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Effects of Torrefied Wood Chips and Vermicompost on Tree Growth and Weed Biomass: Implications for the Sustainable Management of Salt-Affected Reclaimed Lands

Ji Young An [1,2], Aung Aung [1,3], Jonathan Ogayon Hernandez [1,4], Jeong Min Seo [1,5], Si Ho Han [1] and Byung Bae Park [1,*]

[1] Department of Environment and Forest Resources, College of Agriculture and Life Science, Chungnam National University, Daejeon 34134, Korea; ajy2656@cnu.ac.kr (J.Y.A.); aungaung1361986@gmail.com (A.A.); johernandez2@up.edu.ph (J.O.H.); jmseo3@kiam.or.kr (J.M.S.); bupleurumhan@cnu.ac.kr (S.H.H.)
[2] Institute of Agricultural Science, Chungnam National University, Daejeon 34134, Korea
[3] Environmental Conservation Department, Ministry of Natural Resources and Environmental Conservation, Naypyitaw 15011, Myanmar
[4] Department of Forest Biological Sciences, College of Forestry and Natural Resources, University of the Philippines Los Baños, Los Baños 4031, Philippines
[5] Garden Material Research Team, Sejong National Arboretum, Sejong 30106, Korea
* Correspondence: bbpark@cnu.ac.kr; Tel.: +82-42-821-5747

Abstract: A harsh environment, slow tree growth, nutrient deficiencies, and competition between trees and weeds can impede forest establishment on reclaimed lands. We investigated the effects of torrefied wood chips (TWC) and vermicompost (VC) soil amendments on the growth of *Populus euramericana* Guinier, weed biomass, and soil chemical properties on reclaimed land in Saemangeum. The 2.5 Mg ha^{-1} and 5.0 Mg ha^{-1} TWC had a similar effect on tree diameter and height growth (i.e., 2.5 = 5.0 > 0 TWC) and tended to have similar, higher effect on the total biomass of *P. euramericana* than the 0 Mg ha^{-1}. The 2.5 Mg ha^{-1} TWC resulted in a significantly larger root biomass than the 5.0 Mg ha^{-1} TWC. The weed biomass was significantly larger at the 2.7 Mg ha^{-1} VC (i.e., 730.5–810.5 g m^{-2}) than the control (605.1–610.6 g m^{-2}), but VC alone was not effective for tree growth and soil amelioration. The TWC had no effect on weed biomass. Thus, the TWC and VC had contrasting effects on tree growth and weed biomass when they were used as soil amendments on salt-affected reclaimed land. VC application may promote weed proliferation, whereas TWC application may potentially increase the growth of *P. euramericana* and control weed growth on reclaimed lands. Our results enhance the existing knowledge on tree and weed responses to torrefied wood chips and vermicompost amendments for the sustainable management of salt-affected reclaimed lands.

Keywords: afforestation; organic fertilizer; *Populus euramericana*; reclamation; soil amendments; weed control

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1. Introduction

Land reclamation, the process of making lands suitable for more productive use (e.g., cultivation and revegetation), has recently received much recognition as one of the practical development strategies for increasing forest cover and biomass production in response to climate change [1–4]. In Korea, a poplar afforestation plan was proposed for reclaimed land in Saemangeum, one of the largest reclaimed land areas in the world [5], for afforestation and biofuel production [6,7]. In the USA, reclaimed mine soils have also been reforested to restore land productivity [8,9]. However, some factors may limit the success of forest establishment on reclaimed lands, including salinization, a harsh environment,

the slow growth of trees, soil nutrient deficiencies, and severe competition between trees and weeds or other herbaceous plants [3,10,11].

On reclaimed lands, hardwoods often grow slowly and poorly due to unsuitable substrate conditions for plant growth [12]. Trees have been shown to recolonize reclaimed areas very slowly due to shallow soil, a high content of unweathered rocks, and low levels of organic matter and nutrient content, which can result in the proliferation of invasive plants, herbaceous cover crops, and weeds [11,13,14]. For example, many efforts in reclaiming lands in the USA resulted mostly in the proliferation of grasses with shallow roots [15]. Studies have documented the rapid establishment and dominance of weeds (e.g., *Tripleurospermum perforatum* (Merat) M. Lainz and *Andropogon gayanus* Kunth) in reclaimed sites in Canada, Australia, and United States [16–18]. Weeds have inhibited the revegetation of reclaimed lands planted with the desired tree species and other desirable plants, and they are generally more disturbance-adapted compared with trees, regardless of whether they are native or introduced to the area [19–21]. Plants with shallow or fibrous root systems could survive in salt-affected reclaimed areas [3]. Further, studies have shown that high salt concentrations on reclaimed lands have inhibited natural tree community establishment and reduced the survivability of planted trees [22,23]. Salinization also affects both physical and chemical soil properties, such as poor soil structure low, levels of organic matter, and an imbalance in plant nutrients [24,25]. Therefore, it is important to study how to sustainably and effectively grow deep-rooted tree species, alleviate salinization, control weeds, and improve soil conditions in salt-affected reclaimed lands to maximize their productivity in the pursuit of the sustainable management of reclaimed lands.

Soil amendments have long been recognized as one of the methods for improving the productivity of reclaimed lands using either single or combinations of chemical and organic fertilizer not only to improve plant growth, but also to improve soil structure, soil fertility, and microbe populations [26,27]. The application of vermicompost in soil, for example, decreased the adverse effects of sodium and improved soil organic matter, available phosphorus, total nitrogen, and cation exchange capacity (CEC) of salt-affected soils in Turkey [28]. Vermicompost contains essential micro- and macro-nutrients in available forms for plants and it can improve soil physicochemical characteristics [29,30]. However, the effectiveness of vermicompost may be case-specific due to some factors, including the plant taxa and prevailing biophysical and chemical soil characteristics. There is also very little information available regarding the use of vermicompost as a soil amendment in salt-affected reclaimed land areas. Torrefied materials, which are a form of biochar, are also forms of organic amendments which have shown potential for mitigating soil carbon loss and nutrients in forest ecosystems [31]. Torrefied materials are produced from the pretreatment (torrefaction) of biomass at low temperatures (200 °C–300 °C) under anaerobic conditions [32]. It has been reported that soil amended with torrefied materials showed enhanced soil nutrients and microbe composition, which increased plant growth [33,34]. The common explanations of the previous studies include the capacity of torrefied biomass to provide beneficial elements such as potassium (K) and to inhibit toxic element accumulation. Other studies have attributed the increase in plant growth to an increase in the diversity of microbes, which have played key roles in the metabolism of organic acids [35,36].

Despite the positive individual effects of either torrefied materials or vermicompost on plant growth and soil conditions, their interacting effects for enhancing tree growth and soil characteristics in reclaimed lands using a fast-growing tree species has not been fully investigated, to date. The application of vermicompost with torrefied wood chips as an additive could result in a more efficient, cost effective, and environmentally safe amelioration of soils in salt-affected reclaimed lands. This is because torrefied wood chips can be enriched in combination with nitrogen-rich organic compounds, such as vermicompost, during the digestion or charging stages. Thus, the present study aimed at investigating the effects of both torrefied wood chips (TWC) and vermicompost (VC) on the growth of the fast-growing *Populus euramericana* Guinier and weeds and on the

soil chemical properties on reclaimed tidal land in Saemangeum in South Korea. We hypothesized that the growth of *P. euramericana* would increase with the concentrations of TWC and VC due to their positive effects on soil properties at the expense of weed growth. Our findings are of high significance for creating healthy and sustainable forest ecosystems using proportional or optimum amounts of TWC and/or VC in salt-affected reclaimed lands.

2. Materials and Methods

2.1. Study Site and Climatic Conditions

The experiment was conducted on Saemangeum's salt-affected reclaimed land (35°51′51″ N 126°46′32″ E), which was one of the biggest reclaimed lands in the world and was originally planned for augmenting agricultural production in South Korea. However, the area had been unproductive because the soil conditions could not support the growth of most crops, which resulted in an intentional shift in emphasis for using the land from agricultural to afforestation and biomass production in response to climate change [6,7]. The mean annual temperature during the experiment was 14.0 °C in 2016 and 13.7 °C in 2017. Annual precipitation was 896 mm in 2016 and 926 mm in 2017, and the highest rainfall occurred in July 2017 (Figure 1). During the conduct of the study, irrigation was done only through rainwater. The soil in the study site was slightly basic (a pH of 8.2), with very low total nitrogen (0.14%), organic matter content (0.58–1.05%), and available P (71.8–84.7 mg kg^{-1}), and a high Na^+ concentration, i.e., 2.34 to 3.39 $cmol_c$ kg^{-1}. Moreover, the soil in the study site had very low EC (0.39–0.42 ds m^{-1}) and CEC (15.5–19.3 mg kg^{-1}).

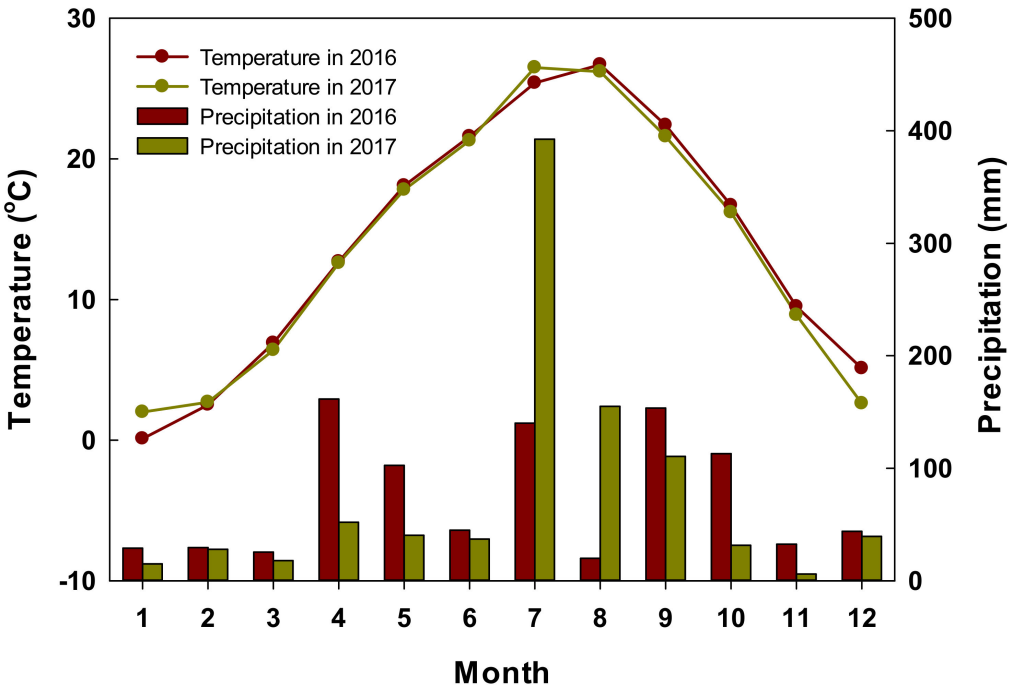

Figure 1. Mean monthly temperature and precipitation during the study period in the experimental site.

2.2. Plant Species

Due to harsh soil conditions in the study site, we used *Populus euramericana* Guinier, which is characterized by rapid growth and rooting ability [37]. Fast growing species are generally well-adapted to a wide range of environmental conditions. The genus *Populus* is also known to have a wide range distribution for different climatic zones [38], making any *Populus* species a good model for explaining growth performance and mechanisms in salt-affected reclaimed land. Poplars are also a common hardwood species used for

afforestation and reforestation in South Korea. Here, the pole sized trees that we used had an initial height of 100 cm and a 2–3 cm root collar diameter (RCD).

2.3. Torrefied Wood Chips and Vermicompost

The torrefied wood chips (TWC) of *Quercus acutissima* (dimensions: 2 cm × 2 cm × 0.5 cm) were used in this study. The TWC were torrefied using a wood roaster torrefaction at the College of Agriculture and Life Sciences, Chungnam National University, following a standard torrefaction process at 200 °C to 250 °C in the absence of oxygen [6]. The chips had moisture, ash, and carbon contents of 3.2%, 0.5%, and 52.2%, respectively. Their pH (5.1) was within the range reported in the literature, i.e., 3.1–12.0. The other physical and chemical properties of the TWC are shown in Table 1. Some studies had already found a positive growth response of trees and/or seedlings grown under the torrefied wood chips of *Quercus acutissima* (e.g., [39]). The peat-like vermicompost fertilizer (VC) used in the study, which is mainly from decomposing food and agricultural wastes, with the help of earthworms, was obtained from the Vermifarm, South Korea. The VC had a high water-holding capacity, porosity, aeration, and microbial activity, with high amounts of micro-and macro-nutrients [40].

Table 1. Physical and chemical properties of the torrefied wood chips (TWC) of *Quercus acutissima* (adapted with permission from Cho et al. 2017 [41]). The values written in parentheses represent standard errors of the mean (n = 3).

Physical Properties	Values
Moisture content (%)	3.2 (0.0)
Ash content (%)	0.5 (0.0)
Volatility (%)	79.9 (0.4)
Chemical properties	
pH	5.1 (0.0)
EC (dS m^{-1})	0.282 (0.054)
Carbon (%)	52.2 (0.0)
Nitrogen (g kg^{-1})	0.7 (0.4)
Phosphorus (g kg^{-1})	0.94 (0.08)
Potassium (g kg^{-1})	0.97 (0.12)
Sodium (g kg^{-1})	0.64 (0.11)
Calcium (g kg^{-1})	10.3 (1.2)
Magnesium (g kg^{-1})	0.83 (0.09)

2.4. Experimental Design

The experiment occupied an area of 1.5 ha in the study site, encompassing 18 experimental plots (50 m × 15 m each) with roadworks (2.5 m width). The plots were first amended with TWC and VC before tree planting. Here, a 3 × 2 split-plot experimental design (n = 3) was used, with three levels of TWC (0 or control, and 2.5 and 5.0 Mg ha^{-1}) and two levels of VC (0 or control, and 2.7 Mg ha^{-1}). The TWC and VC were spread on the soil surface manually and then mixed evenly using a tractor. Thereafter, trees were planted manually in the plots following a 1 m × 1 m distance between rows, with 50 seedlings per row. A total of 13,500 seedlings (750 seedlings × 18 plots) were planted.

2.5. Soil Properties Analysis

The soil samples (c.a., 300 g) were collected twice from three different soil depths (i.e., 0–15 cm, 15–30 cm, and 30–45 cm) in August 2016 and 2017. Sampling was done in the center of each plot using a shovel, and the samples were analyzed in the soils laboratory. We analyzed the soil pH by the pH-meter method (Robotic Analyzer SP2000, Skalar, Breda, The Netherlands), organic matter (OM) and total nitrogen content (TN) by the dry oxidation method (using CN analyzer equipment, Vario Max CN, Elementar, Langenselbold, Germany), available phosphorus (P) with the Lancaster method (San++ continuous flow analyzer, Skalar), cation exchange capacity (CEC) by the 1N-ammonium

acetate replacement leaching method (Kjeltec 8420, FOSS, Hilleroed, Denmark), electrical conductivity by the EC-meter method, and calcium (Ca), potassium (K), magnesium (Mg), and sodium (Na) levels using the 1N-ammonium acetate leaching/atomic absorption spectrophotometry method (Varian AA280FS, Agilent, Santa Clara, CA, USA). The analyses were done both before and after the application of the TWC and VC.

2.6. Measurement of Tree and Weed Growth

For tree growth, the height and diameter at breast height of 60 *P. euramericana* trees in each plot (20 trees per row and 3 rows per plot) were measured across TWC and VC treatments. The stem diameter growth was measured using calipers and the height from the soil surface to the highest terminal bud of the main stem was measured (using a measuring pole) in 2017 and 2018.

Out of the 60 trees in each plot, 4 healthy trees were selected and harvested for biomass measurement. Thereafter, the trees were separated into root, stem, branch, and leaf components. The roots were washed carefully to remove all soil particles while ensuring that the fine roots were not damaged or lost. All the plant samples were then oven-dried at 70° C for 72 h to a constant weight.

The aboveground parts of weeds, dominated by green foxtail (*Setaria viridis* (L.) P. Beauv.) and the common reed (*Phragmites communis* Trin.), were also harvested to determine their biomass across the different TWC and VC treatments. The sampling was conducted twice in 2017 and 2018, and those weeds growing in the center of each plot were included in our study. The weeds were carefully clear-cut, covering three 1 m^2 areas using sickles at each plot, and then oven-dried at 65 °C for 72 h and weighed.

2.7. Statistical Analysis

The significant effects of the interaction of the TWC and VC treatments on tree and weed growth and biomass were tested using two-way analysis of variance (ANOVA) with Tukey's HSD post hoc test. If the interaction was not significant, one-way ANOVA was run to test the main effects of the TWC and VC. The data were analyzed using R software at a significance level of $\alpha = 0.05$.

3. Results

3.1. Growth of Populus Euramericana in Different Amouts of Torrefied Wood Chips and Vermicompost

The application of both the TWC and VC (TWC × VC) had no significant effects on either the height or diameter growth of *P. euramericana* (Figure 2). However, the TWC as a main factor showed a highly significant effect on the diameter ($p = 0.001$) and height ($p < 0.001$) across the TWC treatments. The 2.5 Mg ha^{-1} and 5.0 Mg ha^{-1} of the TWC resulted in a higher height and larger diameter growth than the 0 Mg ha^{-1} or control (Figure 2). In terms of the VC application, the 2.7 Mg ha^{-1} had a marginally higher height ($p = 0.06$) compared with the 0.0 Mg ha^{-1} (Figure 2). VC application alone did not affect the diameter growth.

There was no significant TWC × VC interaction effect on total biomass, but there was a significant effect on branch and root biomass (Figure 3). Here, we found that the 0 Mg ha^{-1} VC and the 2.5 Mg ha^{-1} TWC resulted in a significantly larger root biomass than the other TWC and VC treatments. The branch biomass was larger at the 0 Mg ha^{-1} VC and the 2.5 Mg ha^{-1} TWC and the 2.7 Mg ha^{-1} VC and the 5.0 Mg ha^{-1} TWC than the other treatments. The 2.5 Mg ha^{-1} and 5.0 Mg ha^{-1} TWC tended to have a similar higher effect on total biomass than the 0 Mg ha^{-1}.

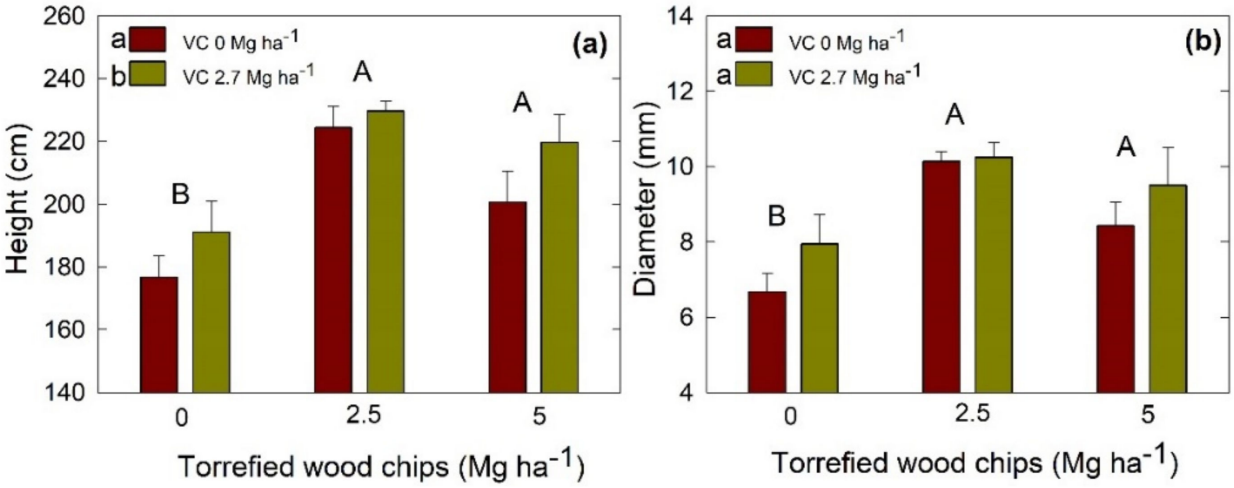

Figure 2. (**a**) Height and (**b**) diameter growth of *Populus euramericana* with different amendments of the TWC (torrefied wood chips) and VC (vermicompost). Different uppercase letters indicate significant differences across the TWC treatments and different lowercase letters (not enclosed by parentheses) indicate significant differences between the VC treatments. Vertical bars indicate standard errors (n = 3).

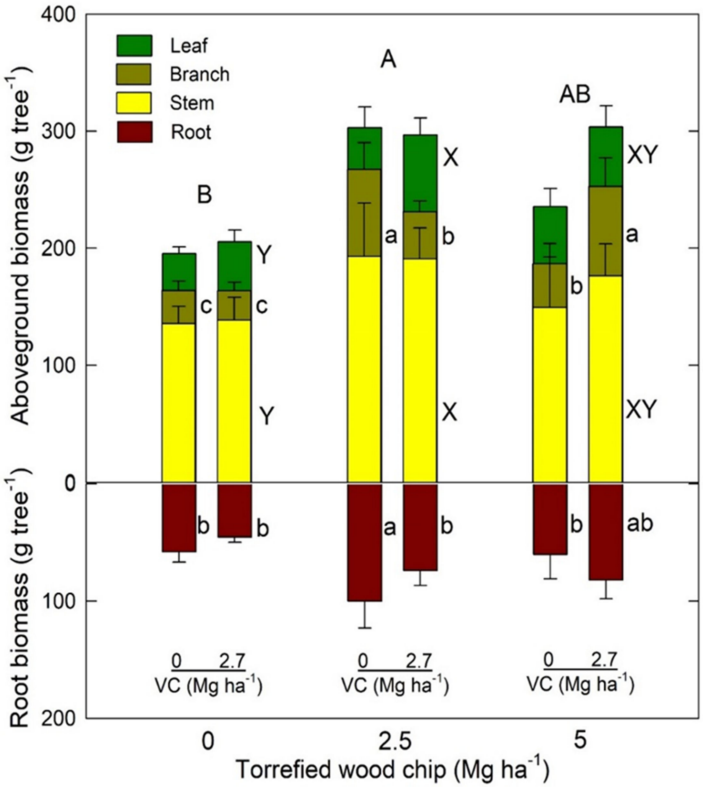

Figure 3. Biomass growth aboveground and belowground of *Populus euramericana* trees with different amendments of the torrefied wood chips (TWC) and vermicompost (VC). The uppercase letters A, AB, and B indicate significant differences across the TWC treatments for total biomass, and the letters X, XY, and Y indicate significant differences across the TWC treatments for leaf and stem biomass. The different lowercase letters (**a**–**c**) indicate significant differences across the combinations of TWC and VC treatments for branch and root tissues. The vertical bars indicate standard errors (n = 3).

In this study, TWC × VC interactions had no significant effects on weed biomass (Figure 4). The TWC as a main factor also did not show any significant effects on weed biomass. However, the main effect of VC was significantly different between treatments

such that the 2.7 Mg ha^{-1} VC yielded a larger weed biomass compared with the 0 Mg ha^{-1} VC (Figure 4).

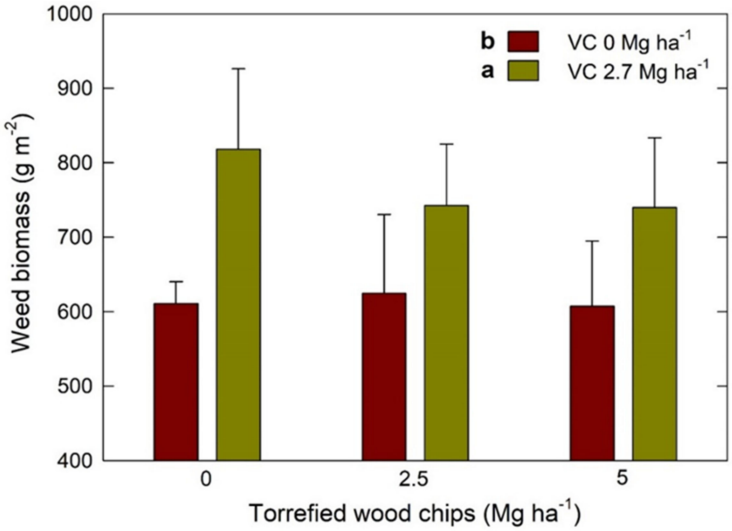

Figure 4. Biomass of weeds in the study site containing different amendments of the torrefied wood chips (TWC) and vermicompost (VC). The different lowercase letters (**a**,**b**) indicate significant differences across the VC treatments. The vertical bars indicate standard errors (n = 3).

3.2. Soil Properties after the Application of the Torrefied Wood Chips and Vermicompost

Generally, the concentrations of soil pH, OM, total N, available P, and K^+, Ca^{2+}, Mg^{2+}, CEC, and EC levels did not vary significantly across the TWC and VC treatments, except in the amounts of exchangeable Na^+ (Table 2; $p = 0.01$). Here, the amounts of exchangeable Na^+ were significantly lower in the 2.5 Mg ha^{-1} TWC and/or the 5.0 Mg ha^{-1} TWC.

Table 2. Soil chemical properties in the study site after the torrefied wood chips (TWC) and vermicompost (VC) treatment impositions.

							Exchangeable Cations					
TWC	**VC**	**Depth**	**pH**	**OM**	**Total N**	**Available P**	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**Na^+**	**CEC**	**EC**
(Mg ha^{-1})		**(cm)**		**(%)**	**(%)**	**(mg kg^{-1})**			**(cmolc kg^{-1})**			**(dS m^{-1})**
0	0	0–15	8.0	1.05	0.14	71.8	1.10	1.60	5.22	2.34	15.5	0.39
		15–30	8.3	0.70	0.13	78.9	1.23	1.57	5.48	3.23	16.1	0.39
		30–45	8.4	0.58	0.16	84.7	1.17	1.53	5.09	3.39	19.3	0.42
	2.7	0–15	8.2	0.87	0.14	81.9	1.10	1.70	4.98	2.53	12.7	0.42
		15–30	8.3	0.71	0.12	74.7	1.12	1.56	4.78	2.65	18.2	0.35
		30–45	8.4	0.56	0.12	81.9	1.17	1.43	4.88	2.65	15.1	0.33
2.5	0	0–15	7.9	0.97	0.16	73.9	1.14	1.67	5.30	2.00	12.8	0.39
		15–30	8.2	0.65	0.14	79.9	1.20	1.64	5.57	2.41	13.0	0.34
		30–45	8.4	0.56	0.13	82.4	1.21	1.46	4.82	2.59	12.7	0.40
	2.7	0–15	7.9	1.05	0.16	77.5	1.11	1.70	5.74	2.19	16.6	0.39
		15–30	8.3	0.65	0.15	85.1	1.30	1.59	5.54	2.63	13.5	0.38
		30–45	8.4	0.62	0.14	85.3	1.27	1.56	4.99	2.92	12.7	0.42
5	0	0–15	7.9	1.14	0.15	74.9	1.14	1.68	4.83	2.23	12.1	0.37
		15–30	8.3	0.70	0.12	79.6	1.29	1.58	5.22	3.02	13.0	0.40
		30–45	8.3	0.62	0.12	84.7	1.24	1.50	4.92	2.75	12.8	0.40
	2.7	0–15	8.0	0.96	0.13	75.4	1.19	1.92	5.38	1.86	11.9	0.26
		15–30	8.2	0.67	0.14	78.4	1.19	1.54	5.40	2.56	13.2	0.32
		30–45	8.3	0.62	0.14	81.5	1.18	1.52	4.94	2.72	12.6	0.32

4. Discussion

In this study, the reliance on only precipitation to irrigate the trees throughout the experimental period can explain the insignificant interaction effect of TWC × VC on most of the parameters measured. The lack of soil moisture, particularly during the dry months from the spring to summer seasons, may have negatively controlled the charging of the TWC with VC. Consequently, the VC may have been digested by the soil for a longer period of time, which may have resulted in microbial and nutrient imbalances. There must be enough moisture to dissolve the nutrients in the VC and recharge the pores of the TWC. Carbon-based nutrients, which are essential for microbial colonization, should have been available or provided by the VC in order to make the TWC × VC effective. This explains the insignificant effect of any of the soil amendments on the soil properties measured. This may also have been exacerbated by the high hydrophobicity of the TWC [42,43] and the location of the study site, i.e., the site was adjacent to the coastal area, which is generally dry and has a basic soil pH.

The 2.5 Mg ha^{-1} and 5.0 Mg ha^{-1} TWC had a similar effect on tree diameter and height growth (i.e., 2.5 = 5.0 > 0 TWC) and tended to have a similar higher effect on the total biomass of *P. euramericana* than did the 0 Mg ha^{-1}. However, between the two amounts of TWC, we could say that the 2.5 Mg ha^{-1} TWC will be more suitable for the sustainable management of salt-affected reclaimed lands than the 5.0 Mg ha^{-1} TWC. This is because the 2.5 Mg ha^{-1} TWC resulted in a significantly larger root biomass than the 5.0 Mg ha^{-1} TWC, which may represent a strategy to combat salt stress. The observed higher root biomass at the 2.5 Mg ha^{-1} TWC may indicate an adaptive response of *P. euramericana* trees to stressful conditions via enhanced anchorage and uptake of water and nutrients. Further, the soil at the 2.5 Mg ha^{-1} TWC had a significantly lower Na concentration than at the 5.0 Mg ha^{-1} TWC treatments, suggesting that such an amount of TWC has a higher capacity to ameliorate salt stress effects on *P. euramericana*. A review indicated that the roots of poplar tree species can accumulate high Na^+ concentrations in plant organs, especially in roots [38]. Holtz et al. [44] also found a significant decrease in soil pH after wood chips addition to soil. Although we also observed a tendency for the root biomass to increase at the 2.7 Mg ha^{-1} VC and the 5.0 Mg ha^{-1} TWC, this combination may not be economically efficient for large tracts of land because both vermicompost and biochar materials are expensive.

The present study found that the TWC did not promote the growth of weeds. Instead, the 2.7 Mg ha^{-1} VC application resulted in a significantly higher increase in weed biomass compared with the untreated one. These results can be ascribed to the abundance of micro- and macro-nutrients and humic acids in vermicompost [40,45,46]. However, the VC was not effective at increasing the plant growth of *P. euramericana* trees or even at reducing Na^+ concentrations in the soil. In some studies, the weeds outgrew the economically important crops due to their generally high response rate to organic fertilizer application [47–49]. Besides a better adaptability to an extreme environment (e.g., a high soil pH and groundwater level), weeds are generally more responsive to high nutrient availability due to their shallow fibrous system compared with the taproot system of tree species. Moreover, weeds that are native to the site generally have greater salt tolerance because of their high intraspecific variability compared with tree species [50]. Such a greater tolerance to salt is often associated with diverse physio-ecological adaptive mechanisms, which are enhanced by earlier and faster emergence [50].

Another factor that can explain the results is the amount of VC that we used, which may not have been enough to promote tree growth, particularly in soils characterized by high pH, low organic matter content, and poor drainage. This is because the effectiveness of an organic soil amendment may be case-specific depending on the materials used, application rate, placement methods, and soil characteristics. For example, a study showed that plant yield and development, leaf area, and biomass significantly increased with increasing concentrations of vermicompost application [51]. However, the results of the study revealed that the amount of VC used (i.e., 2.7 Mg ha^{-1}) had already promoted weed

growth. This implies that increasing the amount of VC will further proliferate weeds in the study site, and this can strengthen the competition between the trees and undesirable plants unless regular weeding is imposed. Weeding, however, may be impractical for plantation areas in large tracts of reclaimed land.

5. Conclusions

The TWC and VC had contrasting effects on the growth of *P. euramericana* and weeds in the study site. Although the 2.5 Mg ha^{-1} and 5.0 Mg ha^{-1} of TWC had similar effects on height, diameter, and total biomass, the 2.5 Mg ha^{-1} TWC seemed to be more suitable for reforestation in infertile, salt-affected reclaimed lands because of the resultant better root growth and the potentially higher phytoextraction capacity of the sodium in the soil. VC should not be recommended as a soil amendment because, in the study site, a small amount of it stimulated the growth of weeds. The TWC did not promote the growth of weeds, suggesting that it is a practical technology for weed control, particularly in newly established restoration or afforestation sites. To improve the effects of the TWC plus VC on tree growth and soil characteristics on the reclaimed tidal land in Saemangeum, we recommend that the application should be done with artificial irrigation to facilitate the charging of the TWC pores with VC and improve the TWC's porosity and absorption ability. Our findings enhance the existing knowledge on tree and weed responses to torrefied wood chips and vermicompost amendments for the sustainable management of salt-affected reclaimed lands.

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