Water Quality Improvement Using a TWF/C-PAM Treatment Agent and Reutilization Potential of Sewage Sludge as an Agricultural Soil Amendment

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The applicability of a torrefied wood flour/cationic polyacrylamide (TWF/C-PAM) treatment agent for pilot-scale wastewater treatment and the reutilization potential of the generated sewage sludge as an agricultural soil amendment were evaluated. The TWF/C-PAM treatment agent showed high removal efficiencies for turbidity 91.8%, suspended solids 96.4%, total phosphorus 90.0%, chemical oxygen demand 67.3%, and biochemical oxygen demand 61.2%. The treatment performance was comparable to that of conventional 10% polyaluminum chloride, although relatively low total nitrogen removal efficiency 10.3% was observed. Lettuce (*Lactuca sativa* L.) was cultivated in sewage sludge-amended soil presented with sludge addition ratios of 1%, 5%, 10%, and 30%. Chlorophyll and carotenoid contents increased up to the 5% treatment level, indicating the potential applicability of sewage sludge as an agricultural soil amendment. These findings demonstrate the potential of the TWF/C-PAM treatment process for simultaneous wastewater treatment and sewage sludge reutilization.

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INTRODUCTION

Urban sewage and industrial wastewater generation have continuously increased because of improved living standards, urbanization, and population growth (Chen *et al.* 2007; Oh *et al.* 2011). Excessive influx of nutrients, such as phosphorus and nitrogen, can deteriorate water quality, resulting in eutrophication and algal blooms. Accordingly, polyaluminum chloride (PAC) coagulants have been widely used in sewage treatment plants to remove dissolved pollutants from water (Park and Kang 2020). However, excessive PAC application can increase the concentration of residual aluminum ions in treated water. Residual aluminum in water has been associated with environmental and health concerns, including neurological diseases, such as Alzheimer's disease (Han and Kang 2016).

In addition to pollutant removal efficiency, floc formation and settling behavior are important factors in wastewater treatment processes. Small flocs generated during coagulation treatment can reduce settling efficiency and prolong sludge dewatering times, thereby increasing the operational burden of downstream filtration and sludge handling processes (Park and Kang 2020). Therefore, recent studies have focused not only on reducing the use of inorganic coagulants such as PAC, but also on improving floc growth and settling efficiency using environmentally friendly biomass-based materials.

Cationic polyacrylamide (C-PAM) has been widely used as a retention aid and polymer-assisted flocculation material in wastewater treatment and papermaking industries because of its particle bridging ability and flocculation performance (Shehram and Rani 2022). However, additional materials capable of improving floc growth, settling behavior, and dispersion stability are often required to further enhance treatment performance under practical wastewater treatment conditions. In particular, untreated wood flour (WF) has limited applicability in aqueous systems because of its poor dispersion behavior (Yang *et al.* 2016).

To overcome these limitations, torrefied wood flour (TWF) was investigated as a biomass-assisted water treatment material (Yang *et al.* 2016, 2019; Park and Kang 2020). Yang *et al.* (2016) studied the surface charge properties of WF under different thermal treatment conditions and reported that untreated WF showed a zeta potential of approximately -22.8 mV, whereas the zeta potential of TWF reached values of -52.5 mV depending on the thermal treatment conditions. The increased negative surface charge of TWF improved its dispersion behavior in water and promoted electrostatic interaction with cationic polymer systems. TWF could be effectively combined with C-PAM to produce a TWF-containing C-PAM water treatment agent (TWF/C-PAM treatment agent) (Yang *et al*. 2019).

Previous studies demonstrated that TWF/C-PAM treatment agent exhibited effective pollutant removal performance and improved flocculation behavior. Yang *et al.* (2017) modified the surface charge of TWF from negative to positive by mixing TWF with C-PAM solution and subsequently drying the mixture to produce surface-modified TWF particles with a maximum zeta potential of +31.2 mV. The surface-modified TWF showed rapid decreases in turbidity and optical density, with a chlorophyll-a removal efficiency greater than 90% for negatively charged algal bloom pollutants. Yang *et al.* (2019) developed a TWF/C-PAM treatment agent by mixing TWF with a C-PAM solution without a drying process and evaluated its applicability to algal bloom water treatment. Removal efficiencies of 86% to 92% for total organic carbon and 53% for ammonia were observed, while the treated water maintained a stable pH range of 6.5 to 7.7 and showed low ecotoxicity toward daphnia. Furthermore, Park and Kang (2020) developed a TWF-containing PAC-reduced water treatment agent (TWF/PAC treatment agent) using TWF and reported high removal efficiencies of turbidity (maximum 90%), T-P (maximum 91%), and T-N (32%) in sewage treatment applications. They also reported that the addition of TWF improved floc settling behavior, shortened sedimentation time, and reduced the residual aluminum concentration in treated water by approximately 70% compared with conventional 10% PAC coagulant. These results indicated that the interaction between TWF and cationic polymers contributed not only to pollutant removal efficiency, but also to improved floc growth and settling performance.

Recently, the reutilization of sewage sludge generated during wastewater treatment processes has become an important environmental issue in South Korea because ocean dumping of sewage sludge was prohibited in 2012, and the regulation was expanded to all waste types in 2014 (Lee *et al.* 2014). Prior to the ban, approximately 69% of the sewage sludge was dumped into the ocean, whereas only 18.5% was recycled, 10.9% was incinerated, and 2.1% was dumped in landfills (Lee *et al.* 2014). Sludge treatment can become a major source of greenhouse gas emissions under anaerobic treatment conditions

(Préndez and Lara-González 2007). Therefore, considerable attention has been focused on developing sustainable sludge treatment and recycling methods (Oh *et al.* 2011; Tanifuji *et al.* 2022).

Previous studies reported that sewage sludge can potentially be utilized as fuel, landscaping materials, soil conditioners, and agricultural soil amendments because of sewage sludge generated after coagulation treatment contains various nutrients (Kwak *et al.* 2005; Bai *et al.* 2013; Moon *et al.* 2013; Um *et al.* 2015). Park and Kang (2020) evaluated the energy conversion potential of sewage sludge generated from a PAC-reduced TWF treatment system and reported a dry calorific value of 3,378 kcal/kg, which satisfied the auxiliary fuel requirements of thermoelectric power plants (Park and Kang 2020). In addition, land application of sewage sludge has been considered an economically and environmentally acceptable management strategy because sewage sludge can improve the physical, chemical, and microbiological properties of soil (Huang and Chen 2009; Lindsay and Logan 1998).

In this study, the applicability of a TWF/C-PAM treatment agent was evaluated using a pilot-scale wastewater treatment plant installed at a sewage treatment facility. In addition, sewage sludge discharged after treatment was evaluated for its potential application as an agricultural soil amendment by analyzing lettuce growth, chlorophyll content, soil nutrient characteristics, and residual heavy metal contents. Therefore, this study aimed to evaluate both the practical applicability of the biomass-assisted hybrid wastewater treatment system and the reutilization potential of generated sewage sludge through the effective utilization of unused forest biomass.

EXPERIMENTAL

The experimental procedure is presented in Fig. 1.

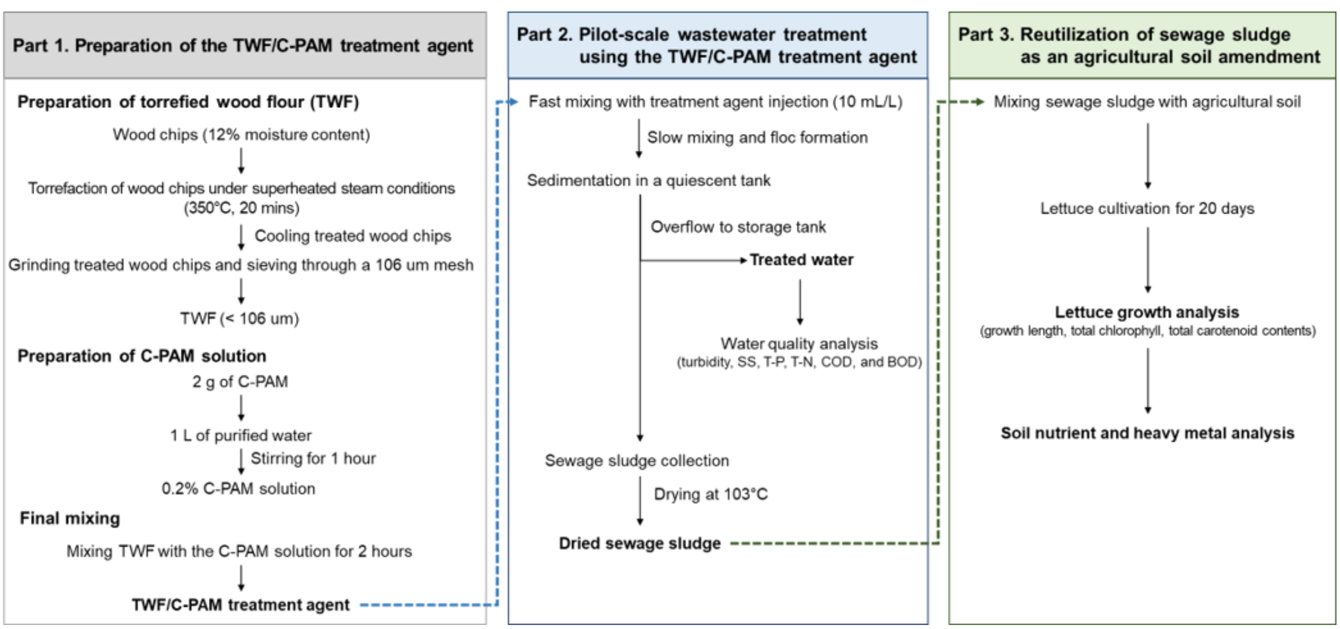

Fig. 1. Experimental procedure for preparation of the TWF/C-PAM treatment agent, pilot-scale wastewater treatment, and reutilization of sewage sludge

Materials

TWF was used to manufacture the TWF/C-PAM treatment agent using oak chips for pulp with a moisture content of 12% (± 0.5%) as the raw material. The supplied oak chips were prepared using a superheated steam treatment method under rapid thermal treatment (350 °C, 20 min). After the thermal-treated, the wood chips were ground and sieved to obtain particles smaller than 106 µm (Yang *et al.* 2019). Cationic polyacrylamide (C-PAM) was supplied by Solenis (Gimcheon-si, South Korea). The C-PAM powder had a molecular weight of 8,000,000 g/mol and is commonly used as a retention aid and flocculant in the papermaking and wastewater treatment process. C-PAM was prepared as a 0.2% aqueous solution. The TWF/C-PAM treatment agent was prepared by adding 10 g of TWF to 1 L of the 0.2% C-PAM solution followed by mixing for 2 hours.

To evaluate the applicability of sewage sludge discharged after treatment, agricultural soil was used, and lettuce (*Lactuca sativa* L.), a representative leafy vegetable crop, was selected as the experimental plant species.

Preparation of the TWF/C-PAM Treatment Agent

To evaluate the water quality improvement performance of the TWF/C-PAM treatment agent, a pilot-scale wastewater treatment system was installed at a sewage treatment plant located in Daejeon, South Korea, where effluent from the primary sedimentation tank was continuously supplied as the influent wastewater (Fig. 2). The pilot-scale treatment system consisted of a flow control tank, fast mixing tank, slow mixing tank, quiescent settling tank, and treated water storage tank. The TWF/C-PAM treatment agent was injected at dosage of 10 mL/L of influent wastewater, and the supernatant collected from the settling tank was used for water quality analysis. The characteristics of the influent wastewater are listed in Table 1.

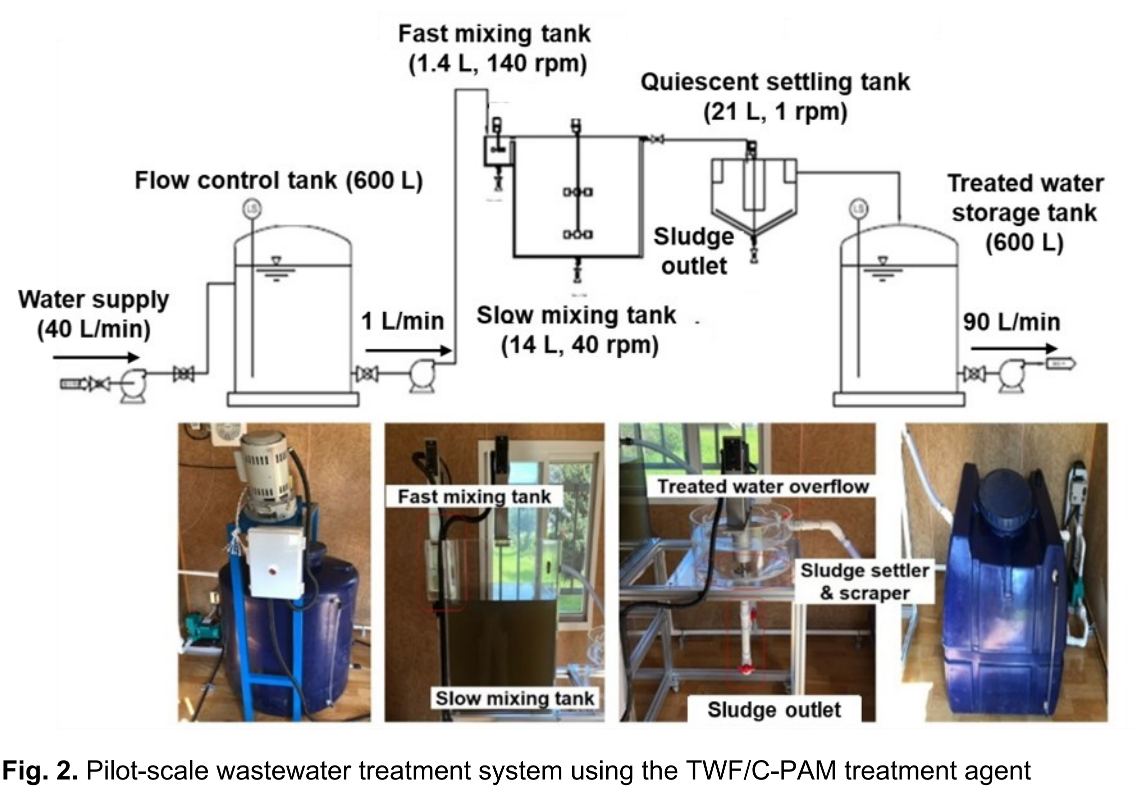

Fig. 2. Pilot-scale wastewater treatment system using the TWF/C-PAM treatment agent

Table 1. Water Quality Characteristics of Influent Wastewater from The Primary Sedimentation Tank

	Turbidity (NTU)	SS (mg/L)	T-P (mg/L)	T-N (mg/L)	COD (mg/L)	BOD (mg/L)
Concentration	60 (± 5.5)	140 to 188	4.9 (± 1.5)	20 (± 2)	31 to 57.8	40.5 to 60.8

Turbidity, suspended solids (SS), total phosphorus (T-P), total nitrogen (T-N), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) were analyzed to evaluate the water treatment performance. Turbidity was measured using a TB 210 IR turbidimeter (Lovibond, UK) with a measurement range of 0 to 1,100 NTU.

SS was measured by filtering a known volume of sample through a glass fiber filter (GF/C) attached to a filtration apparatus. After filtration, the filter paper was dried to a constant weight, and the SS content was calculated based on the weight difference before and after filtration. The SS concentration was calculated using Eq. (1),

$$SS\ (mg/L) = (b - a) \times \frac{1{,}000}{V} \tag{1}$$

where *a*, *b*, and *V* represent the weights of the glass fiber filter before filtration (mg), the weight of the glass fiber after filtration (mg), and the sample volume (mL), respectively.

T-N, T-P, BOD, and COD were analyzed using a water quality analyzer (HS-3300, HUMAS, South Korea) according to the standard method for water pollution analysis (No. 2017-4). The concentrations of raw and treated wastewater were determined based on absorbance measurements.

Preparation of Sewage Sludge-Amended Soil

Effluent from the primary sedimentation tank of the sewage treatment plant was used as the influent wastewater source for generating sewage sludge in this study. The collected sewage sludge was used after the dewatering process, and the moisture content of the dehydrated sewage sludge was 73.9% (± 0.6%). Commercial horticultural soil used for leafy vegetables cultivation showed a moisture content of 120% (± 3%).

The dewatered sewage sludge was mixed with the horticultural soil at sludge addition ratios of 1%, 5%, 10%, and 30% based on dry solid content (Table 2). Before sowing lettuce seeds, water was added to adjust the moisture content of the mixed soil uniformly. Each treatment condition was prepared in triplicate, and the final weight of each soil mixture was 45 g.

Table 2. Mixing Ratios of Sewage Sludge and Horticultural Soil Based on Dry Solid Content

	Control	T1	T5	T10	T30
Sewage sludge	0%	1%	5%	10%	30%
Horticultural soil	100%	99%	95%	90%	70%

Growth Conditions and Characteristics

Five replicate pots were prepared for each treatment condition, and ten seeds were sown in each pot. The seeds were cultivated in a growth chamber under controlled environmental conditions (Fig. 3). The growth chamber was maintained at 21 °C (± 2 °C) with a relative humidity of 50%. The light cycle was controlled at 10,000 lux for 16 h and

0 lux for 8 h per day (Lee *et al.* 2017). After 20 days of cultivation, the lettuce plants were harvested and separated into roots and leaves. The length and fresh weight of the roots and leaves were measured individually (Jeoung *et al.* 2013).

Fig. 3. Lettuce growth after 20 days of cultivation under different sewage sludge amendment conditions

Chlorophyll is an important photosynthetic pigment involved in light absorption and energy transfer in plants (No *et al.* 2016). Chlorophyll-a is the primary pigment response for light energy absorption during photosynthesis, whereas chlorophyll-b acts as an accessory pigment (Lee *et al.* 2005). In addition, carotenoids function as accessory pigments that participate in light absorption and protect plant cells from excessive light energy (Park *et al.* 2015).

To analyze total chlorophyll and total carotenoid content, 0.2 g of lettuce leaves was mixed with 8 mL of 80% acetone and extracted in a cool and dark environment for 7 days. After extraction, the supernatant was separated, and absorbance was measured at 663, 645, and 470 nm using a UV/VIS spectrometer (HS-3700, Humas, South Korea). Total chlorophyll and carotenoid contents were calculated using Eqs. 2, 3, 4, and 5 based on the measured absorbance values (Jeoung *et al.* 2013).

$$Chlorophyll\ a\ (mg/g) = 12.7\ A_{663} - 2.69\ A_{645} \tag{2}$$

$$Chlorophyll\ b\ (mg/g) = 22.9\ A_{645} - 4.68\ A_{663} \tag{3}$$

$$Total\ chlorophyll\ (a+b)\ (mg/g) = 20.29\ A_{645} + 8.02\ A_{663} \tag{4}$$

$$Total\ carotenoid\ (mg/g) = (1000\ A_{470} - 1.82\ Chl_a - 85.02\ Chl_b)/198 \tag{5}$$

Soil Nutrients and Heavy Metal Content

After lettuce cultivation, the soil samples were air-dried and passed through a 100-mesh (≤ 254 μm) sieve prior to nutrient and heavy metal analysis (Elhindi *et al.* 2018). Moisture content was determined based on weight reduction after oven drying at 105 ℃ until a constant weight was reached.

Soil pH was measured after mixing soil and distilled water at a water-to-soil ratio of 5:1 and allowing the mixture to stand for 24 h. Soil chemical analyses were conducted at the Soil Environment Analysis Center, Chungnam National University. Available phosphorus was determined colorimetrically at 720 nm using the Lancaster method. Exchangeable cations were extracted using 1 M NH_4OAc buffer (pH 7.0) and analyzed using an inductively coupled plasma optical emission spectrometer (ICP-OES).

Statistical Analysis

Statistical analyses were performed using SPSS Statistics 26 software (IBM Corp., Armonk, NY, USA). One-way analysis of variance (ANOVA) followed by Duncan's multiple range test was conducted to evaluate the effect of sewage sludge mixing ratio on lettuce growth characteristics. Statistical significance was determined at $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***). According to Duncan's multiple range test, mean values followed by the same superscript letter (*i.e.*, a, b, or c) were not significantly different at the 0.05 significance level.

RESULTS AND DISCUSSION

Water Quality Improvement Effect of TWF/C-PAM Treatment Agent

The TWF/C-PAM treatment agent showed high removal efficiencies for turbidity, SS, and T-P, exceeding 90% and exhibiting performance comparable to those of 10% PAC and the TWF/PAC treatment agent (Table 3). Among the evaluated parameters, phosphorus removal is particularly important because phosphorus discharged from wastewater treatment plants is a major contributor to eutrophication in aquatic environments.

Choi *et al.* (2015) investigated the phosphate adsorption characteristics of oak biochar and reported phosphate phosphorus removal efficiencies ranging from 2.7% to 31%, depending on the biochar dosage (4.0 to 16 g/L) (Choi *et al.* 2015). The TWF/C-PAM treatment agent achieved a T-P removal efficiency of 90%, which was only slightly lower than 10% PAC (92%), These results suggest that the combination of TWF and C-PAM contributed to effective phosphorus removal through combined adsorption and coagulation effects.

Table 3. Water Contaminant Removal Efficiencies of the TWF/C-PAM Treatment Agent

	Turbidity	SS	T-P	T-N	COD	BOD
TWF/C-PAM treatment agent	91.8%	96.4%	90%	10.3%	67.3%	61.2%
10% PAC (Park and Kang 2020)	90.3%	97.9%	92%	35.6%	59.8%	68.0%
TWF/PAC treatment agent (Park and Kang 2020)	90%		91%	22%		

For T-N removal, 10% PAC and the TWF/PAC treatment agent showed removal efficiencies of 35.6% and 22%, respectively, but the TWF/C-PAM treatment agent showed a relatively low removal efficiency of 10.3%. The lower T-N removal efficiency may be attributed to the nitrogen-containing components of both TWF and C-PAM. Lee *et al.* (2012) reported that the oak biomass contained approximately 0.19% nitrogen based on elemental analysis. In addition, C-PAM consists of nitrogen-containing repeating units with the chemical formula $(C_3H_5NO)_n$ (Wang *et al.* 2023). Therefore, the nitrogen containing characteristics of the raw materials may have affected the T-N removal performance.

The COD removal efficiencies of 10% PAC and the TWF/C-PAM treatment agent were 59.8% and 67.3%, respectively. In contrast, the BOD removal efficiencies were 68.0% and 61.2%, respectively. The relatively lower BOD removal efficiency of the

TWF/C-PAM treatment agent may be associated with the organic characteristics of TWF and C-PAM.

Overall, the TWF/C-PAM treatment agent exhibited water pollutant removal efficiencies comparable to those of 10% PAC, except for T-N removal. These results indicate the potential applicability of the TWF/C-PAM treatment agent as an eco-friendly alternative for wastewater treatment while improving the utilization of unused forest biomass resources.

Lettuce Growth in Sewage Sludge-Amended Soil

The growth results of lettuce cultivated for 20 days in sewage sludge-amended soil are presented in Table 4. Increasing the sewage sludge mixing ratio did not significantly affect the number of leaves or root weight. However, leaf length and leaf weight increased with increasing sewage sludge content. In particular, leaf length increased from 30.3 mm in the control to 44.6 mm in the T30 treatment, whereas leaf weight increased from 289.0 mg to 522.2 mg. In contrast, root length and fresh weight showed relatively small differences among treatment conditions. Root length ranged from 84.7 to 95.4 mm, whereas root weight ranged from 67.7 to 79.9 mg. These results suggest that sewage sludge amendment had a greater influence on above-ground lettuce growth than on root development during the early cultivation stage.

Table 4. Growth Characteristics of Lettuce Cultivated in Sewage Sludge-Amended Soil

	Control	T1	T5	T10	T30
Number of leaves (F = 1.604)	4.5	4.4	4.6	4.7	4.9
Leaf length (mm) (F = 4.613**)	30.3^{a}	40.3^{b}	43.8^{b}	43.2^{b}	44.6^{b}
Leaf fresh weight (mg) (F= 7.476***)	289.0^{a}	436.6^{b}	423.7^{b}	451.9^{bc}	522.2^{d}
Root length (mm) (F = 3.143*)	95.4^{c}	94.4^{bc}	87.3^{ab}	84.7^{a}	87.0^{ab}
Root fresh weight (mg) (F = 0.548)	70.1	79.9	67.7	70.4	72.8

The chlorophyll content of lettuce cultivated in sewage sludge-amended soil are presented in Fig. 4. Total chlorophyll content generally increased with increasing sewage sludge addition. However, chlorophyll-a content increased up to the T5 treatment (24.6 mg/g) and remained relatively similar at higher sludge addition levels (24.9- 25.8 mg/g). Chlorophyll-b showed a similar trend, with values of 13.1 and 13.9 mg/g in the T5 and T10 treatments, respectively.

Statistical analysis of total chlorophyll content showed significant differences among treatment conditions (F = 25.679***). The total chlorophyll content increased in the order of T30 > T10 > T5 > T1 > Control. However, no significant difference was observed between T5 and T10 treatments, suggesting that increasing sewage sludge addition beyond 5% had a limited effect on chlorophyll accumulation.

Total carotenoid content increased from the control to the T5 treatment and then slightly decreased at higher sludge addition levels (Table 5). Carotenoids function as accessory pigments involved in light absorption and protection against excessive light energy (Park *et al.* 2015).

Sludge amendment promoted chlorophyll and carotenoid accumulation in lettuce, particularly at sludge addition levels of 5% or higher. Previous studies reported that biochar can improve soil quality and promote nutrient accumulation in plants (Gałązka *et al.* 2019; Torabian *et al.* 2021; Cai *et al.* 2023). Therefore, the organic compounds derived from sewage sludge and torrefied wood have contributed to the enhance plant growth and pigment accumulation observed.

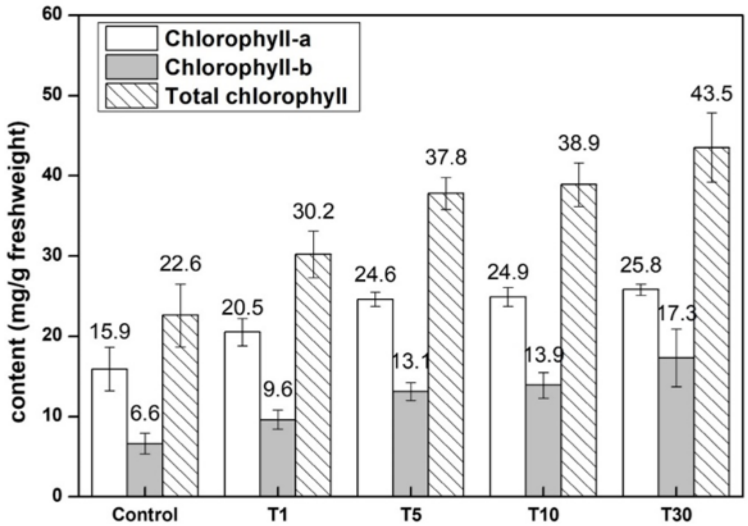

Fig. 4. Chlorophyll-a, Chlorophyll-b, and total chlorophyll contents of lettuce cultivated in sewage sludge-amended soil

Table 5. Total Carotenoid Content in Lettuce Cultivated in Sewage Sludge-Amended Soil Added

	Control	T1	T5	T10	T30
Total Carotenoid content (mg/g) (F = 9.565***)	2.99^{a}	3.76^{b}	4.75^{d}	4.46^{cd}	3.86^{bc}

The soil chemical properties after lettuce cultivation are presented in Table 6. Soil pH slightly increased with increasing sewage sludge addition, ranging from 4.9 in the control to 5.5 in the T30 treatment. Total nitrogen (T-N) and available phosphorus (P_2O_5) contents generally increased as the sewage sludge mixing ratio increased. In contrast, exchangeable sodium and potassium contents tended to decrease with increasing sludge addition.

Table 6. Soil Chemical Properties after Lettuce Cultivation

		Control	T1	T5	T10	T30
pH		5.0	5.0	5.2	5.4	5.5
CEC (cmol (+)/kg)	Na^+	10.18	9.4	8.64	7.63	7
	K^+	6.66	6.05	4.53	4.3	3.1
	Ca^{2+}	24.28	24.83	26.46	24.6	29.3
	Mg^{2+}	12.89	13.75	13.94	12.53	12.55
T-N (%)		1.88	2.65	3.56	4.69	4.88
P_2O_5 (mg/kg)		2804.75	2075.38	2408.84	3130.97	4825.79

The heavy metal contents of the soil are presented in Table 7. Heavy metal concentrations generally increased sludge addition. However, all measured heavy metal contents remained below the soil contamination standards for region 1 defined by the Korean Soil Environment Conservation Act, which includes agricultural and residential land uses such as dry paddy fields, rice paddies, orchards, school grounds, and children's playgrounds. The sewage sludge-amended soil satisfied the regulatory criteria for agricultural soil applications.

Table 7. Heavy Metal Contents of Soil after Lettuce Cultivation

Heavy Metal (mg/kg)	Control	T1	T5	T10	T30	Soil contamination standard (1 Region)
Mn	107.86	96.69	101.85	132.04	141.52	
Cd	0.16	0.17	0.16	0.22	0.29	4
Cu	8	8.3	12.2	22	51	150
Pb	12.2	12.7	11.5	15.1	18.6	200
Zn	22.7	25.8	30.5	53.5	112.9	300

Lee *et al.* (1996) studied the effects of municipal sewage sludge on lettuce cultivation and reported that sludge application promoted lettuce growth while maintaining heavy metal accumulation within acceptable levels. Lettuce growth increased with sewage sludge addition while heavy metal concentrations remained below the regulatory limits.

Therefore, the results indicate that sewage sludge generated from the TWF/C-PAM wastewater treatment process has potential applicability as an agricultural soil amendment. In addition, the utilization of TWF in the treatment agent may contribute to the effective utilization of unused forest biomass resources.

CONCLUSIONS

The study evaluated the applicability of the TWF/C-PAM treatment agent for pilot-scale wastewater treatment and investigated the reutilization potential of the generated sewage sludge as an agricultural soil amendment.

1. The TWF/C-PAM treatment agent showed high removal efficiencies for turbidity (91.8%), SS (96.4%), and T-P (90%), with treatment performance comparable to that of conventional 10% PAC coagulants. However, relatively low T-N removal efficiency (10.3%) was observed because of the nitrogen-containing characteristics of TWF and C-PAM.
2. Sewage sludge amendment promoted lettuce growth characteristics, chlorophyll accumulation, carotenoid content, particularly at sludge addition levels of 5% or higher. Soil analysis showed that the sewage sludge-amended soil remained with the slightly acidic range and contained abundant nitrogen, calcium, and phosphate contents. In addition, all measured heavy metal concentrations satisfied the Korean Soil Environment Conservation Act standards for Region 1 soils.
3. Sewage sludge generated from the TWF/C-PAM treatment process has potential applicability as an agricultural soil amendment while contributing to the effective utilization of unused forest biomass resources. Additional long-term cultivation and field-scale studies are needed to evaluate long-term nutrient balance, soil stability, and heavy metal accumulation under practical agricultural conditions.

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REFERENCES CITED

Bai, Y., Tao, T., Gu, C., Wang, L., Feng, K., and Shan, Y. (2013). "Mudflat soil amendment by sewage sludge: Soil physicochemical properties, perennial ryegrass growth, and metal uptake," *Soil Science and Plant Nutrition* 59(6), 942-952. https://doi.org/10.1080/00380768.2013.866522

Cai, Y., Liu, L., Zhang, W., Xing, S., Liang, X., Gao, M., Yu, H., Jiang, Z., Ogino, K., Chen, X., Wang, B., and Si, H (2023). "Effects of adding pyrochar and hydrochar to calcareous soil and nutrient uptake by maize," *BioResources* 18(2), 2981-2997. https://doi.org/10.15376/biores.18.2.2981-2997

Chen, X., Kuniaki, S., Toshiyuki, W., and Tsugiyuki, M. (2007). "Comparative study of soils and other adsorbents for decolorizing sewage and livestock wastewater," *Soil Science and Plant Nutrition* 53(2), 189-197. https://doi.org/10.1111/j.1747-0765.2007.00124.x

Choi, Y. S., Hong, S. G., Kim, S. C., and Shin, J. D. (2015). "Adsorption characteristics of aqueous phosphate using biochar derived from oak tree," *Journal of the Korea Organic Resource Recycling Association* 23(3), 60-67. https://doi.org/10.17137/korrae.2015.23.3.060

Elhindi, K. M., Al-Mana, F. A., El-Hendawa, S., Al-Selwey, W. A., and Elgorban, A. M. (2018). "Arbuscular mycorrhizal fungi mitigate heavy metal toxicity adverse effects in sewage water contaminated soil and *Tagetes erecta* L.," *Soil Science and Plant Nutrition* 64(5), 662-668. https://doi.org/10.1080/00380768.2018.1490631

Gałązka, A., Jończyk, K., Gawryjołek, K., and Ciepiel, J. (2019). "The impact of biochar doses on soil quality and microbial functional diversity," *BioResources* 14(4), 7852-7868. https://doi.org/10.15376/biores.14.4.7852-7868

Han, S. W., and Kang, L. S. (2016). "Comparison of Fe (III) coagulants and their characterization for water treatment," *Journal of Korean Society of Environmental Engineers* 38(4), 169-176. https://doi.org/10.4491/KSEE.2016.38.4.169

Huang, C. C., and Chen, Z. S. (2009). "Carbon and nitrogen mineralization of sewage sludge compost in soils with a different initial pH," *Soil Science and Plant Nutrition* 55(5), 715-724. DOI: 10.1111/j.1747-0765.2009.00410.x

Jeoung, Y. H., Kim, Y. N., Kim, K. R., and Kim, K. H. (2013). "Physiological response and cadmium accumulation of Mus1 transgenic tobacco exposed to high concentration of Cd in soil: Implication to phytoremediation of metal contaminated soil," *Korean Journal of Soil Science and Fertilizer* 46(1), 58-64. https://doi.org/10.7745/KJSSF.2013.46.1.058

Kwak, Y. S., Hwangbo, J. K., Yun, H. C., Kang, S. J., and Kang, J. S. (2005). "Evaluation of sludge-derived bio-soil for landscape management," *RIST* 19, 11-14.

Lee, B. J., Min, H. G., Kim, M. S., and Kim, J. G. (2017). "Effects of copper (II) treatment in soil on tetracycline toxicity to growth of lettuce (*Lactuca sativa* L.)," *Ecology and Resilient Infrastructure* 4(1), 63-70. https://doi.org/10.17820/eri.2017.4.1.063

Lee, J. W., Kim, Y. H., Lee, S. M., and Lee, H. W. (2012). "Torrefaction characteristics of wood chip for the production of high energy density wood pellet," *Korean Chemical Engineering Research* 50(2), 385-389. https://doi.org/10.9713/kcer.2012.50.2.385

Lee, J. Y., Kim, C. H., Lee, G. S., Jo, H. S., Nam, H. G., Park, H. H., and Moon, S. O. (2014). "Physico-chemical characteristics of biodegradable seedling pots made of paper mill sludges," *Journal of Korea Technical Association of the Pulp and Paper Industry* 46(5), 9-18. https://doi.org/10.7584/ktappi.2014.46.5.009

Lee, M. H., Han, J. S., and Nobuyuki, K. (2005). "Changes of chlorophyll content in spinach by growth periods and storage," *Korean Journal of Food and Cookery Science* 21(3), 339-345.

Lee, S. U., Yoon, W., and Oh, I. (1996). "Effects of sewage sludge application on the growth of lettuce (*Lactuca sativa* L.)," *Journal of Natural Science* 9(1), 39-44.

Lindsay, B. J., and Logan, J. J. (1998). "Field response of soil physical properties to sewage sludge," *Journal of Environmental Quality* 27(3), 534-542. https://doi.org/10.2134/jeq1998.00472425002700030009x

Ministry of Environment. (2017). "A study on the revision of the water pollution standard method".

Moon, K. H., Kim, J. Y., Chang, M. I., Kim, U. S., Kim, S. J., and Baek, S. H. (2013). "Heavy metal and amino acid contents of soybean by application of sewage and industrial sludge," *Journal of the Korean Society of Food Science and Nutrition* 42(2), 268-277. https://doi.org/10.3746/jkfn.2013.42.2.268

No, J. H., Yoon, H. N., Park, S. R., Yoo, S. J., and Shin, M. (2016). "Color stability of chlorophyll in young barley leaf," *Journal of the East Asian Society of Dietary Life* 26(4), 314-324. https://doi.org/10.17495/easdl.2016.8.26.4.314

Oh, T. S., Kim, M. J., Lim, J. J., Kim, Y. S., and Yoo, C. K. (2011). "Estimate and environmental assessment of greenhouse gas (GHG) emission and sludge emission in wastewater treatment processes for climate change," *Korean Chemical Engineering Research* 49(2), 187-194. https://doi.org/10.9713/kcer.2011.49.2.187

Park, H. K., and Kang, S. G. (2020). "A study on the applicability of torrefied wood flour natural material based coagulant to removal of dissolved organic matter and turbidity," *Journal of the Korean Wood Science and Technology* 48(4), 472-487. https://doi.org/10.5658/WOOD.2020.48.4.472

Park, H. K., and Kang, S. G. (2020). "A study on the stability and sludge energy efficiency evaluation of torrefied wood flour natural material based coagulant," *Journal of the Korean Wood Science and Technology* 48(3), 271-282. https://doi.org/10.5658/WOOD.2020.48.3.271

Park, W. S., Kim, H. J., Chung, H. J., Chun, M. S., Kim, S. T., Seo, S. Y., Lim, S. H., Jeong, Y. H., Chun, J., An, S. K., and Ahn, M. J. (2015). "Changes in carotenoid and anthocyanin contents, as well as antioxidant activity during storage of lettuce," *Journal of the Korean Society of Food Science and Nutrition* 44(9), 1325-1332. https://doi.org/10.3746/jkfn.2015.44.9.1325

Préndez, M., and Lara-González, S. (2007). "Application of strategies for sanitation management in wastewater treatment plants in order to control reduce greenhouse gas emissions," *Journal of Environment Management* 88(4), 658-664. https://doi.org/10.1016/j.jenvman.2007.03.041

Shehram, M., and Rani, U. (2022). "Design of multijunction solar cells based potable water purification system using cationic polyacrylamide alum lime and ozone to remove COVID-19," *Journal of Independent studies and Research-Computing* 20(10), 56-62. https://doi.org/10.31645/JISRC.22.20.1.7

Tanifuji, K., Yamasaki, Y., Miyamoto, T., and Shigemura, H. (2022). "Effect of structural features of plant biomass as a dewatering aid for digested sludge from a wastewater treatment plant," *BioResources* 17(2), 2043-2052. https://doi.org/10.15376/biores.17.2.2043-2052

Torabian, S., Farhangi-Abriz, S., and Alaee, T. (2021). "Hydrochar mitigates salt toxicity and oxidative stress in maize plants," *Archives of Agronomy and Soil Science* 67, 1104-1118. https://doi.org/10.1080/03650340.2020.1779227

Um, K. R., Jang, Y. H., An, G. H., Cha, Y. L., Yu, G. D., Lee, J. E., Moon, Y. H., and Ahn, J. W. (2015). "Transitional patterns of vegetation in reclaimed land applied with solidified sewage sludge," *Korean Journal of Crop Science* 60(3), 381-387. https://doi.org/10.7740/kjcs.2015.60.3.381

Wang, H., Zhao, R., Wu, X., Zhao, D., Xue, H., Zhang, Y., Dai, N., Song, D., Zhang, M. L., and Ding, H. (2023). "Preparation and properties of bio-based attapulgite copolymer (BAC) sand-fixing material," *Polymers* 15(2), article 265. https://doi.org/10.3390/polym15020265

Yang, S. M., Lee, H. J., Choi, C., Kim, H. J., Lee, W. J., and Kang, S. G. (2016). "Study on adsorption performance of surface modified torrefied wood flour using cationic PAM," *Journal of Korea Technical Association of the Pulp & Paper Industry* 48(6), 271-276. https://doi.org/10.7584/JKTAPPI.2016.12.48.6.271

Yang, S. M., Lee, H. J., Nam, J. B., Oh, G. H., Lee, S. E., and Kang, S. G. (2017). "A study on the removal of algal bloom using positively charged torrefied wood flour," *Journal of Korea Technical Association of the Pulp and Paper Industry* 49(6), 31-37. https://doi.org/10.7584/JKTAPPI.2017.12.49.6.31

Yang, S. M., Lee, S. E., Park, H. K., and Kang, S. G. (2019). "A study on the impacts of paste type torrefied wood flour coagulants on water ecosystem," *Journal of the Korean Wood Science and Technology* 47(6), 709-720. https://doi.org/10.5658/WOOD.2019.47.6.709

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