horticulturae

MDPI

Article

Recycling Nutrient-Rich Municipal Wastes into Ready-to-Use Potting Soil: An Approach for the Sustainable Resource Circularity with Inorganic Porous Materials

Cemile Dede [1], Hasan Ozer [2], Omer Hulusi Dede [3], Ahmet Celebi [2] and Saim Ozdemir [2,*]

[1] Vocational School of Health Science, Sakarya University, 54187 Sakarya, Turkey
[2] Department of Environmental Engineering, Faculty of Engineering, Sakarya University, 54187 Sakarya, Turkey
[3] Department of Environmental Protection, Sakarya University of Applied Sciences, 54100 Sakarya, Turkey
* Correspondence: saimo@sakarya.edu.tr; Tel.: +90-264-295-56-35

Abstract: Using waste products is a promising and sustainable alternative to conventional non-renewable peat and nutrient-rich renewable materials. Their products are gaining importance for closing the loop in the ornamental plant industry. Porous inorganic materials have recently become potential bulking agents (BA) for sewage sludge (SS) owing to their high porosity, surface area, passivation capacity, high recycling potential, and potting soil components. The main purpose of the present work was to investigate the feasibility of pumice (PU) and expanded perlite (EP) on composting parameters, nutrient bioavailability and suitability of SS to serve as an ornamental substrate. The addition of PU and EP at 50% (v/v) resulted in higher porosity, optimal initial moisture content, higher temperature rise (56.24 ± 0.13 °C, 56.21 ± 0.11 °C, respectively), and higher CO_2 evolution (39.41 ± 0.17%, 41.70 ± 0.22% daily peaks). Composting with inorganic BA at EP-50 and PU-50 mixtures was beneficial owing to high nitrogen content (3.82 and 3.70%, respectively) and readily bioavailable nutrients (270 mg kg^{-1} phosphates and 1835 mg kg^{-1} potassium). The use of PU and EP was found helpful in improving the slow-release nutrient properties of the compost. The overall results indicated that composting SS with PU and EP is a viable approach to achieve good composting properties and a good nutrient-providing profile if the compost is used as a component for potting soil components or garden soil amendments.

Keywords: sewage sludge; pumice; perlite; compost; nutrient value

check for updates

Citation: Dede, C.; Ozer, H.; Dede, O.H.; Celebi, A.; Ozdemir, S. Recycling Nutrient-Rich Municipal Wastes into Ready-to-Use Potting Soil: An Approach for the Sustainable Resource Circularity with Inorganic Porous Materials. *Horticulturae* **2023**, *9*, 203. https://doi.org/10.3390/horticulturae9020203

Academic Editor: Miguel de Cara-García

Received: 22 December 2022
Revised: 31 January 2023
Accepted: 1 February 2023
Published: 3 February 2023

1. Introduction

One-way material cycle in rapidly growing urban habitats depletes organic matter (OM) and plant nutrients in the agroecosystem whilst enriching urban waste streams, impacting ecosystem services and United Nations' global sustainability goals [1,2]. Potting soil production could be a possible solution for minimizing urban waste accumulation and recycling nutrients during ornamental plant production. In line with the circular economy perspective, the management of organic waste and its reuse as a soil conditioner, potting soil, and fertilizer resources in the soil have gained popularity in recent years [3]. As a nutrient resource, municipal organic wastes potentially replace chemical fertilizers in the ornamental industry, urban gardens, and landscape plantations [4,5]. Non-renewable peat has long been a favorite source of potting and garden soil amendments. However, the problem of dependence on a single source and concerns about replacing peat as a horticultural substrate are forcing researchers to find other renewable sources of organic matter to meet future potting soil requirements [6,7]. Recent studies are searching for new, innovative, and eco-friendly technologies for promoting municipal waste recycling [8,9]. In this context, in situ composting can provide solutions for the ornamental plant industry by offering low operating costs, and greater social and environmental benefits as a growing medium [10,11].

As a biological method, composting converts renewable waste materials into value-added resources that will be available forever [12]. During microbial decomposition, heterogeneous organic wastes become more stable humus-like substances under controlled moisture, temperature, and aeration conditions [13]. However, composting organic waste have restrictions owing to its high water content, high dry bulking agent requirement, odor gas emissions, and significant nitrogen losses [14,15]. The low nutrient content is the main reason for reduced compost quality and willingness for horticultural use by potential users [16]. Ammonia (NH_3) emissions have been significantly contributing to gaseous nitrogen, causing odor nuisance and nitrogen fertilizer loss [17,18].

Lignocellulosic organic materials such as sawdust and crop residues are common bulking agents for sewage sludge composting [19]. However, their availability in large quantities and supply are difficult. Reusable inorganic bulking agents such as horticultural grade pumice and perlite could serve as dry structural mix components for municipal wastes, which have high water content [20]. The porous structures of both pumice and expanded perlite allows for high absorption ratios, provide a greater surface area for microbial reactions [21], allow gas exchange for microbial respiration [22], and moisture diffusion for drying [23]. In addition, non-biodegradable inorganic materials can be recovered during screening and reused in subsequent composting cycles. Additionally, inorganic bulking materials play a role in improving the soil structure [11], passivation of heavy metals [21], and degradation of persistent pollutants [6]. The structural and functional properties of inorganic porous materials associated with adsorption, complexation, ion exchange, and pore filling during composting can preserve plant nutrients such as nitrogen in a pile and enrich the final compost product.

Recycling locally available resources on-site is a sustainable policy that achieves energy efficiency and limits pollutant emissions, waste accumulation, and environmental sustainability [24,25]. Composted nutrient-rich organic waste is a possible alternative to organic waste as a substitute for non-renewable resources and energy-intensive fertilizers in horticulture [26]. Although expanded perlite (EP) and pumice (PU) have been used for horticulture, solid-liquid separation, and wastewater treatment, only a few studies have addressed their use as bulking agents (BA) in sewage sludge (SS) composting [19,22]. Therefore, the present study aimed to investigate the two research hypothesis that: (1) the of composting SS with recyclable porous PU and EP could have recruitment on porosity and aeration parameters, and (2) the improvement on preserving total and bioavailable plant nutrients in final product.

2. Materials and Methods

2.1. Material Preparation and Properties

The dewatered sewage sludge cake was taken from the outlet of the municipal wastewater treatment plant (WWTP) in Sakarya, Turkey, which treats mainly domestic wastewater in an extended aeration system. The WWTP produces 35,000 m^3 of raw sludge per year with an organic matter content of 56 ± 2.50%. The sludge cake has a high moisture content (81 ± 0.85%). The samples of inorganic bulking agents PU and EP were obtained from local markets as horticultural grades, mainly used for landscaping and as an ingredient of potting soil. Then PU and EP were sieved to obtain the desired particle size of >5.00 mm for EP and >10.00 mm for PU. Sawdust (SW), which served as a control, was obtained from a local sawmill.

2.2. Compost Mixes and the Compost Production Process

To lower the moisture content (MC) of the SS to the desired range of 40–60% for the initial compost pile [14], experimental bulking agents PU, EP and SW were homogeneously mixed into the sludge cake to improve the porosity of the compost. The mixing ratio for SW—control was chosen to be 50%, which has been reported as the optimum dose in previous studies on sewage sludge compost [14]. Inorganic mixing materials, PU and EP, were mixed with SS at increasing levels of 12.5%, 25%, and 50% (*v*/*v*), respectively. Seven different treatments with three replicates in 3 PU, 3 EP and the control SW were investigated in the study. The prepared mixtures were placed in a 6-litre experimental composting container with thermal insulation, sealed, and stored at room temperature for three weeks. Temperature, CO_2 and H_2S emissions were measured daily during the three-week composting period. Moisture content, organic matter, pH, and Kjeldahl nitrogen were measured every five days. The mixtures were aerated daily by manual turning after the gas measurements were recorded. At the end of the active composting period, the composts were screened and the inorganic materials PU and EP were separated.

2.3. Analytical Methods

Moisture content was determined by drying at 105 °C until a constant weight was reached. The pH was measured at a ratio of 1:5 (dry weight of samples/volume of water) after 60 min of shaking followed by filtration of aqua regia using a pH meter (Schott CG 840, Eindhoven, The Netherlands). Temperature measurements were taken daily with a digital thermometer. CO_2 and H_2S emissions were measured once per day using a portable gas analyzer (Geotech Biogas 5000 Portable Gas Analyzer, QED Environmental, Coventry, UK). The OM contents were determined by measuring the weight difference of dried samples (105 °C) after ignition in a muffle furnace at 550 °C for 4 h [9]. Total Kjeldalh nitrogen (ammoniacal and organic) content was determined by the Kjeldahl method [9].

The nutrient analysis procedures presented in Table 1 were performed to determine the total and readily available nutrient forms in compost samples.

Table 1. Methods used for total and available plant nutrient determination in compost samples.

Parameter (mg/kg).	Method
Total P Total Na Total K Total Ca Total Mg Total Fe Total Cu Total Mn Total Zn	ISO 22036 (Detection with ICP-OES)
Available P Available Na Available K Available Ca Available Mg	TS 8341:1990 (Ammonium Acetate Method)
Available Fe Available Cu Available Mn Available Zn	TS EN ISO 14870:2004 Extraction of Trace Elements with DTPA ISO 22036:2008
Total Kjeldahl N	Kjeldahl method

The seed germination test was performed to evaluate the phytotoxicity of the compost samples germinating cress seeds, and the germination index (GI) was calculated. For the test, an aqueous extract of the compost samples was prepared. For this purpose, the samples were mixed with distilled water, shaken in a shaker and then filtered. Ten cress seeds were incubated with this extract (5 mL) on the filter paper in a germination tray. Deionized water was used as a control. The seeds were incubated at 25 °C for 3 days in the dark. The percentage of germination and radicle length were measured and GI was estimated using Equation (1) [15].

$$GI(\%) = 100 \times (G_e \times L_e)/(G_c \times L_c) \quad (1)$$

GI: Germination index
G_e: Number of germinated seeds (sample)
L_e: Length of roots (sample)
G_c: Number of germinated seed (control)
L_c: Length of roots (control)

2.4. Statistical Analysis

The effect of inorganic mixed materials on the composting of SS was evaluated with a one-way analysis of variance (ANOVA). When necessary, data were transformed to meet normality assumptions and then compared using multiple comparison tests (Tukey HSD test) when effects were statistically significant. The Kruskal-Wallis test was performed if the data did not have a normal distribution using the Statgraphics Centurion version of XVI developed by Statpoint Technologies Inc., Warrenton, VA, USA. Also, Pearson's correlation coefficient was determined among the investigated parameters and plotted using Microsoft Excel 2016 and, $p \leq 0.05$ and $p \leq 0.01$ were used to indicate statistical significance.

3. Results and Discussions

3.1. Temperature Change and Gaseous Evolution

In composting process, temperature is generally considered an important indicator of microbial activity in the compost pile. In the thermophilic phase, heat is generated by the decomposition of readily biodegradable organic matter and the metabolism of simple organic carbon compounds by microorganisms, and the accumulation of this heat leads to an increase in temperature [27]. Statistical testing of the temperature raise was performed by subjecting daily recorded data to ANOVA analysis (Table 2). The hygienization temperature (>55 °C) for the SW control was found to be 61.6 ± 0.24 °C on day 8, and the addition of PU and EP at 50% to SS resulted in a higher temperature (56.2 ± 0.13 °C and 56.0 ± 0.11 °C, respectively) during the same period (Figure 1). Then, towards the end of the process, the temperatures started to decrease to the ambient temperature as the readily degradable organics diminished. The temperature profile of 12.5 and 25% PU and EP showed that the increase was slower and did not reach the thermophilic temperatures of >45 °C. The significant higher composting temperature observed in EP-50 and PU-50 compared to the SW control indicates the positive contribution of the inorganic BA in promoting aeration for microbial activity.

Table 2. Analysis of variance with probability (*p* values) for composting parameters affected by various rates of inorganic porous bulking agents expanded perlite and pumice.

Parameters	Mean Square	F Values	*p* Values
Temperature change	235.08	2.02 *	0.044
CO_2 evolution	676.49	7.96 **	<0.001
CH_4 generation	877.83	11.73 **	<0.001
H_2S generation	279.76	6.11 **	<0.001
Organic matter	392.95	23.89 **	<0.001
Moisture content	672.66	84.28 **	<0.001
pH	0.06	19.60 **	<0.001
Total Kjeldahl nitrogen	0.56	29.13 **	<0.001
Germination Index	641.95	39.97 **	<0.001

Significance levels: * $p \leq 0.05$ (significant) and ** $p \leq 0.01$ (highly significant).

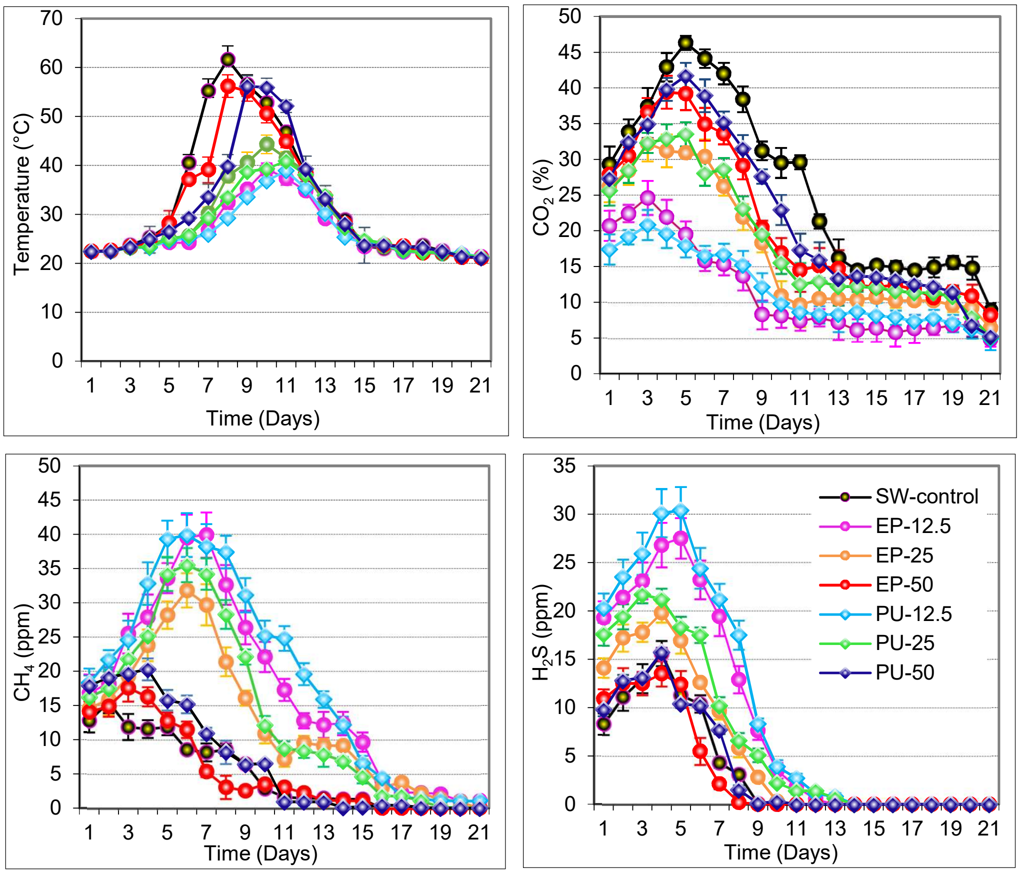

Figure 1. Temperature change, CO_2 evolution, CH_4 generation and H_2S emission during composting. Error bars represent the standard deviation for mean values of three replicates. SW sawdust, EP expanded perlite, and PU pumice at 12.5, 25, and 50% incorporation rate into compost mixture.

Microbial decomposition and OM transformation during composting generate CO_2 and H_2O vapors that are either absorbed by bulking agents (BA) or released from the pile [28]. Based on the ANOVA results presented in Table 2, the BA effect was statistically significant because of its low *p*-value of < 0.001 and high F-value. The CO_2 evolution measured daily correlated with the temperature profile, which showed a rapid increase at the beginning of the composting phase and then a gradual decrease until the end of composting (Figure 1). The reason could be the improvement of gas exchange, which accelerated the OM transformation due to the accumulation of microbial activity. After two weeks, all compost treatments reached the low and stable CO_2 evolution phase, indicating stabilization and maturation of the compost [29].

During composting, the generation of undesirable odors is a critical issue that needs to be controlled. The absence of sufficient oxygen plays a significant role in the formation of odor emissions. The accumulation of CH_4 and H_2S during composting has been associated with the aeration problems of SS. As shown in Figure 1, the CH_4 and H_2S content of all treatments significantly increased from day 1 to 5 and gradually decreased as fermentation progressed. The CH_4 and H_2S evolution rates of EP-50, PU-50 and SW-control treatments were significantly lower than the other treatments ($p < 0.001$, Tukey's post-hoc test). We observed the highest H_2S evolution (i.e., 34.09 ± 0.08 ppm and 30.92 ± 0.16 ppm) for PU-12.5 and EP-12.5 (Figure 1), which was due to insufficient porosity and gas exchange [30]. This is because low oxygen availability for microbial decomposition favors anaerobic gas emissions during SS composting [14]. The low CH_4 and H_2S evolution in EP-50 and PU-50 was similar to the SW-control treatment, indicating the feasibility of composting SS with these materials to support aeration and aerobic conditions for microbial activity and to control odorous gas emission [14]. In addition, the concentrations of CH_4 and H_2S showed a similar trend to the thermophilic phase, decreasing to undetectable levels after day 7 for H_2S and day 11 for CH_4.

3.2. Changes in Physicochemical Parameters

The success of the composting process can be expressed by the rate at which the biological treatment transforms the OM of the raw material into a more stable, humified product. The composting system, environmental conditions, and the structural and chemical composition of the compost raw materials affect the mineralization rate and OM transformation [31]. Therefore, the addition of organic or inorganic BA to the SS cake significantly affects the OM, rate of degradation and conversion to the new products [16]. In this study, the progressive decrease of organic matter was observed in all mixtures, as shown in Figure 2. This decrease can be attributed to the decomposition of the volatile components of the SS, since the inorganic bulking agents PU and EP are inert and contain hardly any volatile components. The removal rate of OM was 13% and 12% for EP-50 and PU-50, respectively. On the other hand, the removal rate of OM was higher (27%) than that of the inorganic bulking agents due to the high content of biodegradable carbonaceous materials and showed a much higher OM for both the initial and final products.

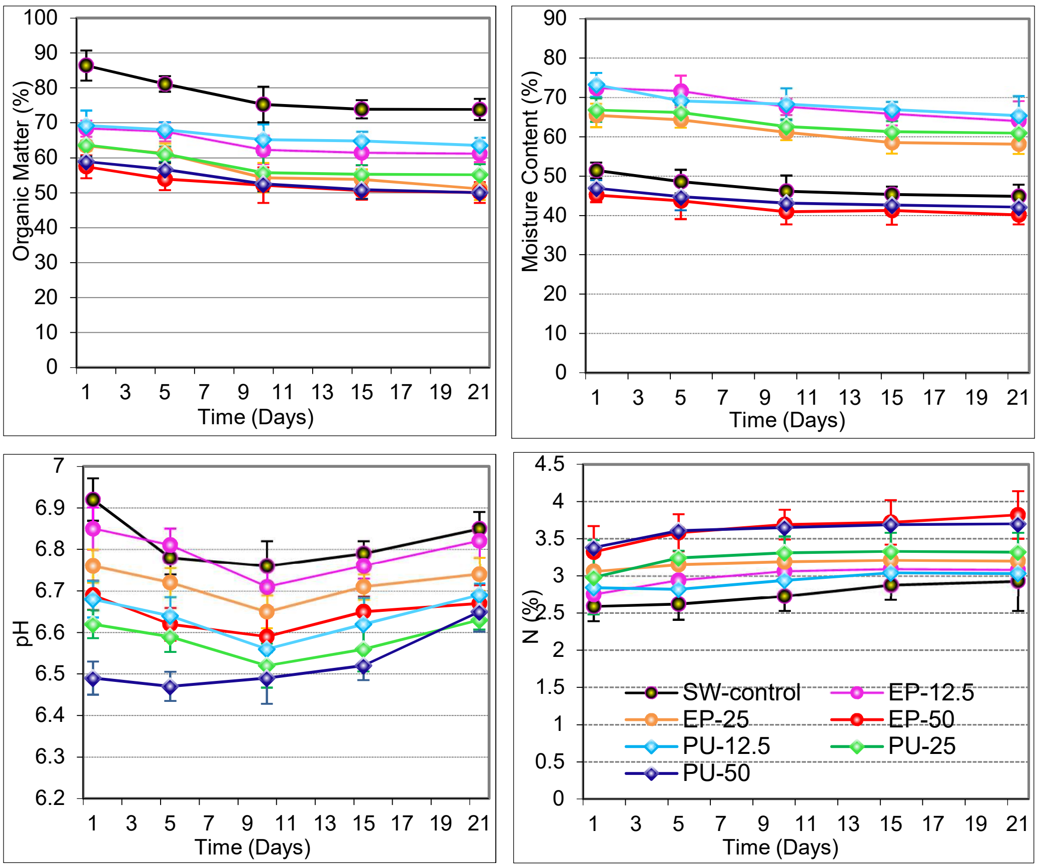

Figure 2. Variation of physicochemical parameters during sewage sludge composting mixed with inorganic porous bulking agents. Error bars represent the standard deviation for mean values of three replicates. SW sawdust, EP expanded perlite, and PU pumice at 12.5, 25, and 50% incorporation rate into compost mixture.

Moisture content is a critical factor that can significantly affect microbial activity, biochemical reactions, diffusivity of gasses, and functional properties of composting. The initial MC of the compost samples ranged from 45.25 (EP-50) to 70.67% (PU-12.5) wet basis (Figure 2). Based on the Kruskal-Wallis one-way ANOVA results, the rate of BA incorporation to the SS significantly affected the compost MC. During the composting period, MC decreased significantly in all treatments tested. However, only EP-50 and PU-50 were in a range suitable for composting MC, e.g., 30–40% [5]. The remaining treatments, including the SW-control, had high MC above an optimal range and required drying to achieve acceptable quality. In general, the addition of a dry bulking agent is believed to absorb excess moisture, optimizing free air spaces and aeration in the compost pile to maximize microbial decomposition and gas exchange [14,19]. Wu et al. [22] reported that increased pumice content significantly reduced MC in sewage sludge compost with 65.23% water absorption at a mass ratio of 0.6:1 (PU: SS). In our case, the addition of PU or EP in proportions of 12.5% to SS had not increased the initial porosity of the pile and did not ensure an optimal initial moisture content. On the other hand, mixing SS with PU or EP in proportions of 50% had resulted in higher porosity, optimal initial MC for microbial activity, and suitable final MC for further processing (Figure 2).

The pH is a key parameter affecting microbial degradation and, in particular, determining pH-dependent N losses in the form of NH_3 [27]. In the current study, pH showed a typical decreasing pattern in the initial phase and followed a gradually increasing trend in all tested compost treatments (Figure 2), depending on the decomposition of OM and conversion to subsequent products. However, all observed pH values ranged from 6.45to 6.85, which is within the recommended range for microbial activity and maintenance of pH-dependent nitrogen loss due to NH_3 volatilization [28].

Nitrogen loss by gaseous emission, mainly NH_3 formed during composting SS, is a frequently reported mechanism that generates odor gasses during composting, thereby reducing the nutritional value of the final product [31]. Published studies report that approximately 40–80% of nitrogen is lost during SS composting due to NH_3 volatilization, depending on the management practices and mitigation measures used [29]. Previous studies have well documented that nitrogen is the most needed nutrient affecting plant growth. Therefore, retention of nitrogen during composting is a critical factor in increasing the fertilizer value of the final compost product. In the present study, average TKN concentrations were found to be significantly higher at the higher BA rate ($p < 0.001$) based on Tukey's honestly significant difference test compared with the other BA rates. In general, nitrogen concentrations showed an upward trend in all treatments, as shown in Figure 2.

Several methods have been proposed in the literature to reduce nitrogen loss during composting. One practical approach is to use bulking fillers that have the ability to absorb released nitrogen forms, mainly NH_3. Wu et al. [22] used sucrose-improved pumice and rescued pumice as BA, to reduce nitrogen loss. They reported that NH_3 emissions were reduced by 21.25% for reused pumice and 43.37% for sucrose-decorated pumice [22]. Awasti et al. [32] recommended the addition of 12% biochar + 10% zeolite in dewatered fresh sewage sludge to reduce ammonia emissions during composting. Similar to the previously tested porous materials, the inorganic porous PU and EP tested in the present study were beneficial in 50:50 mixtures as they retained the highest content of Kjeldahl nitrogen in the final compost (Figure 2). The final Kjeldahl nitrogen values ranged from 3.70% for PU-50 to 3.82% for EP-50. The relatively low nitrogen content in SW-control may be attributed to the high C/N ratio, which converts mineralized nitrogen to microbial OM during composting [31].

3.3. Germination Index

The quality of compost should be investigated before use in order to avoid the various negative effects that unstable or immature compost can cause. When evaluating compost quality, it is important to examine the toxicity of the compost. Germination index (GI) is a powerful tool to study the toxicity of compost [15,33]. A significant relationship between BA rate and GI index was found ($p < 0.001$). A GI value of more than 80% generally indicates that the compost has no phytotoxicity [33]. In this study, the GI value increased significantly with increasing addition of inorganic BA, and the highest value was observed at PU-50 and EP-50 with similar statistical group according to the Tukey's honestly significant difference test. Based on this classification, PU-50, PU-25 and EP-50 showed GI > 80 which address that compost has been completely detoxificated and matured, and can be accepted as safe for use as potting soil amendment (Figure 3). While SW-control, PU-12.5, EP-12.5 and EP-25 the GI gave values between 60–80 indicating low toxicity (Figure 3). The extracts of these treatments did not affect germination but negatively affected root elongation, probably due to the phytotoxic compound not completely eliminated during composting period [14].

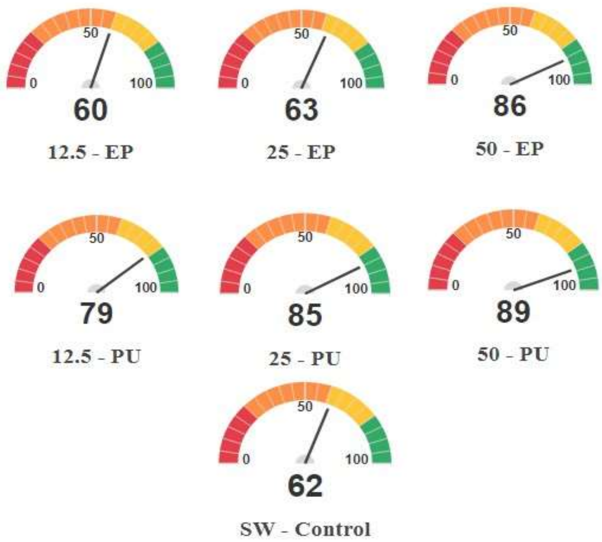

Figure 3. Germination indexes (GI) of cress seeds grown on compost extracts of inorganic BA comparing to the SW-control. Green range indicates full stability, and yellow range indicates the negative effect to root elongation.

3.4. Total and Bioavailable Plant Nutrients

Knowing the plant nutrient content and understanding the changes in plant nutrient forms during composting is essential to determine their utility in soil and plant growth [34]. Inorganic BA is expected to enhance sludge organic matter decomposition and increase the rate of nutrient release. The nutrients released from OM may either accumulate in the readily available nutrient pool, adsorb to PU and EP during composting to serve slow-release nutrient pools [21], or strongly associate with inorganic BA to passivate certain plant nutrients and pollutants [35].

The major macro- and micro-plant nutrients were measured for samples to reveal the readily available and total nutrients of composts. The data in Figure 4 shows the available element content (mg kg^{-1}) of the experimental composts as affected by different incorporation rates of EP and PU compared to the SW-control. These data reveal that, all nutritional parameters, except Mn, decreased with an increase in the amount of inorganic BA. In general, the bioavailable forms were significantly higher in the SW-control than in inorganic BA. The decrease was significant for P and Fe at addition rates of 25 and 50% of EP and PU. The higher total but low readily available P in the compost samples may be explained by the fact that P tends to form less readily available Fe, Al, and Ca-bound P during the composting process [16]. Iron (Fe) was recorded in higher concentrations in the SW-control than in EP and PU treatments. These results may be due to the fact that Fe is more labile under low pH conditions, and by raising the pH with EP and PU during composting reduced its bioavailability [21]. However, the total concentration of all tested plant nutrients was within the range reported for sewage sludge composts.

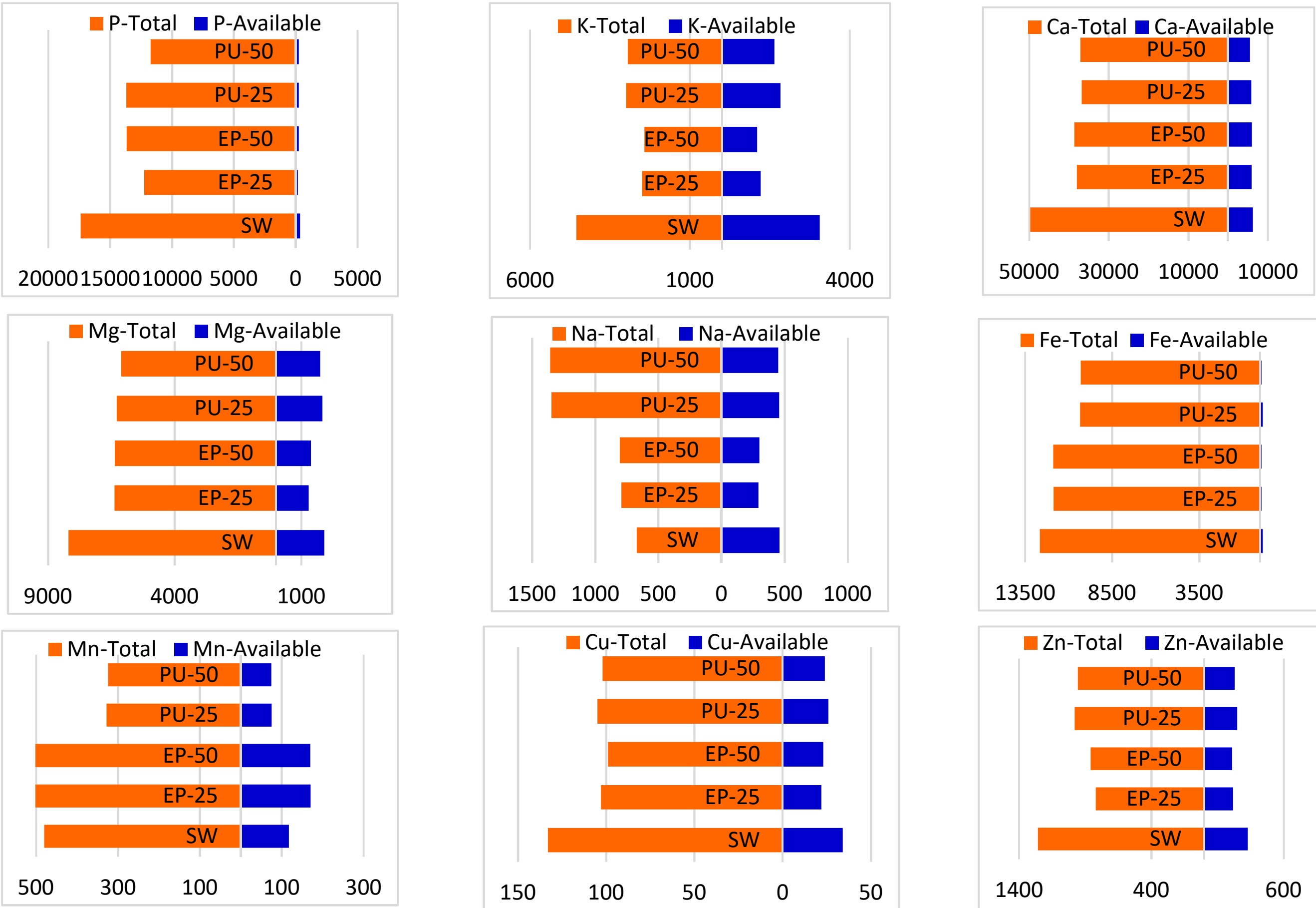

Figure 4. Bi-directional presentation of total and bioavailable plant nutrients (mg kg^{-1} dry weight basis) of compost samples composted with increasing rate of the PU and EP comparing to the SW-control. SW sawdust, EP expanded perlite, and PU pumice at 25, and 50% incorporation rate into compost mixture.

In general, PU and EP acted similarly for the total and readily available plant nutrients, except for Mn and Na. An increasing amount of BA did not change the amount of total and readily available nutrient forms, which might signify that nutrients are in organic form rather than bound to inorganic BA. Accordingly, the enhancement in nutrients released from OM may be moderated by a decrease in bioavailable forms by inorganic PU and EP addition, except Mn, because inorganic porous materials serve as compartments for sorption to nutrients [35].

The readily bioavailable amounts are crucial for nutrient supplementation to cultivated crops and those slowly released nutrients during active crop growth [16]. However, as shown in Figure 4, the lowest readily bioavailable amounts of P and Fe need to be further studied to identify the labile, less labile, and hardly labile fractions when inorganic PU and EP are used as bulking agents for composting SS. The readily available fractions of P and K in the compost samples were within the reported P and K% values [36].

Nonetheless, from the total and bioavailable nutrient results, it can be concluded that EP and PU could support the retention in the compost of the investigated plant nutrients, which would reduce their mobility and increase their concentration during the organic matter mineralization. The passivation and nutrient binding mechanism of inorganic porous materials have been frequently demonstrated by previous studies for perlite [19], zeolite [21], and pumice [22]. The different immobility mechanism of expanded perlite and pumice is confirming the variation among the different retention mechanism for different nutrients in compost matrix.

3.5. Correlation of Investigated Parameters

A correlation matrix of the composting parameters showed the positive and negative relationship between the inorganic BA incorporation and the physicochemical characteristics of composting treatments (Figure 5). The increasing rate of BA incorporation to SS correlated positively with the stability parameters GI, composting parameters temperature rise and CO_2, and nutrient parameter TKN, which was interpreted as the complete decomposition of phytotoxic compounds and preserved valuable primary nutrient, nitrogen, in the compost. Accordingly, a higher rate of BA incorporation had a negative correlation with parameters such as the pH, OM, and nutrient parameters phosphorus and potassium contents due to the dilution effect of in higher dose of BA incorporation.

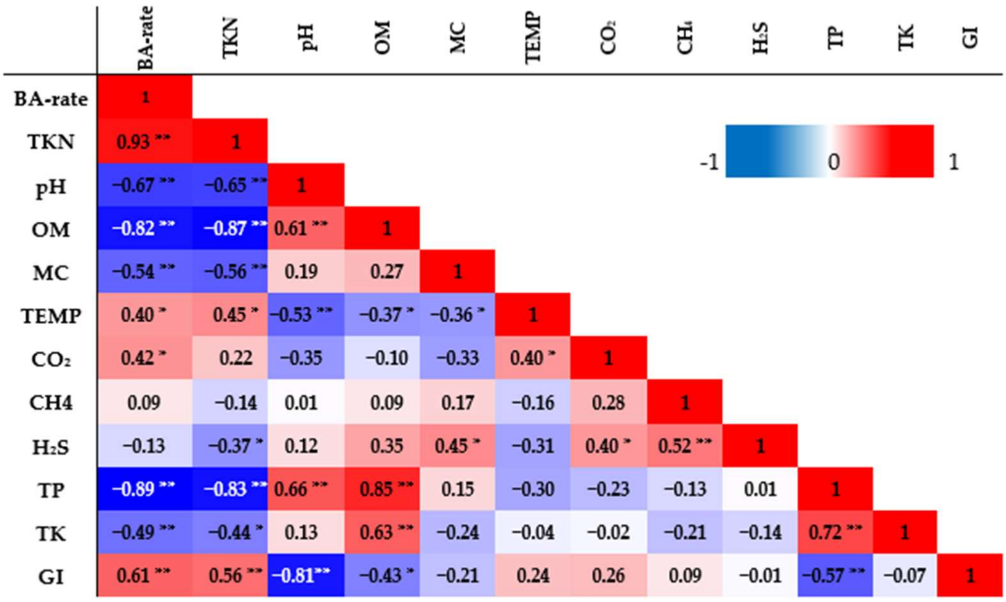

Figure 5. Correlation heatmap from composting parameters, nutrient characteristics, and stability with increasing incorporation rate of inorganic porous BA incorporation to SS. Correlation value ranges between 0 to ±0.35 specified weak, ±0.36 to ±0.47 indicated moderated, and ±0.48 to ±1.0 represented strong positive/ negative correlation. * $p < 0.05$; ** $p < 0.01$.

Since most of the strong positive and negative correlation was related to the BA incorporation rate, the SS was suggested as a suitable condition created by inorganic porous pumice and expanded perlite for the decomposition of organic matter. The moisture-related parameters associated with H_2S and CH_4 generation and CO_2 evolution demonstrated the positive contribution of BA to microbial activity and temperature increase. The correlations of stability parameter GI were strongly positive with BA rate and total Kjeldahl nitrogen TKN and strongly negative with pH, which also related to the pH balancing capacity of BA.

4. Conclusions

Ornamental and horticultural applications demand large amounts of potting soils and soil amendments, as well as the slow release of nutrient resources to maintain healthy plant production. This study investigated the producing growing media components using environmentally friendly, inexpensive materials. Pumice and expanded perlite were composted with municipal sludge with a focus on composting performance and nutrient bioavailability performance. PU and EP at an incorporation rate of 50:50% (v/v) gave a similar composting indicator of temperature rise, gaseous evolution, organic matter removal, and moisture content decrease compared to the SW-control. Phytotoxic compounds were also significantly reduced during the composting process, and PU-50 and EP-50 showed the highest GI results. Considering that fertilizer nutrients are the primary factor for farmers' willingness to choose compost applications, it is claimed that PU and EP help to retain macro- and micro-plant nutrients in compost for ornamental applications. The composting results confirmed the potential of horticultural growing medium components produced by pumice and expanded perlite in a 50% mixture with wastewater sludge as a peat replacement in planting substrates. The total and bioavailable nutrient analysis results indicated that PU and EP could act as promising inorganic BA for SS to mitigate composting and retain plant nutrients.

Author Contributions: Conceptualization, C.D., S.O., A.C. and O.H.D.; methodology, S.O. and O.H.D.; formal analysis, A.C. and H.O.; writing-original draft, S.O. and C.D.; writing-review and editing, S.O. and A.C.; supervision, S.O., A.C. and C.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare that there are no conflicts of interest including any financial, personal, or other relationships with other people or organizations.

References

1. Zhang, J.; Liang, Z.; Matsumoto, T.; Zhang, T. Environmental and economic ımplication of ımplementation scale of sewage sludge recycling systems considering carbon trading price. *Sustainability* **2022**, *14*, 8684. [CrossRef]
2. Ozdemir, S.; Aslan, T.; Celebi, A.; Dede, G.; Dede, O.H. Effect of solarization on the removal of indicator microorganisms from municipal sewage sludge. *Environ. Technol.* **2013**, *34*, 1497–1502. [CrossRef] [PubMed]
3. De Corato, U. Agricultural waste recycling in horticultural intensive farming systems by on-farm composting and compost-based tea application improves soil quality and plant health: A review under the perspective of a circular economy. *Sci. Total Environ.* **2020**, *738*, 139840. [CrossRef] [PubMed]
4. Ozdemir, S.; Yetilmezsoy, K.; Dede, G.; Sazak, M. Application of solarization for sanitization of sewage sludge compost. *J. King Saud. Uni.-Sci.* **2020**, *32*, 443–449. [CrossRef]
5. Sayara, T.; Basheer-Salimia, R.; Hawamde, F.; Sánchez, A. Recycling of organic wastes through composting: Process performance and compost application in agriculture. *Agronomy* **2020**, *10*, 1838. [CrossRef]
6. Lü, H.; Chen, X.H.; Mo, C.H.; Huang, Y.H.; He, M.Y.; Li, Y.W.; Cai, Q.Y. Occurrence and dissipation mechanism of organic pollutants during the composting of sewage sludge: A critical review. *Bioresour. Technol.* **2021**, *328*, 124847. [CrossRef]
7. Özbay, İ.; Özbay, B.; Akdemir, U. Biodrying for fuel recovery from sewage sludge: An integrated evaluation by ultimate and proximate analyses. *Environ. Prog. Sust. Energ.* **2022**, *41*, e13723. [CrossRef]
8. Bilgin, M.; Tulun, Ş. Biodrying for municipal solid waste: Volume and weight reduction. *Environ. Technol.* **2015**, *36*, 1691–1697. [CrossRef]
9. Dede, G.; Özdemir, S.; Dede, Ö.H.; Altundağ, H.; Dündar, M.Ş.; Kızıloğlu, F.T. Effects of biosolid application on soil properties and kiwi fruit nutrient composition on high-pH soil. *Int. J. Environ. Sci. Technol.* **2017**, *14*, 1451–1458. [CrossRef]
10. Ozdemir, S.; Ozdemir, S.; Yetilmezsoy, K. Agro-economic and ecological assessment of poultry abattoir sludge as bio-nutrient source for walnut plantation in low-fertility soil. *Environ. Prog. Sust. Energ.* **2019**, *38*, 13225. [CrossRef]
11. Ding, S.; Zhou, D.; Wei, H.; Wu, S.; Xie, B. Alleviating soil degradation caused by watermelon continuous cropping obstacle: Application of urban waste compost. *Chemosphere* **2021**, *262*, 128387. [CrossRef]
12. Yüksel, O.; Kavdır, Y. Improvement of soil quality parameters by municipal solid waste compost application in clay-loam soil. *Tr. J. Agric.-Food Sci. Technol.* **2020**, *8*, 603–609. [CrossRef]
13. Vida, C.; de Vicente, A.; Cazorla, F.M. The role of organic amendments to soil for crop protection: Induction of suppression of soilborne pathogens. *Ann. Appl. Biol.* **2020**, *176*, 1–15. [CrossRef]
14. Ozdemir, S.; Dede, O.H.; Dede, G. Comparison of the composting performance of four different sewage sludge amendments. *Compost Sci. Util.* **2014**, *22*, 207–215. [CrossRef]
15. Meng, L.; Li, W.; Zhang, S.; Zhang, X.; Zhao, Y.; Chen, L. Improving sewage sludge compost process and quality by carbon sources addition. *Sci. Rep.* **2021**, *11*, 1–8. [CrossRef]
16. Turp, G.A.; Turp, S.M.; Ozdemir, S.; Yetilmezsoy, K. Vermicomposting of biomass ash with bio-waste for solubilizing nutrients and its effect on nitrogen fixation in common beans. *Environ. Technol. Innov.* **2021**, *23*, 101691. [CrossRef]
17. Elsalam, H.E.A.; El-Sharnouby, M.E.; Mohamed, A.E.; Raafat, B.M.; El-Gamal, E.H. Effect of sewage sludge compost usage on corn and faba bean growth, carbon and nitrogen forms in plants and soil. *Agronomy* **2021**, *11*, 628. [CrossRef]
18. Kabak, E.T.; Yolcu, O.C.; Temel, F.A.; Turan, N.G. Prediction and optimization of nitrogen losses in co-composting process by using a hybrid cascaded prediction model and genetic algorithm. *Chem. Eng. J.* **2022**, *437*, 135499. [CrossRef]
19. Wang, X.; Chen, T.; Zheng, G. Perlite as the partial substitute for organic bulking agent during sewage sludge composting. *Environ. Geochem. Health* **2020**, *42*, 1517–1529. [CrossRef]

20. Aygun, Z.; Aygun, M. A study on usability of Ahlat ignimbrites and pumice as radiation shielding materials, by using EpiXS code. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 5675–5688. [CrossRef]
21. Ozdemir, S.; Turp, S.M.; Oz, N. Simultaneous dry-sorption of heavy metals by porous adsorbents during sludge composting. *Environ. Eng. Res.* **2020**, *25*, 258–265. [CrossRef]
22. Wu, C.; Li, W.; Wang, K.; Li, Y. Usage of pumice as bulking agent in sewage sludge composting. *Bioresour. Technol.* **2015**, *190*, 516–521. [CrossRef] [PubMed]
23. Shan, G.; Li, W.; Gao, Y.; Tan, W.; Xi, B. Additives for reducing nitrogen loss during composting: A review. *J. Clean. Prod.* **2021**, *307*, 127308. [CrossRef]
24. Ahn, T.I.; Son, J.E. Application of an alternative nutrient replenishment method to electrical conductivity-based closed-loop soilless cultures of sweet peppers. *Horticulturae* **2022**, *8*, 295. [CrossRef]
25. Bonaguro, J.E.; Coletto, L.; Sambo, P.; Nicoletto, C.; Zanin, G. Environmental analysis of sustainable production practices applied to cyclamen and zonal geranium. *Horticulturae* **2021**, *7*, 8. [CrossRef]
26. Kelley, A.J.; Campbell, D.N.; Wilkie, A.C.; Maltais-Landry, G. Compost composition and application rate have a greater ımpact on spinach yield and soil fertility benefits than feedstock origin. *Horticulturae* **2022**, *8*, 688. [CrossRef]
27. Zhang, B.; Xu, Z.; Jiang, T.; Huda, N.; Li, G.; Luo, W. Gaseous emission and maturity in composting of livestock manure and tobacco wastes: Effects of aeration intensities and mitigation by physiochemical additives. *Environ. Technol. Innov.* **2020**, *19*, 100899. [CrossRef]
28. Liu, L.; Ye, Q.; Wu, Q.; Liu, T.; Peng, S. Effect of biochar addition on sludge aerobic composting and greenbelt utilization. *Environ. Technol. Innov.* **2021**, *21*, 101279. [CrossRef]
29. Li, X.; Shi, X.S.; Yang, Z.M.; Xu, X.H.; Guo, R.B. Effects of recyclable ceramsite as the porous bulking agent during the continuous thermophilic composting of dairy manure. *J. Clean. Prod.* **2019**, *217*, S344–S351. [CrossRef]
30. Weligama Thuppahige, R.T.; Gheewala, S.H.; Babel, S. Environmental impact of organic fraction of municipal solid waste treatment by composting in Sri Lanka. *J. Mater. Cycles Waste Manag.* **2022**, *24*, 189–199. [CrossRef]
31. Sülük, K.; Tosun, İ.; Ekinci, K. Co-composting of two-phase olive-mill pomace and poultry manure with tomato harvest stalks. *Environ. Technol.* **2017**, *38*, 923–932. [CrossRef]
32. Awasthi, M.K.; Wang, Q.; Ren, X.; Zhao, J.; Huang, H.; Awasthi, S.K.; Zhang, Z. Role of biochar amendment in mitigation of nitrogen loss and greenhouse gas emission during sewage sludge composting. *Bioresour. Technol.* **2016**, *219*, 270–280. [CrossRef]
33. Phoungthong, K.; Zhang, H.; Shao, L.M.; He, P.J. Leaching characteristics and phytotoxic effects of sewage sludge biochar. *J. Mater. Cycles Waste Manag.* **2018**, *20*, 2089–2099. [CrossRef]
34. Eneji, A.E.; Honna, T.; Yamamoto, S.; Masuda, T. Influence of composting conditions on plant nutrient concentrations in manure compost. *J. Plant Nutr.* **2003**, *26*, 1595–1604. [CrossRef]
35. Turan, N.G.; Akdemir, A.; Ergun, O.N. Removal of volatile organic compounds by natural materials during composting of poultry litter. *Bioresour. Technol.* **2009**, *100*, 798–803. [CrossRef]
36. Machado, R.M.; Alves-Pereira, I.; Robalo, M.; Ferreira, R. Effects of municipal solid waste compost supplemented with inorganic nitrogen on physicochemical soil characteristics, plant growth, nitrate content, and antioxidant activity in Spinach. *Horticulturae* **2021**, *7*, 53. [CrossRef]