2	30.18	30.68
	T3	17.49	7.52
Aluminium, Al	T1	120.70	76.48
	T2	210.10	83.18
	T3	146.20	113.80
Chromium, Cr	T1	82.37	52.07
	T2	166.40	55.33
	T3	79.68	50.46
Zinc, Zn	T1	1.46	0.13
	T2	0.23	0.17
	T3	0.23	1.84
Copper, Cu	T1	0.08	0.37
	T2	0.14	0.27
	T3	0.01	0.21

3.2 *Coleus amboinicus* Growth Performance

Figure 1 shows the height progression of *Coleus amboinicus* grown under four treatment groups: T0, T1, T2, and T3. All sludge-amended treatments demonstrated enhanced plant growth relative to the control (T0), which exhibited the slowest increase in height throughout the 54-day observation period. Among the treatment groups, T3 showed the highest growth rate, with plants reaching approximately 36.0 ± 1.0 cm by Day 54. The growth rate of T3 was rapid from Day 18 to Day 36, followed by a plateau phase, indicating earlier maturity. Plants in T1 also displayed substantial growth (32.3 ± 1.2 cm), marginally exceeding T2 (30.7 ± 0.6 cm). This suggests that the medium sludge ratio may not have provided a proportionally higher nutrient availability. As shown in Table 2, the treatment groups exhibited distinct differences in nutrient drawdown efficiency. In the T3 group, a substantial reduction in both K and Ca concentrations by Day 54 indicates highly efficient root assimilation, which directly correlated with the maximum plant height achieved [27]. In contrast, plants grown in T0, which received no sludge amendment, recorded the lowest final height of 19.7 ± 0.6 cm, emphasizing the beneficial role of sludge in enhancing plant development. A similar growth trend has been documented in previous literature [28, 29]. These results suggest that optimized sludge amendment, especially at higher ratios, significantly improves the growth performance of *Coleus amboinicus* under controlled conditions. However, the long-term effects on plant productivity and soil health should be further explored.

Figure 2 illustrates the changes in leaf width of *Coleus amboinicus* in different sludge-soil ratios (T0, T1, T2 and T3). All treatment groups exhibited an increase in leaf width over a 54-day cultivation period, with growth rates varying. The unamended soil control (T0) recorded the lowest final leaf width (4.0 ± 0.0 cm) and the slowest development, whereas T3, which contained the highest sludge content, demonstrated the most substantial increments. Growth in the T3 initially progressed at a slightly slower rate; however, after Day 3, a noticeable increase trend was observed, with the leaf width eventually peaking at approximately 6.6 ± 0.5 cm. T1 and T2 groups followed a similar development trajectory, both reaching a final leaf width of approximately 6.0 ± 0.0 cm, respectively meanwhile T0 showed minimal leaf growth of about 4.0 ± 0.0 cm, at the end of the observation period. The rapid growth phase for T3 occurred between Day 21 and Day 36, after which it began to plateau. In contrast, T0 showed minimal leaf growth, indicating limited nutrient supply to *Coleus amboinicus*. A similar growth trend was observed by [28], in which plants exhibited satisfactory growth despite the application of relatively high proportions of water treatment sludge, supporting the findings of the present study. This indicated that the addition of sludge to soil can promote soil fertility and nutrient content, which contribute to plant growth performance.

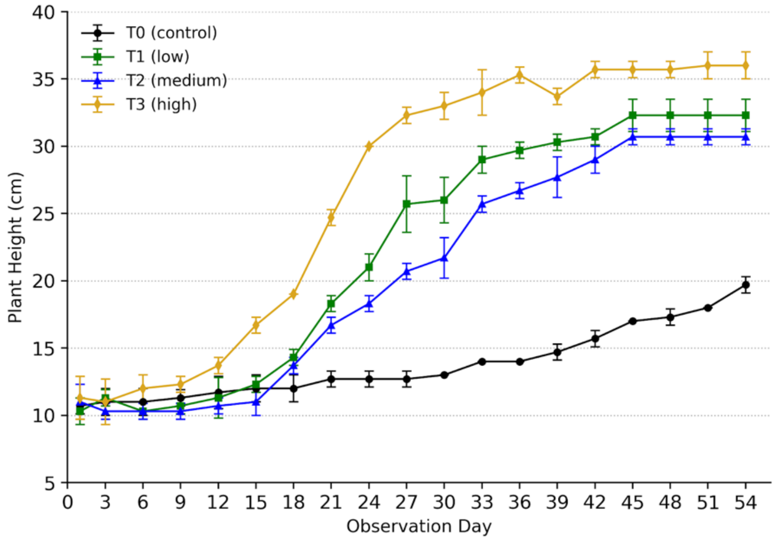

Figure 1: Plant height progression in response to sludge-soil ratios.

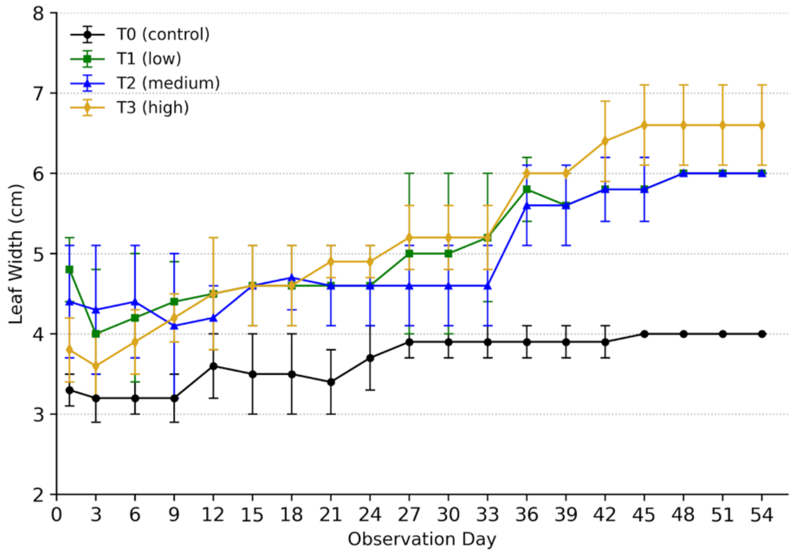

Figure 2: Effect of sludge-amend ratios to leaf width over 54 days of observation.

3.3 Macronutrients and Micronutrients Effect on the Growth

Based on the chemical evolution of the substrate among various sludge-soil treatments presented in Table 2, both K and Ca showed substantial decreases from initial to final concentrations across all ratios. This significant depletion indicates rapid and active plant uptake. Potassium is a critical macronutrient that governs water regulation, enzyme activation, and various physiological functions, while calcium is essential for basic biological functions and structural integrity [29, 30]. The massive draw of these macronutrients from the substrate supported the rapid increase in growth and early maturity observed between Days 18 and 36 in all treatments. [29]. The unamended control (T0) lacked this vast nutrient reservoir, which explains why it recorded the lowest final height. Integrating the phenotypic growth data (Figures 1 and 2) with the chemical analysis of the substrate (Table 2) reveals that T3 promoted greater plant development than T1, despite the higher initial K concentration in the T1 substrate. The findings indicate that plant growth is influenced not only by K concentration but also by the availability and balance of other essential nutrients [31]. Specifically, T3 plants achieved a high Ca uptake efficiency that significantly exceeded that of T1, thereby compensating for a marginally lower absolute K reduction in the T3. Excessive K^+ levels in the soil may suppress the uptake of essential cations, including Mg^{2+} and Ca^{2+}, as a result of competitive cation antagonism [31]. This finding aligned with [32], which found that excessive application of a single nutrient can disturb nutrient balance and restrict plant growth, even when macronutrients are abundant.

The observed increase in micronutrient concentrations, particularly Cu and Zn, across all treatment ratios suggests active nutrient mineralization within the sludge-amended soils. Cu levels rose steadily from initial to final measurements in all treatments, while Zn showed a marked increase, especially in T3, where concentrations increased from 0.23 mg/L to 1.84 mg/L. This enrichment is likely associated with the progressive decomposition of organic matter, which facilitates the gradual release and concentration of trace metals into the soil solution over time. Although heavy metals are often associated with phytotoxic risks, Cu and Zn at low to moderate concentrations are essential micronutrients that play key roles in physiological processes such as chlorophyll synthesis, enzyme activation, and overall plant metabolic function [33]. The absence of growth inhibition, despite the elevated micronutrient levels, indicates that the concentrations remained within a beneficial range rather than reaching toxic thresholds [33]. In fact, the enhanced plant performance observed, including superior growth reaching up to 36.0 cm in the highest sludge ratio treatment (T3), suggests that these micronutrients contributed positively to plant vitality and productivity. This demonstrates that sludge amendment, when applied at appropriate ratios, can improve soil fertility through controlled release of micronutrients while maintaining plant health and growth performance [33].

A primary constraint when utilizing water treatment residues is the presence of potentially toxic elements, particularly Al derived from alum coagulants used during the water treatment process. The experimental findings demonstrate substantial, natural stabilization of these potentially phytotoxic elements within the sludge-soil treatments. By Day 54, accessible Al concentrations dropped significantly across all treatments, with T2 showing the largest decrease, falling from 210.10 mg/L to 83.18 mg/L. Chromium (Cr) followed an identical pattern, dropping from 166.4 mg/L to 55.33 mg/L in the same treatment group. The decrease in the final substrate suggests these elements were either taken up by the plant or stabilized in the different sludge-soil treatments. High organic matter content and neutral-to-alkaline pH in sludge typically help immobilize these heavy metals, thereby reducing their bioavailability and preventing them from reaching toxic levels in plant tissues [33]. The normal growth observed in the plants indicates that these metals remained safely below phytotoxic levels, demonstrating that sludge amendment at appropriate ratios can effectively mitigate metal toxicity while maintaining overall plant health and growth [34].

4. CONCLUSION

Using water treatment sludge (WTS) as a soil amendment for plant cultivation demonstrates a positive relationship between sludge-soil and plant growth, with higher sludge incorporation promoting greater plant height and overall development. This accelerated growth performance is driven by the essential macronutrients within the sludge; specifically, potassium (K) is an important nutrient that supports plant growth. Moreover, while WTS naturally contains inorganic materials like Al, the inherent properties of the sludge-soil treatments ensure that these elements do not jeopardize plant development or cause phytotoxicity. The plants exhibited normal growth, indicating that the alum content did not adversely affect nutrient uptake or plant productivity under the conditions studied. However, to fully validate the potential of sludge usage in agriculture and land application, future studies should focus on conducting a thorough toxicity analysis to ensure safety. Furthermore, comparative assessments with standard commercial substrates and an evaluation of its performance alongside supplementary fertilizers are highly recommended to optimize its practical application.

Overall, the findings suggest that WTS can serve as a potential and sustainable growth medium, providing valuable nutrients while maintaining a safe environment for plant growth. By turning the industrial waste stream into valuable, renewable resources, it directly supports waste reduction and circular economy practices by repurposing water treatment residuals as a beneficial soil amendment. This reduces the volume of waste requiring landfill disposal and minimizes transportation costs associated with transporting the residuals from the treatment plant to disposal sites (in accordance with SDG12 targets). Additionally, the recycling of natural compounds promotes environmental sustainability and contributes to SDG15 by transforming the sludge into a valuable soil amendment that combats land degradation.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to Universiti Teknologi MARA Cawangan Johor for providing the facilities and technical support necessary for this research. The authors also gratefully acknowledge Universiti Malaysia Perlis (UniMAP) for its support in the publication of this research.

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Conflict of interest statement: The authors declare no conflict of interest.

Author contributions statement: Conceptualization, Siti Hajar Anaziah Muhamad & Narita Noh; Methodology, Mohamad Faris Mohamad Yusri; Investigation, Mohamad Faris Mohamad Yusri; Data Analysis, Siti Hajar Anaziah Muhamad; Writing & Editing, Siti Hajar Anaziah Muhamad & Narita Noh.

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Data Availability Statement: Data sharing is not applicable to this article as no new datasets were created or analyzed during this study.