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Physical and Chemical Properties of Water Treatment Residue and the Characteristics of Red Pepper Growth by Using it

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Physical and chemical properties of the water treatment residue (WTR) and the WTR_{CP}, which contained compost (CP), were measured, and the effect of the properties on growth of the red pepper (*Capsicum annuum* ‘Takanotsune’) was studied to reuse the WTR as an alternative material for decomposed granite soil (DGS). The physical properties of relative gas diffusivity (D/D_0), saturated hydraulic conductivity (K_s), water retention curve, porosity and plant-available water, and the chemical properties of total-N and cation-exchange capacity (CEC), etc. were compared between the WTR and DGS, and between the WTR_{CP} and DGS_{CP}, respectively. D/D_0 , K_s , total-N and CEC were higher in WTR_{CP} than in DGS_{CP}. The growth of the red pepper was better in WTR_{CP} than in DGS_{CP} because the physical and chemical properties of the WTR_{CP} were considered to be beneficial to the growth of the red pepper. The WTR_{CP} was suitable as an alternative material of DGS_{CP}.

INTRODUCTION

Water treatment residue (WTR) is the by-product from the production of the potable water (Titshall and Hughes, 2005). Most of WTR are discarded at landfill sites or waste disposal stations everywhere in the world (Heil and Barbarick, 1989; Moodley *et al.*, 2004; Titshall and Hughes, 2005; Babatunde and Zhao, 2007).

Technology that can reuse a large amount of WTR is required. Following examples to reuse the WTR as a substitute soil materials were reported; clay substitute material of cement and brick manufacture (Pan *et al.*, 2004; Ramadan *et al.*, 2008), subbase material of geotechnical works (Furukawa *et al.*, 2006). Currently, applications of the WTR as a soil amendment is gaining increasing attention as an alternative landfill option for its recycling (Heil and Barbarick, 1989; Moodley *et al.*, 2004; Moodley and Hughes, 2006).

However, typically high application rate of the WTRs (>10%) cause the deficiency of plant-available phosphorus (P) for plants (e.g., Elliott and Singer, 1988; Dayton and Basta, 2001). Ahmed *et al.* (1997) investigated the water retention characteristics of the WTR and concluded that WTR was unsuitable for use it as a growth medium due to its low plant available water content. Little information is available to use the WTRs as an alternative soil material (Dayton and Basta, 2001).

On the other hand, Roppongi (1993) suggested that the possibility to reuse the WTR to which organic matter (OM) was added as an alternative soil material. He

reported that the vegetables growth in the WTR to which hull and sawdust–cattle manure were mixed was similar to that in nursery soil (control). Elliot and Dempsey (1990) showed that the WTR generally had little fertilizer value. The addition of fertilizer and/or OM, such as compost and biosolids, can help to improve nutritional value of the WTR. With regard to potential fixation of plant-available P, Hyde and Morris (2004) noted that amendment of WTR with P before application to agricultural soil may eliminate the problem of P deficiencies for plant growth. Park *et al.* (2009) reported that the available water capacity of the WTR was increased by the adjustment of particle size distribution and the pore structure of the WTR. Moreover, the aeration and water retention ability of the WTR were superior to the decomposed granite soil (DGS).

Red peppers grow well on loamy soils rich in OM; Since inadequate field drainage results in a low yield of the red pepper, the plant should be grown in well-drained plots; The optimum pH ranges for the red pepper were from 6.0 to 7.0, and the plant is fairly tolerant to soil acidity. A large number of the red pepper cultivars is suited to an atmospheric temperature ranging from 21 to 25 °C, while very high temperatures (above 32 °C), lead to parthenocarp; Irrigation should be moderately adjusted because the red pepper roots are highly susceptible to excessive soil moisture (AICAF, 1993).

The our purposes of this study are therefore, 1) to compare physical and chemical properties between the WTR and DGS, and between the WTR_{CP} and DGS_{CP}, which contained OM, and 2) to clarify the effect of the properties above mentioned on a growth of red pepper, which is used as a representative crop plant, in order to examine the possibility of reuse of WTR_{CP} for an alternative material of DGS_{CP}.

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MATERIALS AND METHODS

Materials and its treatment

The WTR was collected from the Tatara Water Purification Plant in Fukuoka City, Japan for the experimental use. Nearly 0.02 m³ in volume of the WTR was collected from the plant in 2007. The WTR was produced from aggregates by a flocculation process with polyaluminium chloride and dehydration by filter press in the filtration process. The original WTR materials were angular blocks of 12–35 mm long and wide and 4 mm thick having an average water content of 121% (w w⁻¹). Those WTR were ground and sieved into particles less than 3 mm in diameter. DGS of around 0.02 m³ was collected from Mt. Tachibana in Fukuoka Prefecture in 2007. The DGS was sieved to particles of less than 3 mm in diameter.

Particle density of the collected WTR and DGS was measured by the pycnometer method and was 2.35 Mg m⁻³ and 2.69 Mg m⁻³, respectively. The particle size distribution of the WTR and DGS was determined by dry sieving and the hydrometer method (Gee and Or, 2002). The WTR consisted mostly of sand (78.0 % in content), and the content of clay was very low (2.4%). While the DGS consisted of gravel (47.2%) and sand (45.7%). The WTR and DGS belonged to loamy sand, and sandy loam, respectively by US Department of Agriculture scheme.

Compost (CP) was added to the WTR and DGS for making growth medium. The CP was matured cattle manure and wood waste from commercial products (Orizin, dozyoubiseibutsu Inst. Inc., Japan). This CP was also sieved to less than 3 mm. The particle size of nearly half in amount of the CP was > 1 mm in diameter. The electrical conductivity, total-N and cation-exchange capacity of the CP employed in the study were 20.0 dS m⁻¹, 26.1 g kg⁻¹ and 58.4 cmol kg⁻¹, respectively. Exchangeable bases (K⁺, Ca²⁺, Mg²⁺) and plant-available P of the CP were 798.0, 80.6 and 64.3 cmol kg⁻¹, and 460.2 mg kg⁻¹, respectively.

For WTR and DGS, the CP was added at 10% of the total volume of the dried originals of WTR and DGS. The original WTR and DGS are denoted as WTR and DGS, and the CP added WTR and DGS are denoted as WTR_{CP} and DGS_{CP} hereafter, respectively.

Physical and chemical properties

To measure the physical properties of the WTR_{CP} and DGS_{CP}, the air-dried samples of these were packed uniformly by hand into stainless steel cylinder (51 mm high and 50 mm i.d.) with three replications. The samples were saturated by the upward infiltration method overnight, and saturated hydraulic conductivities (K_s) of samples were measured by the falling head method (Reynolds *et al.*, 2002). Then the water retention curves of the samples were determined at -1, -4, -6, -13, -40, -100, -600 and -1,500 kPa matric potentials in the water desorption process (Flint and Flint, 2002). Here, water contents were measured at high matric potentials of -6 kPa by the hanging-water column method (Dane and Hopmans, 2002a), and at -40 kPa by the pressure

plate method (Dane and Hopmans, 2002b). Moreover, water content at the low matric potentials of -600 and -1,500 kPa was determined by the centrifuge method (Reatto *et al.*, 2008).

Gas diffusivity (D) was measured at -6 and -100 kPa matric potentials. Relative gas diffusivity (D/D₀) was determined by the methods shown by Osozawa (1987) and Rolston and Moldrup (2002). Then, the bulk density (Bd) and gravimetric water content were obtained by weighing the oven-dried samples for 24 hrs at 105 °C. Total porosity was calculated from the bulk density and particle density (Flint and Flint, 2002). The total porosity is the sum of capillary and macro porosities. The capillary porosity (capillary water) was defined as the amount of water retained at -4 kPa (Bigelow *et al.*, 2004), while the macro porosity was determined by subtracting the amount of water at -4 kPa from total porosity. The amount of plant-available water (PAW) for WTR_{CP} and DGS_{CP} was determined as the water content difference between the matric potentials at -6 and -1,500 Pa (Moodley *et al.*, 2004). These determined data of physical properties of the WTR and DGS were cited from Park *et al.* (2010).

The samples of WTR, DGS, WTR_{CP} and DGS_{CP} were air-dried and gently ground to pass through a 2 mm sieve for chemical analysis. The pH of samples was determined in a 1 (water): 2.5 (sample) calcium chloride (CaCl₂) solution using a glass electrode. Electrical conductivity (EC) was measured in a 1 (water): 5 (sample) deionized water solution. Cation-exchange capacity (CEC) and exchange bases were determined by the NH₄⁺-acetate method and the 1 M NH₄⁺-acetate extraction method at pH 7 (Sumner and Miller, 1996). Total-C and total-N were determined by using a CN corder (MT-5, CHN corder, Yanaco New Science Inc., Japan) and amount of plant-available P by using dilute acid method (Kuo, 1996). P-adsorption coefficient was determined by the vanadomolybdate spectrophotometric method (SEAC, 1997).

Greenhouse growth experiment

Greenhouse growth experiment was conducted using WTR_{CP} and DGS_{CP}. Each WTR_{CP} and DGS_{CP} was placed in a plastic pot (20 cm tall, 11 cm i.d.). Red pepper (*Capsicum annuum* 'Takanotsume') was chosen to compare plant growth between the treatments, because the plant's growth and root swelling were comparatively early, and it was sown at a rate of five seeds per pot. After seedlings emerged, all but the one strongest plant were removed. The seedlings were grown in a glass-covered greenhouse controlled at 30 °C under natural light condition for 14 weeks, from January 20 to April 18. Seedlings were watered as needed.

The pots were arranged in a randomized complete block design with six replications. At the end of experiment, growths of height, root-collar diameter and dry mass of the whole seedlings were measured. For the determination of dry mass, the seedlings were oven-dried at 75 °C for 48 hrs. Growth experiment was carried

out in controlled greenhouses at the Biotron Institute, Kyushu University, Fukuoka, Japan.

Statistical analysis

Statistical difference of the growths of red pepper between WTR_{CP} and DGS_{CP} was examined by a t-test for the mean difference between them by using the SPSS software (Version 11). To test the differences of the physical properties among WTR, DGS, WTR_{CP} and DGS_{CP}, one-way analysis of variance (ANOVA) and Tukey multiple comparison test (Tukey's test) were used.

RESULTS

Physical and chemical properties of WTR_{CP} and DGS_{CP}

Porosity, relative gas diffusivity (D/D_0), plant-available water (PAW), bulk density (Bd), saturated hydraulic conductivity (K_s) of the samples of WTR, DGS, WTR_{CP} and DGS_{CP} (averaged for the 3 replications, respectively) are shown in Table 1. Total, macro and capillary porosities were significantly higher for WTR_{CP} than for DGS_{CP}, respectively. Because the macro porosity was higher for WTR_{CP} than for DGS_{CP}, the D/D_0 was significantly higher for WTR_{CP} than for DGS_{CP} at -6 kPa matric potential. The capillary porosity was higher for WTR_{CP} than for DGS_{CP}, but the PAW was lower for WTR_{CP} than for DGS_{CP}.

The Bd was significantly lower for WTR_{CP} than for DGS_{CP}. Addition of CP to WTR tended to increase the K_s , but the K_s was not significantly different between the WTR_{CP} and WTR. The K_s was significantly higher for WTR_{CP} than for DGS_{CP}. Addition of CP to WTR increased the macro porosity, but the capillary porosity of the WTR_{CP} was decreased. The D/D_0 was increased in WTR_{CP} at matric potential of -6 kPa by the addition of CP, but the D/D_0 of -100 kPa, PAW, K_s and Bd did not change in WTR_{CP}.

Chemical properties of the samples are shown in Table 2. In comparison with the neutral DGS, pH of the WTR was low (pH 6.4). EC did not differ largely between the WTR and DGS. Total-C and total-N of the WTR were 130 and 45 times higher than those of the DGS, respectively. P-adsorption coefficient and CEC of the WTR were 14 and 2 times higher than those of DGS, respectively. However, plant-available P of the WTR was 2.7 times lower than that of DGS. The EC, total-C, total-N, plant-available P, CEC and exchangeable bases were higher for WTR_{CP} than those for WTR. However, pH of the WTR and DGS did not change by the addition of the CP. The EC and total-N of the WTR_{CP} were 1.9 and 5.9 times higher than those of DGS_{CP}, respectively. Moreover, the CEC of the WTR_{CP} was 1.9 times higher than that of DGS_{CP}. However, The Mg^+ of the WTR_{CP} was 7 times lower than that of DGS_{CP}.

Table 1. Porosity, relative gas diffusivity (D/D_0), saturated hydraulic conductivity (K_s), plant-available water (PAW) and bulk density (Bd) of water treatment residue (WTR), decomposed granite soil (DGS), and WTR_{CP} and DGS_{CP}, which contained compost (CP)

Media	Porosity ($m^3 m^{-3}$)			$D/D_0^{(2)}$		K_s	PAW ⁽³⁾	Bd
	Total	Macro	Capillary	-6 kPa	-100 kPa	($m s^{-1}$)	($m^3 m^{-3}$)	($Mg m^{-3}$)
WTR	0.660 ^a	0.205 ^b	0.455 ^a	0.033 ^b	0.080 ^b	2.28×10^{-3a}	0.119 ^c	0.77 ^b
DGS	0.485 ^b	0.181 ^b	0.304 ^c	0.012 ^c	0.035 ^c	1.10×10^{-5b}	0.192 ^a	1.37 ^a
WTR _{CP} ⁽¹⁾	0.677 ^a	0.313 ^a	0.364 ^b	0.050 ^a	0.111 ^a	3.68×10^{-3a}	0.107 ^c	0.74 ^b
DGS _{CP} ⁽¹⁾	0.486 ^b	0.189 ^b	0.297 ^c	0.024 ^{bc}	0.080 ^b	6.85×10^{-5b}	0.161 ^b	1.36 ^a

⁽¹⁾ The compost was added to WTR and DGS at the rate of 10% of the dry-mass.

⁽²⁾ Relative gas diffusivities (D/D_0) at -6 and -100 kPa matric potentials.

⁽³⁾ Plant-available water (water retained between -6 and $-1,500$ kPa)

Different superscript letters (a–c) indicate significant difference between the treatments at $p < 0.05$ according to the Tukey's test with 3 replications.

Table 2. Chemical properties of water treatment residue (WTR), decomposed granite soil (DGS), and WTR_{CP} and DGS_{CP}, which contained compost (CP)

Media	pH (H ₂ O)	EC	Total C	Total N	C/N	Avail. P ₂ O ₅	P ₂ O ₅ ad. Coef.	CEC	Exchangeable bases		
		dS m ⁻¹	g kg ⁻¹	mg kg ⁻¹			K		Ca	Mg	
							cmol(+) kg ⁻¹				
WTR	6.4	0.4	64.8	4.5	14.4	2.4	26702.3	17.2	0.7	8.3	0.2
DGS	7.1	0.3	0.5	0.1	5.0	6.4	1878.9	8.9	0.2	11.3	7.6
WTR _{CP} ¹⁾	6.3	1.3	82.5	5.9	14.0	7.3	26530.0	17.9	13.5	9.5	1.2
DGS _{CP} ¹⁾	7.0	0.7	12.2	1.0	12.2	6.9	24380.0	9.6	11.4	12.3	8.4

⁽¹⁾ The compost was added to WTR and DGS at the rate of 10% of the dry-mass.

EC: electric conductivity; CEC: cation exchange capacity; Avail. P₂O₅: plant-available phosphorus; P₂O₅ ad. Coef.: phosphate adsorption coefficient.

Growths of the red pepper

The red pepper growth in WTR_{CP} and DGS_{CP} (averaged for the 6 replications) are shown in Fig. 1. The growth of the root-collar diameter and dry mass of the red pepper, was significantly higher in WTR_{CP} than in DGS_{CP}. However, the height growth was not significantly different between the WTR_{CP} and DGS_{CP}.

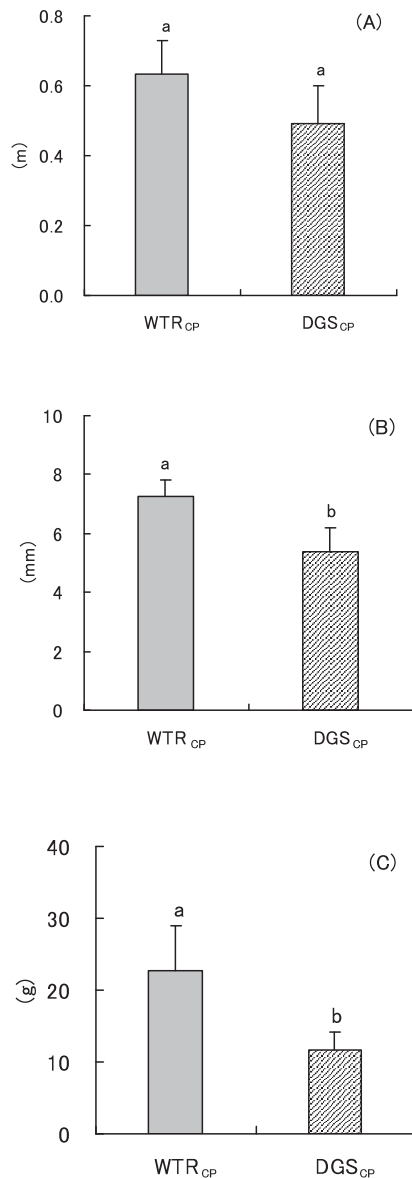


Fig. 1. Growth of the red pepper in the water treatment residue (WTR_{CP}) and decomposed granite soil (DGS_{CP}), which contained compost (CP), at the end of experiment. (A) Height growth, (B) Root-collar diameter, (C) Dry mass. Different alphabets above the columns indicate a significant difference between the treatments at $p < 0.05$, according to the *t*-test. The error bars indicate the standard deviations (for 6 replications).

DISCUSSION

Difference in the physical properties between WTR_{CP} and DGS_{CP}

When oxygen was not provided adequately to soil, respiration of plant roots was obstructed (Janick, 1986). According to Glinski and Stepniewski (1985), D/D_0 of greater than 0.02 is required for plant roots to the normal respiration. The D/D_0 of the WTR_{CP} was higher than that of DGS_{CP}, but the D/D_0 of both WTR_{CP} and DGS_{CP} was over 0.02, thus aerobic respiration of plant roots can be done normally. The PAW of the WTR_{CP} was lower than that of the DGS_{CP} (Table 2). Generally the amount of available water, which is different between growth mediums, is one of the growth limiting factors. However, there would be little influence of the PAW on the seedling growth of the red pepper in our study, because the seedlings were watered as needed. Since the coagulants like aluminum, iron salts and/or organic polymers, added during the water treatment process, bind the silt and clay, the aggregates of WTR are highly stable and have a limited potential of swelling during water absorption (Moodley and Hughes, 2006). Therefore, the K_s of the WTR_{CP} was higher than that of the DGS_{CP} (Fig. 2).

It is known that permeability and aeration of the DGS were poor because DGS, composed of sands and clays, was easy to be compacted by receiving pressures (Masuda, 1992). Therefore, the D/D_0 and K_s of the DGS_{CP} were lower than those of WTR_{CP}, and the porosity of the DGS_{CP} was lower than that of the WTR_{CP}.

Addition of the CP to the WTR did not change the PAW, K_s and B_d (Table 1). Since the D/D_0 and K_s of the WTR were already high enough, the improvement of these physical properties was not promising. The results suggest that addition of the CP has a negative effect on the PAW. Since the CP used here was too coarse, the macro porosity of the WTR might have increased largely, causing the decrease in water retention ability. In order to improve the PAW, finer and humified OM like sphagnum peat moss is better to be added. Additionally, measurement of the physical properties will be necessary after the start of plant growing in CP added WTR because plant growth will be accelerated by the decomposition of CP, which will changes in the physical properties of WTR.

Difference in the chemical properties between WTR_{CP} and DGS_{CP}

The pH of the WTR_{CP} and DGS_{CP} were 6.3 and 7.0, which were within the adequate range of 6 to 7 for plant growth (Janick, 1986). The EC of the WTR_{CP} and DGS_{CP} were 1.3 and 0.7 dS m⁻¹ (Table 2). EC of below 4 dS m⁻¹ was associated with reduced plant growth caused by soil salinity. Elliott and Dempsey (1991) reported that the total-N of the WTR ranged from 4.4 to 10 g kg⁻¹. Dayton and Basta (2001) reported that the CEC of the WTR ranged from 13.6 to 56.5 cmol kg⁻¹, which was considerably greater than that of the typical soil of less than 3.5 to 35.6 cmol kg⁻¹. The total-N and CEC were higher in WTR_{CP} than in DGS_{CP} in our study. The high

CEC and total-N were associated with the WTR_{CP}, indicating that a growth medium had an ability to supply nutrients for the red pepper growth.

On the other hand, the plant-available P of the WTR_{CP} was 7.3 mg kg⁻¹ in our study, which was slightly lower than that of the adequate soil of 12 mg kg⁻¹ for most crops (Tisdale *et al.*, 1985). However, the P-adsorption coefficient, which was associated with P-adsorption capability, was higher for WTR than for DGS. Elliott and Dempsey (1991) reported that the P content of the WTR was typically low. It is known that the P-adsorption capability of the WTR can make soil P unavailable to plants (e.g., Elliott and Singer, 1988; Dayton and Basta, 2001). The chemical properties of the WTR_{CP} were adequate for plant growth. None of the WTR_{CP} was considered unsuitable as alternative material of the DGS_{CP} in terms of the supply of nutrients, excepting the P content.

Difference in the red pepper growth between the WTR_{CP} and DGS_{CP} and its cause

The root-collar diameter and dry mass of the red pepper were significantly higher in WTR_{CP} than in DGS_{CP} (Fig. 3). Rengasamy *et al.* (1980) and Kim *et al.* (2002) reported that the plant growth was promoted by the addition of WTR due to the relatively high total-N, CEC and Ca²⁺ of the WTR, improved bulk density, hydraulic conductivity, and water-holding capacity. Park *et al.* (2010) reported that the WTR had a good possibility to be used as a planting base material instead of the DGS from the view point of aeration, water retention, and permeability. Because the growth media of the WTR could provide beneficial plant nutrition and better physical properties, the growths of the red pepper were better in WTR_{CP} than in DGS_{CP}.

On the other hand, plant-available P and crop yield were significantly lower at higher application rates of WTR (e.g., Elliott and Singer, 1988; Dayton and Basta, 2001). Typically, soil P availability was significantly reduced at WTR application rates above 10% (Dayton and Basta, 2001). However, Ippolito *et al.* (1999) reported that alternative soil material to which fertilizer and/or OM such as compost and biosolids were added, mitigate soil P deficiencies. In our study, the WTR_{CP} produced larger growth of the red pepper without creating a purple venation of leaves indicated by Elliott and Singer (1988) and growth disorder according to deficiency of P was not observed, because addition of the CP to the WTR might corrected P deficiencies during the red pepper growth. Therefore, the growths of the red pepper were better in WTR_{CP} than in DGS_{CP}.

CONCLUSIONS

The chemical properties of total-N and CEC, and the physical properties of D/D₀ and K_s were better for WTR_{CP} than for DGS_{CP}. The growth of the red pepper was better for WTR_{CP} than for DGS_{CP} because the properties of the WTR_{CP} were beneficial to the growth.

However, the improvement of these physical properties of WTR by the addition of the CP was not promising, because D/D₀ and K_s were already high enough in WTR. The macro porosity of the WTR might increase largely by the addition of the CP, because the CP used was too coarse, which caused the decrease in water retention ability.

It is necessary to add fertilizer and/or OM for mitigate soil P deficiencies, when a WTR is reused actually as a growth medium. The chemical and physical properties of the WTR_{CP} were adequate for red pepper growth. WTR_{CP} has a possibility to be used as an alternative material of DGS.

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