PEMANFAATAN LUMPUR SEKUNDER NON-B3 DARI IPAL INDUSTRI MINUMAN BERKARBONASI SEBAGAI PENGGANTI KOMPOS PADA MEDIA TANAM

UTILIZATION OF NON-HAZARDOUS SECONDARY SLUDGE FROM BEVERAGE INDUSTRY WWTP AS A COMPOST SUBSTITUTE IN PLANTING MEDIA

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Abstrak

Lumpur sekunder yang dihasilkan dari proses pengolahan biologis aerobik pada industri minuman berkarbonasi terbentuk dalam jumlah besar dan mengandung unsur hara penting yang berpotensi untuk dimanfaatkan kembali. Penelitian ini mengevaluasi pemanfaatan lumpur sekunder non-B3 sebagai media tanam melalui karakterisasi awal serta pengujian kinerja melalui pencampuran dengan tiga sumber yang tanah yang berbeda (Tanah A, B, dan C) dan bahan tambahan. Lumpur kemudian dicampur dengan setiap jenis tanah sebagai kontrol, serta diberikan perlakuan tambahan berupa (a) dolomit, (b) *Trichoderma* sp., dan (c) kombinasi keduanya. Campuran tersebut diamati selama dua minggu untuk parameter rasio C/N serta kadar N, P, dan K sebagai indikator kualitas media tanam atau kompos. Hasil penelitian menunjukkan bahwa sebagian besar campuran mencapai rasio C/N ≥10 setelah dua minggu, kecuali campuran dengan Tanah A baik tanpa maupun dengan dolomit. Seluruh perlakuan memenuhi bahkan melampaui persyaratan minimum unsur hara dalam kompos berdasarkan SNI 19-7030-2004. Penambahan *Trichoderma* sp. memberikan peningkatan unsur hara paling signifikan, dengan kadar nitrogen mencapai 1,8% dan fosfor mencapai 4,0% pada campuran Lumpur–Tanah C, sedangkan kadar kalium tertinggi (0,4%) diperoleh pada campuran Lumpur–Tanah B dengan *Trichoderma* sp. Temuan ini menunjukkan bahwa sludge sekunder dari IPAL industri minuman berkarbonasi dapat diolah menjadi media tanam atau pengganti kompos yang layak, sehingga mendukung pengelolaan limbah yang berkelanjutan dan penerapan ekonomi sirkular.

Kata kunci: *Secondary sludge, Planting Media, Soil Amendment*.

Abstract

Secondary sludge produced from aerobic biological treatment in wastewater plants of the beverage industry is generated in substantial quantities and contains essential nutrients, offering potential for beneficial reuse. This study examines the use of non-hazardous secondary sludge as a planting medium by characterizing its properties and evaluating its performance when mixed with three different soil types (Soil A, B, and C) and amendments. The sludge cake was combined with each soil type as a control, and additional treatments included (a) dolomite, (b) Trichoderma sp., and (c) a combination of both amendments. The mixtures were *monitored over a two-week period for C/N ratio and N, P, K content, in accordance with compost quality parameters. Results indicate that most mixtures achieved a C/N ratio of ≥10 after two weeks, with the exception of Soil A with and without dolomite. All treatments surpassed the minimum compost nutrient requirements established by SNI 19-7030-2004. The application of Trichoderma sp. resulted in the highest nutrient enhancement, with nitrogen reaching 1.8% and phosphorus reaching 4.0% in sludge–Soil C mixtures, while potassium peaked at 0.4% in sludge–Soil B with Trichoderma sp. These findings confirm that secondary sludge from beverage industry wastewater treatment plants can be processed into viable planting media or compost substitutes, supporting sustainable sludge management and circular economy practices.*

Keywords: *Secondary sludge, Planting Media, Soil Amendment*.

1. INTRODUCTIONS

Wastewater produced during soft drink manufacturing emerges from various production stages, including discarded beverages and syrups, the rinsing of bottles and cans containing detergents and caustic agents, as well as the leakage or washing of machine lubricants. These processes generate wastewater rich in organic pollutants and key parameters such as biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), and varying concentrations of nitrogen, phosphorus, sodium, and potassium. (Alonso et al., 2024). Due to this composition, biological treatment, particularly aerobic processes, is a viable option for the secondary stage of wastewater treatment in beverage industries, given its effectiveness in reducing organic loads.(Muhamad Ng et al., 2021).

Aerobic biological treatment, while effective, yields considerable quantities of sludge (Cárdenas-Talero et al., 2022) that must undergo dewatering, handling, and final disposal. Such management steps often account for a substantial portion of wastewater treatment operational costs. Despite being classified as non-hazardous (non-B3), sludge from the soft drink industry is typically managed as a waste product, contributing to both economic and environmental burdens. Notably, sludge generated from biological treatment processes still contains valuable components such as organic matter and macronutrients (N, P, K) that are essential for plant growth (Shaddel et al., 2019). Yet, opportunities for beneficial reuse remain insufficiently explored across the beverage industry sector.

The limited utilization of non-hazardous industrial sludge reveals a clear gap in current waste management practices. Previous studies have examined sludge composting or its agricultural use in general contexts (Abdul Khaliq et al., 2017), including the enhancement using dolomite (Olego et al., 2021) and *Trichoderma sp.(Yao et al., 2023)* (Asghar & Kataoka, 2021)*but* research specifically targeting secondary sludge from carbonated beverage industries is scarce. Furthermore, little is known about how different soil types and specific amendments can enhance its agronomic properties. Addressing this knowledge gap aligns with global efforts to implement circular economy strategies, reduce the burden of sludge disposal, and create value-added products from industrial by-products.

The limited utilization of non-hazardous industrial sludge reveals a clear gap in current waste management practices. Previous studies have examined sludge composting or its agricultural use in general contexts (Abdul Khaliq et al., 2017), including the enhancement of sludge properties through amendments such as dolomite and Trichoderma sp.

Dolomite, a mineral rich in calcium and magnesium carbonates (Shaaban et al., 2018), functions primarily as a chemical amendment that improves soil pH by neutralizing acidity, which is critical in optimizing nutrient availability and microbial activity during composting and soil amendment processes (Olego et al., 2021). Its addition buffers acidic conditions commonly found in sludge-amended soils, stabilizing the environment to favor organic matter decomposition. The calcium and magnesium supplied by dolomite also contribute essential nutrients that support microbial enzymatic functions and promote the formation of soil aggregates, thereby improving soil structure and aeration. Mixtures amended with dolomite demonstrated slight increases in pH toward neutrality, fostering an environment conducive to microbial colonization and activity without causing excessive alkalinity (Xiong et al., 2024). This buffering effect facilitates more stable and efficient mineralization of organic compounds within the sludge, enhancing the overall quality and agronomic value of the resulting planting media.

Conversely, *Trichoderma sp*., a genus of beneficial fungi, serves as a biological amendment with multifaceted mechanisms that accelerate nutrient mineralization and suppress soil-borne pathogens (Yao et al., 2023; Asghar & Kataoka, 2021). Trichoderma species colonize the rhizosphere and organic matter, producing extracellular enzymes such as cellulases, chitinases, and proteases that break down complex organic polymers into simpler forms, thereby accelerating the release of plant-available nutrients like nitrogen and phosphorus. Furthermore, Trichoderma enhances microbial diversity and activity, promoting synergistic interactions that improve nutrient cycling. Its antagonistic properties inhibit pathogenic fungi through competition, mycoparasitism, and secretion of antifungal metabolites, contributing to healthier soil microbial communities (Shahriar et al., 2022).

Despite these known benefits, research specifically targeting the application of dolomite and Trichoderma sp. to secondary sludge from carbonated beverage industries remains limited. The interaction between these amendments and different soil types also influences nutrient dynamics and stabilization rates. The combined use of dolomite and Trichoderma sp. may offer synergistic effects by simultaneously optimizing chemical conditions and biological activity, although further experimental data are needed to elucidate these interactions fully.

The present study evaluates the potential of secondary sludge from an aerobic wastewater treatment plant (WWTP) in the soft drink industry as a component of planting media. The sludge was combined with various soil types and enriched with dolomite and Trichoderma sp. By assessing the carbon-to-nitrogen (C/N) ratio and nutrient content (nitrogen, phosphorus, potassium) over a two-week conditioning period, this research offers new insights into the feasibility of using specific industrial sludge as a compost substitute. The findings aim to support sustainable sludge valorization and expand practical alternatives for waste reuse in beverage manufacturing operations.

2. METHODS

Sludge Characterisation

Sludge samples were procured from a wastewater treatment facility associated with a carbonated beverage industry. Two distinct types of sludge were collected. The first sample comprised dry sludge obtained from the sludge drying bed of the treatment plant. The second sample consisted of wet sludge collected from the inlet channel immediately preceding the sludge drying bed. Both samples were transported to the Laboratory of Environmental Engineering at the Institut Teknologi Sepuluh Nopember and to Angler Laboratory Surabaya for comprehensive analysis. The sludge was analyzed for key parameters pertinent to its suitability as a planting medium. These parameters included organic content, assessed through chemical oxygen demand and biochemical oxygen demand, solid content, evaluated through total suspended solids, volatile suspended solids, and fixed suspended solids, as well as nutrient content, including nitrogen and phosphorus. Additionally, several heavy metals commonly associated with soft drink wastewater sludge were examined to ensure compliance with non-hazardous solid waste criteria. Furthermore, X-ray fluorescence analysis was conducted to determine the elemental composition of the sludge and to support further evaluation of its potential application as a soil amendment.

Soil Characterisation

Soil samples were procured from three distinct sites located on the medial slope of Mount Arjuno in East Java, Indonesia. These soils originated from regions historically affected by Arjuno lava flows and were selected to represent diverse natural soil conditions. The soils were designated as Soil A, Soil B, and Soil C. Sampling was conducted randomly within each site to obtain representative material, and each soil type was analyzed independently without compositing. This methodology facilitated a comparative evaluation of how varying soil characteristics influence the performance of sludge-amended media.

Each soil type was subjected to laboratory analysis to evaluate total solids, organic solids (expressed as total volatile solids), inorganic solids (expressed as total fixed solids), moisture content, and concentrations of total carbon, nitrogen, phosphorus, potassium, boron, cadmium, copper, lead, nickel, total arsenic, total chromium, total mercury, zinc, and fluoride. Additionally, the ratio of organic to inorganic content was calculated to elucidate the fundamental composition of each soil. These baseline data were employed to ascertain the response of each soil to sludge addition and to determine whether specific soil properties enhance or constrain the efficacy of sludge as an amendment.

Soil Amendment Experiments

Following the initial characterization of both soil and sludge, experimental mixtures were formulated by combining each soil type with sludge. These mixtures were placed in controlled observation containers for a duration of two weeks. Daily observations were conducted to monitor key environmental variables, including moisture content, temperature, pH, and light intensity. These parameters were selected due to their significance in evaluating the stability and suitability of soil amendment materials. For further reference, Table 1 is utilized to determine which sample numbers correspond to specific variable types.

Table 1. Research Variable

Sample No.	Sample
1	Soil A+Sludge
2	Soil B+Sludge
3	Soil C+Sludge
4	SA+Sludge+Dolomit
5	SB+Sludge+Dolomit
6	SC+Sludge+Dolomit
7	SA+SL+*Trichoderma*
8	SB+SL+*Trichoderma*
9	SC+SL+Trichoderma
10	SA+SL+D+Trichoderma
11	SB+SL+D+Trichoderma
12	SC+SL+D+Trichoderma

Nutrient-related parameters, including moisture content, total carbon, nitrogen, phosphorus, and potassium, were assessed biweekly during the experiment, specifically at the conclusion of the first and second weeks. This schedule facilitated the evaluation of nutrient dynamics and potential stabilization trends over time. Various treatment combinations were prepared for each soil type, comprising soils mixed with sludge, soils combined with sludge and dolomite, soils integrated with sludge and Trichoderma species, and soils amalgamated with sludge, dolomite, and Trichoderma species. The incorporation of dolomite and Trichoderma species reflects common agricultural practices aimed at enhancing soil quality and augmenting microbial activity. This experimental design enabled the assessment of whether sludge exhibits differential performance based on soil type and amendment strategy.

Data Analysis

All observational and analytical data were systematically processed and descriptively presented through tables and graphs to elucidate differences among treatment combinations. Each measured parameter was assessed based on the outcomes from each treatment group, with comparative analysis conducted across various soil types and amendment variations. As this study represents an exploratory assessment without statistical replication, no inferential statistical tests were conducted. The interpretation was centered on identifying trends, relative differences, and directional changes over the two-week observation period. Furthermore, nutrient-related findings were compared with the national compost standard SNI 19 7030 2004 to evaluate the suitability of sludge-amended mixtures as planting media.

3. Result and Discussion

Sludge Characteristic

The sludge generated from the secondary biological treatment of beverage industry wastewater exhibited consistently high organic content, reflecting the organic rich nature of influent soft drink wastewater. Both dry and wet sludge samples demonstrated a predominance of organic solids over inorganic solids, indicating that the sludge retains substantial biodegradable and nutrient bearing material despite undergoing biological treatment. This characteristic is advantageous for soil amendment applications, as organic matter contributes to soil structure, nutrient retention, and microbial activity.

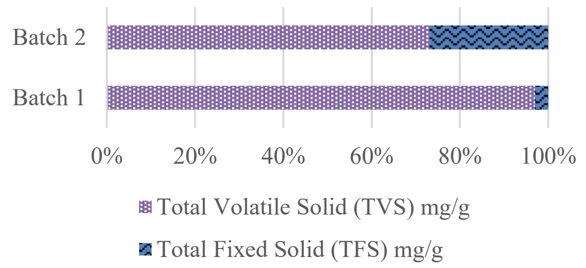

Figure 1. TVS vs TFS Ratio in dry Sludge

As shown in Fig 1., dry sludge analysis from two separate batches revealed total solids of 352.8 milligrams per gram and 474.6 milligrams per gram, with total volatile solid of 342.0 milligrams per gram and 346.8 milligrams per gram respectively. The TVS presents that the organic fraction consistently dominated the total solids, whereas the inorganic portion remained comparatively lower. Similar trends were observed in wet sludge samples, where the first batch contained 406.38 milligrams per gram total solids with 398.78 milligrams per gram organic solids, and the second batch contained 356.8 milligrams per gram total solids with 348.2 milligrams per gram organic solids. These observations confirm that the sludge, regardless of moisture content, maintains a highly organic character that aligns with its origin from high strength organic wastewater typical of the carbonation beverage industry.

Table 2. Inorganic content of Dry Sludge

Parameter	Unit	Batch 1	Batch 2	Thres-hold
Boron (B)	mg/kg	75.3	53.1	
Kadmium (Cd)	mg/kg	0.527	0.31	2
Tembaga (Cu)	mg/kg	10.7	4.77	
Timbal (Pb)	mg/kg	15.8	12.3	50
Nikel (Ni)	mg/kg	1.35	1.06	62
Total Arsenic (As)	mg/kg	-	-	10
Total Chromium (Cr)	mg/kg	5.98	5.,12	210
Total Merkuri (Hg)	mg/kg	-	-	1
Zinc (Zn)	mg/kg	37.3	34.,4	5000
Fluor (F)	mg/kg	13.2	17.6	

Heavy metal analysis across all sludge samples in table 2 indicated the presence of cadmium, copper, chromium, lead, nickel, fluoride, and zinc. Importantly, although the amount fluctuate between each batch, all detected concentrations remained well below the regulatory limits for soil conditioners as outlined in the Ministry of Agriculture Regulation Number 70 of 2011. Pathogen levels were also minimal, with values far lower than the maximum permissible counts. These findings confirm that the sludge meets the safety requirements for non-hazardous solid material and is suitable for further consideration as a soil amendment or planting media component.

A dedicated batch of dry sludge prepared for the soil mixture experiments, as shown in table 3, displayed enhanced nutrient characteristics. This batch contained 35.48 percent carbon, 17.57 percent nitrogen, 1.49 percent phosphorus, and 0.24 percent potassium, representing a nutrient profile comparable to that of composting feedstock. However, this result also show higher content of nitrogen (2.35%-4.2%) along with lower phosphorus and potassium content (2.46%-3.2% and 0.83%-1.24% respectively) compared to typical sludge from municipal wastewater (V. Singh et al., 2022) The elevated nitrogen content, in particular, suggests that the sludge could serve as a strong nitrogen contributor when mixed with soils, potentially enhancing plant available nutrients and supporting early-stage microbial activity.

Table 3. Nutrient Content of Dry Sludge for Soil Amendment

Parameter	Unit	Amount
Total Solid (TS)	mg/g	539.1
Total Volatile Solid (TVS)	mg/g	532.8

Total Fixed Solid (TFS)	mg/g	6.3
Kadar air	-	8.77
Karbon C (db)	%C	35.48
Nitrogen N (db)	%N	17.57
Pospat (db)	%P	1.490
Kalium (db)	%K	0.24
Patogen	Koloni/g	13

Elemental composition obtained through XRF analysis in Figure 2., and table 4 further illustrated the mineralogical structure of the sludge. The dominant inorganic elements were iron and calcium, comprising 29.4 percent and 25.65 percent respectively. Corresponding oxide analyses identified iron oxide and calcium oxide as the predominant compounds, at 22.25 percent and 21.3 percent. The presence of calcium oxide may contribute to the buffering of soil pH, while iron compounds support micronutrient availability (Mcbride et al., 2004; Tang et al., 2022). Together, these elements strengthen the agronomic potential of the sludge, particularly when integrated into soils with low mineral content.

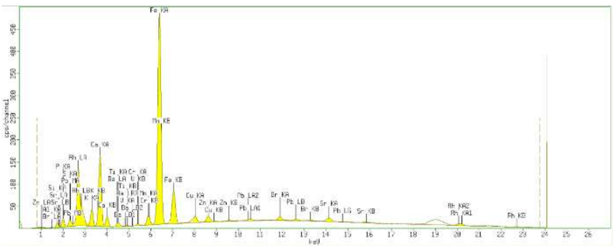

Figure 2. XRF of Dry Sludge Elements

Overall, the sludge characterisation demonstrates that the material possesses a favourable combination of organic matter, essential nutrients, and acceptable trace metal concentrations. Its compliance with national standards for soil conditioners and its nutrient rich composition support its suitability for application as a planting media amendment. The findings provide a strong foundation for evaluating the performance of sludge enriched soil mixtures in subsequent analyses.

Soil Characteristic

The three soils collected from the medial slope of Mount Arjuno exhibited distinct physical and chemical properties that reflect the geological variability of volcanic landscapes. All soils contained measurable concentrations of several heavy metals typically present in mineral rich soils influenced by eruptive deposits, including cadmium, copper, chromium, mercury, arsenic, lead, and nickel, (Bi et al., 2025) . Zinc was also detected as a micronutrient.

Table 4. XRF Analysis of Dry Sludge

Compound	Conc (%)
Al_2O_3	15,5
SiO2	14
P2O5	13
SO3	4,3
K2O	5,07
CaO	21,3
TiO2	1
V2O5	0,04
Cr2O3	0,205
MnO	1
Fe2O3	22,25
CuO	0,62
ZnO	0,5
Br	0,305
SrO	0,495
BaO	0,2
PbO	0,425

The presence of these metals does not inherently restrict agricultural use, as their concentrations remained within commonly reported ranges for naturally occurring soils in volcanic regions. Nevertheless, the detection of these trace metals underscores the importance of evaluating potential interactions between soil composition and added sludge, particularly when assessing long term suitability for plant growth.

The balance between organic and inorganic matter provides a useful indicator of soil fertility, structure, and nutrient holding capacity. Soil A contained 55 percent organic solids and 45 percent inorganic solids, suggesting a moderately organic rich material capable of supporting microbial activity. Soil B presented a nearly equal distribution between the two fractions, with 51 percent organic solids and 49 percent inorganic solids, reflecting a more mineral dominant soil. Soil C exhibited the highest organic fraction, with 57 percent organic solids and 43 percent inorganic solids, indicating greater natural nutrient content and potential for improved aggregation and water retention.

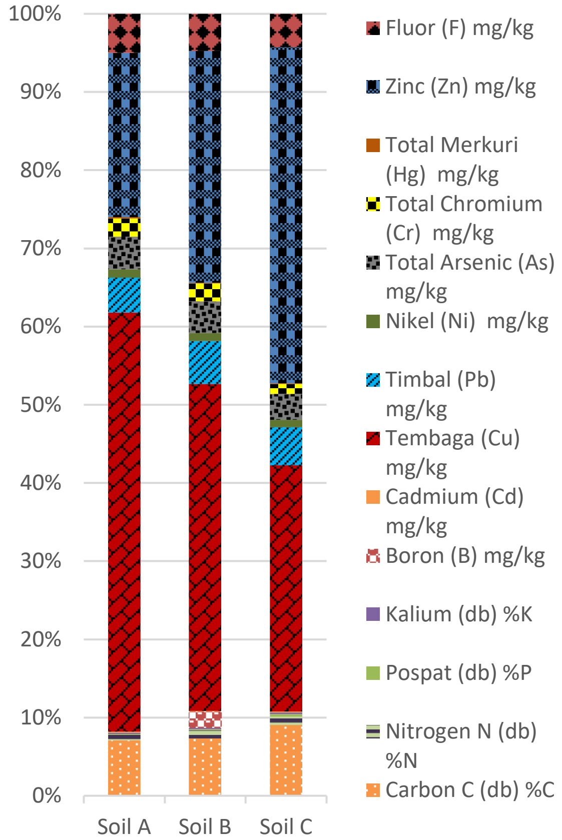

Figure 3. Heavy Metals Content on Soil

The variation across soil types has meaningful implications for their response to sludge amendment. Higher organic content, such as in Soil C, typically enhances the integration of organic waste materials due to stronger microbial activity and improved aeration. Conversely, more mineral rich soils such as Soil B may require additional organic input to achieve similar levels of nutrient mineralization. Soil A, with a moderately high organic fraction, presents an intermediate condition between the two. These inherent differences provided a comparative framework to assess how sludge affects the nutrient dynamics, carbon nitrogen ratio, and overall suitability of each soil for use as planting media.

Overall, the initial characterisation confirmed that all three soils possess adequate baseline fertility and structural stability, making them suitable candidates for evaluating the performance of sludge-based soil amendments. Their contrasting organic content provided valuable diversity for assessing how soil type influences the behaviour of sludge enriched mixtures.

Soil Amendment Mixtures Characteristic

The performance of the sludge–soil mixtures was evaluated over a two-week observation period to assess their suitability as planting media and to understand how different amendment strategies influence the physical and chemical dynamics of each mixture. The environmental parameters measured daily included moisture content, temperature, pH, and light intensity. These parameters serve as key indicators of mixture stability, microbial activity, and environmental suitability for nutrient transformation.

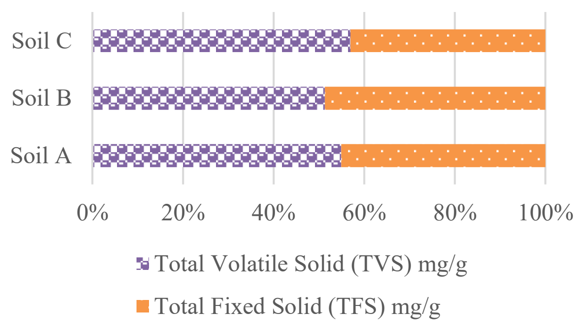

Figure 4. Ratio TVS vs TFS on Soils

Throughout the experimental period shown in table 5, moisture content in all treatment combinations remained within typical operational ranges for composting or organic soil amendments. This stability indicates that the mixtures were able to retain water effectively, likely due to the high organic matter content in both sludge and the soils, particularly Soil A and Soil C. Temperature profiles also showed little fluctuation, remaining between 30 and 35 degrees Celsius across all treatments. These temperatures are consistent with mild microbial activity rather than thermophilic composting, which is expected given the short observation period and relatively small volume of material. The moderate temperature also suggests that the addition of sludge did not induce excessive biological heating, which can be detrimental to plant beneficial microorganisms.

The pH values of all mixtures ranged from 6.0 to 6.5, reflecting mildly acidic to neutral conditions.

Table 5. Two-Week Observation of Soil Amendment Parameters on Moisture, Temperature, pH, and Light Intensity

Parameter	Satuan	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
A. Day 1													
Moisture	mg/kg	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Wet	Normal	Normal	Normal
Temperature (°C)	mg/kg	31	30	31	31	30	31	31	31	31	31	32	32
pH	mg/kg	6	5	5.5	6.5	6.5	6.5	6.5	6.5	5.5	6	6	6
Light Intensity	mg/kg	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
B. Day 8													
Moisture	Wet	Normal	Wet	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Wet
Temperature (°C)	33	32	31	32	32	32	31	31	32	32	32	32	33
pH	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Light Intensity	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
C. Day 14													
Moisture	Normal	Normal	Normal	Normal	Normal	Normal	Wet	Normal	Normal	Normal	Normal	Normal	Normal
Temperature (°C)	31	32	32	33	31	32	33	33	32	31	31	31	31
pH	6	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6
Light Intensity	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Moisture	Normal	Normal	Normal	Normal	Normal	Normal	Wet	Normal	Normal	Normal	Normal	Normal	Normal

This pH range is generally considered suitable for most soil biological processes and early plant development. The presence of dolomite in several treatments did not cause large pH shifts, although slight increases toward neutrality were observed in the dolomite enriched mixtures. Light intensity remained consistently low owing to the controlled indoor conditions, and therefore did not significantly influence temperature or moisture dynamics. Taken together, these findings demonstrate similarities that many sludge amendments did not introduce extreme environmental conditions and that all mixtures showed stable physicochemical behavior (R. P. Singh et al., 2012)throughout the two-week period.

In addition to environmental parameters, nutrient-related characteristics were evaluated at the conclusion of the first and second weeks, as illustrated in Figure 5. A fundamental indicator of compost or planting media quality is the carbon-to-nitrogen (C/N) ratio. According to the minimum requirements for compost, the C/N ratio must be at least 10, with an upper limit of 20. The majority of sludge–soil mixtures achieved C/N ratios equal to or exceeding 10, indicating adequate nitrogen balancing for early-stage application as planting media. The findings strongly indicate that the substantial organic content of secondary sludge contributes to enhancing the C/N ratio by augmenting the organic matter in the soil (Tian et al., 2019). Furthermore, the application of sewage sludge improves microbial biomass and enzymatic activities associated with the biogeochemical cycles of carbon and nitrogen, thereby promoting more efficient nutrient turnover and potentially optimizing the soil C/N ratio for plant growth (Ros et al., 2003).

However, as illustrated in Figure 6, mixtures comprising Soil A and sludge (designated as sample 1) exhibited carbon-to-nitrogen ratios below 10, a benefit that remains contingent upon the intrinsic properties of the soil itself (Mazen et al., 2010). This finding indicates that Soil A possesses a lower carbon content relative to nitrogen, necessitating the addition of carbon-rich materials to satisfy the minimum standard. Enhancing the carbon-to-nitrogen ratio can be accomplished by incorporating high-carbon inputs such as sawdust, dry leaves, or other lignocellulosic biomass prior to further composting. This modification would enhance microbial stability and mitigate the risk of nitrogen loss through volatilization.

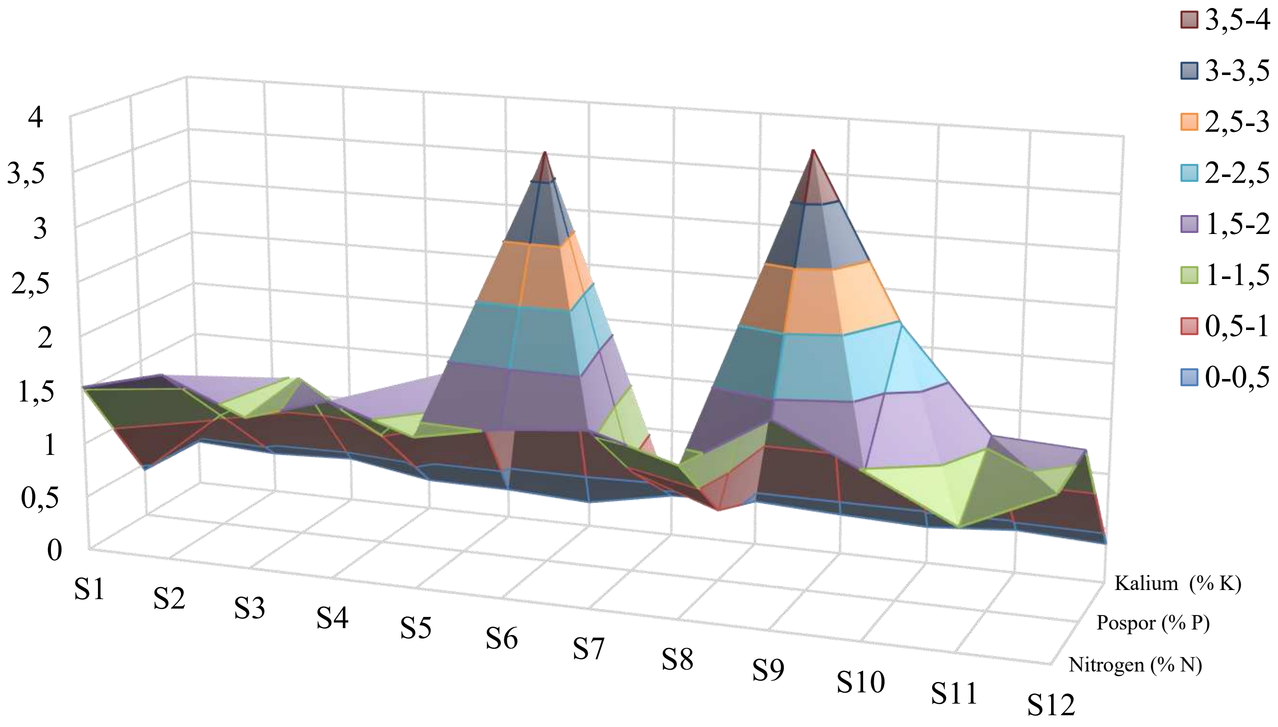

Figure 5. Nutrient Content Comparison of Soil Amendment

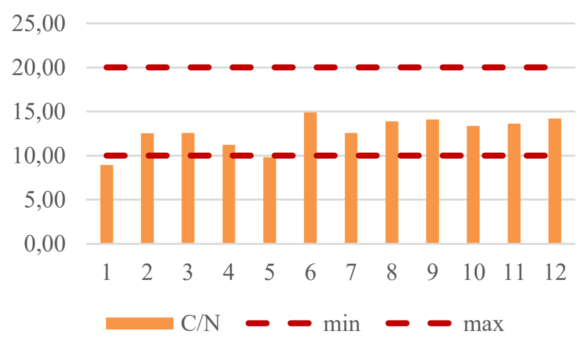

Figure 6. C/N Ratio of Soil Amendment after two-week period

Nutrient analysis for nitrogen, phosphorus, and potassium demonstrated that all sludge–soil mixtures met the minimum nutrient content requirements for compost as specified in SNI 19 7030 2004. Treatments enriched with Trichoderma species generally exhibited higher nutrient availability, particularly in mixtures containing Soil C, Sludge and *Trichoderma* species (shown as sample 9) are known to enhance nutrient mineralization and suppress pathogenic fungi, which may have contributed to the observed increases in nutrient levels. Phosphorus and nitrogen concentrations, as shown in Figure 6 and 7, were particularly enhanced, with some mixtures exceeding the minimum compost standard even at the first week of observation. These findings suggest that biological amendment techniques can accelerate early-stage nutrient release in sludge-based planting media.

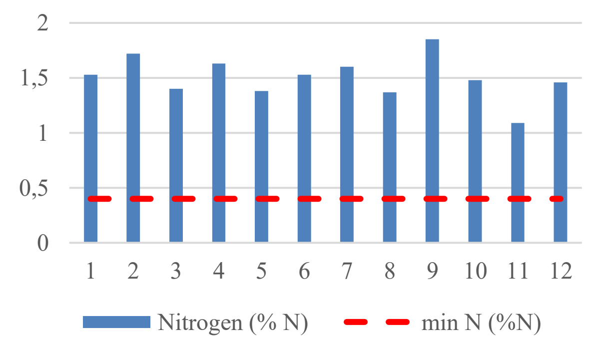

Figure 7. %Nitrogen of Soil Amendment after two-week period

The results also indicate that soil type strongly influences the performance of sludge amendments. Soil C, with its higher organic matter content, especially Phosphor as suggested in Figure 8, consistently demonstrated better nutrient retention and a more favorable balance of carbon and nitrogen. Soil B produced moderate performance across parameters, while Soil A required additional carbon supplementation to align with compost standards. This interaction highlights the importance of matching sludge characteristics with appropriate soil types to optimize agronomic benefits.

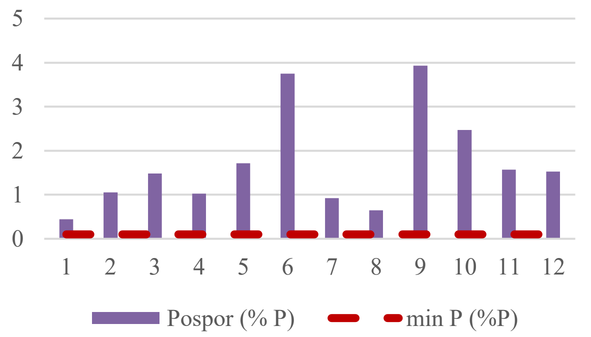

Figure 8. %Phosphor of Soil Amendment after two-week period

The reason why the combined application of both dolomite and Trichoderma sp. to soil amendment using sludge does not exceed the nutrient enhancement performance of Trichoderma sp. alone may be related to microbial interactions, nutrient availability, and soil chemistry dynamics. Trichoderma sp. is known for its capacity to improve soil nutrient availability, particularly nitrogen (N), phosphorus (P), and potassium (K), by producing enzymes that facilitate nutrient mineralization and by altering soil microbial communities favorably for nutrient cycling. However, co-application with dolomite might introduce competitive or inhibitory interactions within the soil microbial community. For instance, shifts in pH due to dolomite could alter the fungal-bacterial balance or reduce Trichoderma's competitive advantage or enzyme efficacy, limiting its nutrient mobilization capacity (Stark et al., 2011)

Overall, the sludge–soil mixtures exhibited stable environmental conditions, acceptable nutrient dynamics, and compliance with key standards for planting media. These findings support the feasibility of utilizing sludge from beverage industry wastewater treatment as an effective soil amendment, particularly when combined with suitable soil types and biological enhancers such as dolomite and Trichoderma species.

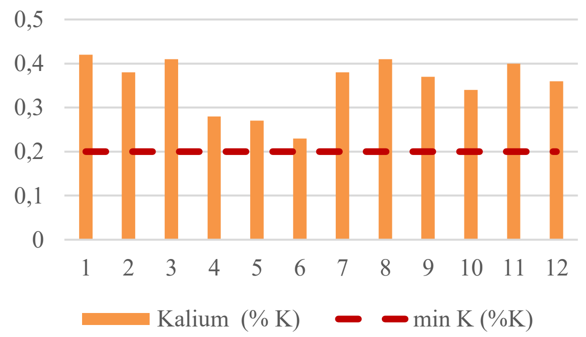

Figure 9. %Kalium of Soil Amendment after two-week period

4. Conclusion

This study demonstrates that non-hazardous secondary sludge generated from aerobic biological treatment in a carbonated beverage industry WWTP has strong potential to be reused as planting media when combined with suitable soil types and amendments. Characterization results showed that, after two weeks of conditioning, most sludge–soil mixtures achieved a C/N ratio ≥10, meeting the lower limit of compost maturity standards, except for mixtures involving Soil A with and without dolomite. All treatments, regardless of soil type or amendment, exceeded the minimum SNI 19-7030-2004 requirements for N, P, and K content.

The addition of *Trichoderma* sp. consistently enhanced nutrient levels, with the highest nitrogen (1.8%) and phosphorus (4.0%) observed in sludge mixed with Soil C and *Trichoderma* sp., while the highest potassium content (0.4%) occurred in sludge mixed with Soil B and *Trichoderma* sp. These findings indicate that secondary sludge from beverage industry wastewater can be utilized as an alternative planting media or compost substitute after simple amendments, contributing to waste valorization and circular resource use in the industrial sector.

DAFTAR PUSTAKA

Abdul Khaliq, S. J., Al-Busaidi, A., Ahmed, M., Al-Wardy, M., Agrama, H., & Choudri, B. S. (2017). The effect of municipal sewage sludge on the quality of soil and crops. *International Journal of Recycling of Organic Waste in Agriculture*, *6*(4), 289–299. https://doi.org/10.1007/s40093-017-0176-4

Alonso, J. M., Abreu, A. H. M. de, Andreoli, C. V., Teixeira, P. C., Polidoro, J. C., & Leles, P. S. dos S. (2024). Chemical characteristics and valuation of sewage sludge from four different wastewater treatment plants. *Environmental Monitoring and Assessment*, *196*(1). https://doi.org/10.1007/s10661-023-12211-8

Asghar, W., & Kataoka, R. (2021). Effect of co-application of Trichoderma spp. with organic composts on plant growth enhancement, soil enzymes and fungal community in soil. *Archives of Microbiology*, *203*(7), 4281–4291. https://doi.org/10.1007/s00203-021-02413-4

Bi, R., Fu, W., & Fu, X. (2025). Heavy Metal Spatial Variation Mechanism and Ecological Health Risk Assessment in Volcanic Island Soils: A Case Study of Weizhou Island, China. *Land*, *14*(1). https://doi.org/10.3390/land14010035

Cárdenas-Talero, J. L., Silva-Leal, J. A., Pérez-Vidal, A., & Torres-Lozada, P. (2022). The Influence of Municipal Wastewater Treatment Technologies on the Biological Stabilization of Sewage Sludge: A Systematic Review. In *Sustainability (Switzerland)* (Vol. 14, Issue 10). MDPI. https://doi.org/10.3390/su14105910

Mazen, A., Faheed, F. A., & Ahmed, A. F. (2010). Study of potential impacts of using sewage sludge in the amendment of desert reclaimed soil on wheat and jews mallow plants. *Brazilian Archives of Biology and Technology*, *53*(4), 917–930. https://doi.org/10.1590/S1516-89132010000400022

Mcbride, M. B., Richards, B. K., & Steenhuis, T. (2004). Bioavailability and crop uptake of trace elements in soil columns amended with sewage sludge products. In *Plant and Soil* (Vol. 262).

Muhamad Ng, S. N., Idrus, S., Ahsan, A., Tuan Mohd Marzuki, T. N., & Mahat, S. B. (2021). Treatment of wastewater from a food and beverage industry using conventional wastewater treatment integrated with membrane bioreactor system: A pilot-scale case study. *Membranes*, *11*(6). https://doi.org/10.3390/membranes11060456

Olego, M. Á., Quiroga, M. J., López, R., & Garzón-Jimeno, E. (2021). The importance of liming with an appropriate liming material: Long-term experience with a typic palexerult. *Plants*, *10*(12). https://doi.org/10.3390/plants10122605

Ros, M., Hernandez, M. T., & Garcja, C. (2003). Bioremediation of Soil Degraded by Sewage Sludge: Effects on Soil Properties and Erosion Losses. *Environmental Management*, *31*(6), 741–747. https://doi.org/10.1007/s00267-002-2839-8

Shaaban, M., Wu, Y., Peng, Q., Wu, L., Van Zwieten, L., Khalid, M. S., Younas, A., Lin, S., Zhao, J., Bashir, S., Zafar-ul-hye, M., Abid, M., & Hu, R. (2018). The interactive effects of dolomite application and straw incorporation on soil N_2O emissions. *European Journal of Soil Science*, *69*(3), 502–511. https://doi.org/10.1111/ejss.12541

Shaddel, S., Bakhtiary-Davijany, H., Kabbe, C., Dadgar, F., & Østerhus, S. W. (2019). Sustainable sewage sludge management: From current practices to emerging nutrient recovery technologies. *Sustainability (Switzerland)*, *11*(12). https://doi.org/10.3390/su11123435

Shahriar, S. A., Islam, M. N., Chun, C. N. W., Kaur, P., Rahim, Md. A., Islam, Md. M., Uddain, J., & Siddiquee, S. (2022). Microbial Metabolomics Interaction and Ecological Challenges of Trichoderma Species as Biocontrol Inoculant in Crop Rhizosphere. *Agronomy*, *12*(4), 900. https://doi.org/10.3390/agronomy12040900

Singh, R. P., Singh, P., Ibrahim, M. H., & Hashim, R. (2012). *Land Application of Sewage Sludge: Physicochemical and Microbial Response* (pp. 41–61). https://doi.org/10.1007/978-1-4614-0668-6_3

Singh, V., Phuleria, H. C., & Chandel, M. K. (2022). Unlocking the nutrient value of sewage sludge. *Water and Environment Journal*, *36*(2), 321–331. https://doi.org/10.1111/wej.12739

Stark, S., Eskelinen, A., Mannisto, M., Regulation of Microbial Community Composition and Activity by Soil Nutrient Availability, Soil pH, and Herbivory in the Tundra. *Ecosystem*, 15, 18-33. https://doi.org/10.1007/s10021-011-9491-1

Tang, J., Davy, A. J., Wang, W., Zhang, X., Wu, D., Hu, L., & Yin, J. (2022). Effects of Biogas Slurry on Crop Yield, Physicochemical Properties and Aggregation Characteristics of Lime Concretion Soil in Wheat–Maize Rotation in the North China Plain. *Journal of Soil Science and Plant Nutrition*, *22*(2), 2406–2417. https://doi.org/10.1007/s42729-022-00817-9

Tian, Y., Cui, L., Lin, Q., Li, G., & Zhao, X. (2019). The Sewage Sludge Biochar at Low Pyrolysis Temperature Had Better Improvement in Urban Soil and Turf Grass. *Agronomy*, *9*(3), 156. https://doi.org/10.3390/agronomy9030156

Xiong, R., He, X., Gao, N., Li, Q., Qiu, Z., Hou, Y.,

& Shen, W. (2024). Soil pH amendment alters the abundance, diversity, and composition of microbial communities in two contrasting agricultural soils. *Microbiology Spectrum*, *12*(8). https://doi.org/10.1128/spectrum.04165-23

Yao, X., Guo, H., Zhang, K., Zhao, M., Ruan, J., & Chen, J. (2023). Trichoderma and its role in biological control of plant fungal and nematode disease. In *Frontiers in Microbiology* (Vol. 14). Frontiers Media S.A. https://doi.org/10.3389/fmicb.2023.1160551