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Environmental and economical assessment of sewage sludge compost application on soil and plants in a landfill

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ABSTRACT

Composting of sewage sludge is one of the most suitable solutions for managing and recycling such waste. With the aim to decrease ocean disposal and increase recycling, composting of sewage sludge and its application to reclaimed soil in landfills were studied, including measurements of various parameters for composting and feasibility study. Pot experiments with three tree species (*Quercus acutissima*, *Liriodendron tulipifera*, and *Betula schmidtii*) were performed to evaluate the effects of compost treatments on the soil properties and tree growth responses. Sewage sludge compost improved soil characteristics such as moisture, organic matter, N content, and respiration. It also improved soil porosity and bulk density. The leaf biomass and tree physiological parameters such as the chlorophyll contents and photosynthesis rates increased after the compost treatments. Heavy metal accumulation in the soil after the treatments was lower than the Ecological Soil Screening Levels (Eco-SSLs) for plants set by the US Environmental Protection Agency (EPA). Further, heavy metal accumulation in the leaves was insignificant compared with that of the control. Recycling sewage sludge compost as fertilizer will generate economical profits. Therefore, the use of sewage sludge compost as a soil conditioner in landfills would be an efficient and cost-effective method to restore the fertility of reclaimed soil and an environment-friendly solution for disposal problems.

1. Introduction

Sewage sludge is concentrated wastewater composed of domestic liquid wastes after treatment. It is an inevitable by-product of wastewater treatment processes (Wei and Liu, 2005). Although it contains much organic matter (OM), most of the sewage sludge is not recycled. In 2003, 2,266,888 tons of sewage sludge was produced in Korea (KME, 2007); 74.9% of this sludge was disposed in the ocean whereas only 7% was recycled. In 2011, the London Convention 96 Protocol will come into effect in Korea, prohibiting ocean disposal. As a result of the growing environmental interest worldwide, more countries will adopt this protocol henceforth. Further, with rapid urbanization, proper treatment of sewage sludge is important, but its recycling rate (11% in 2007) is still very low (Cho et al., 2008).

Recently, the use of sewage sludge as a nutrient source has become an interesting research topic. Its high OM contents allow its use as a fertilizer after composting (Rathod et al., 2009). Although the application of sewage sludge to crops (Wei and Liu, 2005) and the plant growth reactions to compost have already been studied (Wong et al., 1996; Gómez et al., 2003; Bustamante et al., 2008), most of the studies focused on the composting process (Mousty et al., 1984; Vasskog et al., 2009) and heavy metal concentrations (Manios et al., 2003; Cai et al., 2007). With increasing garbage segregation and the use of separate drainage systems, the toxic material contents of sewage sludge will decrease. Further, because the use of sewage sludge has been mostly examined for crops and forests (Borken et al., 2002), its application to barren fields and non-crop plants would be useful, as would studies of plant N and P uptake (Petersen et al., 2003). However, former researches are focused only on single aspects such as composting process, biological responses and economical analysis. So a comprehensive research, from composting, environmental effects (on soil and plants) to feasibility study would be very important.

Landfills, where most of the sewage sludge is reclaimed, use mined soil for reclamation. As reclaimed soil has a very low level of OM, a large amount of organic fertilizers is required to restore its fertility and induce revegetation after landfill closure. Landfills generally involve very large areas; therefore, using the OM and nutrients in sewage sludge would be an effective and economical option. The Sudokwon Landfill, Korea, is the biggest sanitary landfill in the world and approximately 25,000 tons of sludge is disposed here each year (Lee et al., 2004). There are plans to develop an eco-park after its closure, but the low OM content of the mined soil used for reclamation is a limiting factor for rapid revegetation and tree planting. Application of sewage sludge compost to this land-

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fill could improve the soil conditions and aid in rapid revegetation (Walker et al., 2004).

The purpose of this study was to validate the use of sewage sludge compost as a soil conditioner for reclamation and revegetation. In addition, the changes in the soil properties, plant physiological responses, heavy metal accumulations and feasibility were examined for comprehensive assessment.

2. Materials and methods

2.1. Study site, composting, and experimental design

2.1.1. Study site

The Sudokwon Landfill is located in Incheon, Korea. All household waste from Seoul and Gyeonggi Province (population of ~25 million) is carried to this landfill. Its total area is about 20,000,000 m^2 and has been planned to reclaim 250 million tons of waste from 1992 to 2025. The landfill processes 6700 tons of leachate and 600 tons of sludge per day. An eco-park and eco-resort have been planned for this area after landfill closure. The center of the landfill is located at 37°34′52″N and 126°37′29″E. The average annual temperature and precipitation in this area were 11.4 °C and 1170 mm in 2004 (KMA, 2005).

2.1.2. Composting

Sewage sludge compost was made in association with Kalim Environmental Company, Korea. Sewage sludge compost was prepared with 40% sewage sludge from the landfill, 30% return compost (compost right after complete composting process: mixed into another composting materials to accelerate fermentation process; Bruce, 1945), and 30% sawdust and bark by volume. Aerobic microorganisms medium (0.1% by volume) were added for composting and mixed in a 30 m^3 (2.5m × 5m × 2.4m) fermenter with a continuous air supply of 3.6 m^3 min^{-1}. The fermenter was operated in a warehouse at room temperature (about 20 °C). The return compost, used as a protein and nutrient source for the microorganisms, was composed of 50% slaughter by-products and 50% plant OM. The microorganisms included photosynthetic bacteria (*Anabaena* sp.), bacilli (*Bacillus pumilus*, *Bacillus subtilis*, *Bacillus licheniformis*, *Bacillus amyloliquefaciens*, and *Bacillus megateriem*), yeast, and lactic acid bacteria. After 20 days of composting in the fermenter, the temperature-stabled compost was piled to a height of 1.5 m.

2.1.3. Experimental design

Trees were grown with three types of compost treatments (and a control treatment) for the pot experiments in 2004 (10 replicates each). The same treatments were repeated without trees (5 replicates each) to exclude the effects of the plants on the soil properties. Treatment 1 consisted of 50% reclaimed soil (soil used for reclaiming) and 50% sewage sludge compost. Treatment 2 consisted of 50% reclaimed soil and 50% bark and sawdust (in equal volume). The composition of Treatment 3 was 50% reclaimed soil, 25% bark, and 25% sewage sludge compost, and 100% reclaimed soil served as the control treatment. Three tree species, sawtooth oak (*Quercus acutissima*), tulip tree (*Liriodendron tulipifera*), and Schmidt birch (*Betula schmidtii*), were selected to test the effects of sewage sludge compost. Sawtooth oak and Schmidt birch are common native species in this area and tulip trees commonly line the roadsides in North America and Korea. And these species are planted in many areas of the landfill. We used 2-year-old sawtooth oak and tulip trees and 1-year-old Schmidt birch (not lignified) in the pot experiments. Trees of these ages are generally used for afforestation. Each tree was transplanted in early May (10 replicates for each treatment) into Wagner pots (1/5000 a). The plants were grown in a greenhouse with a cooling system and sufficient amount of water was irrigated without leaching from the pots.

2.2. Soil, compost, and plant analyses

2.2.1. Soil characteristics

The soil was dried at 105 °C for 48 h to measure its water content. Its OM content was determined by loss on ignition (combustion at 550 °C for 4 h) according to Dean (1974). For density and porosity measurements, the soil was sampled with a 100 ml soil core (Eijkelkamp BV, Netherlands) and dried at 40 °C. Its bulk density was determined as the dry weight volume/100 and porosity was calculated as 1-(bulk density/2.60) according to Elliott et al. (1999). The pH and electrical conductivity (EC) of the soil and compost were determined by using a suspension of the soil samples in water (20 g/30 ml). The soil respiration rate was measured with EGM-4 (PP Systems, USA).

2.2.2. Heavy metals

One gram of dried and milled soil, compost, and plants was pretreated with 60% HNO_3 for 24 h and heated to 80 °C for 2 h. Then, 10 ml of 70% perchloric acid was added and the solution was heated to 200 °C until it became clear. The samples were then filtered with Whatman 44 filter paper and their heavy metal contents were analyzed by using an ICP emission spectrometer (ICPS-1000IV, Shimadzu, Japan).

2.2.3. C, N, and H analyses

To determine the C, N, and H contents of the soil and plants, three compost and plant samples were analyzed with an elemental analyzer (Flash EA 1112; Thermo Electron Co.) NH_4^+–N and NO_3^-–N analyses were performed by using a Kjeldahl protein/nitrogen analyzer (Kjeltec Auto 1035 System; Tecator AB, Denmark).

2.2.4. Photosynthesis and chlorophyll

Photosynthesis was measured with a portable photosynthesis measurement system (Li-6400; Li-cor Biosciences, USA) in September (30 °C, 400 ppm CO_2). The chlorophyll contents of the leaves were measured by using SPAD 502 (Minolta Co., Japan).

2.2.5. Plant height and biomass

The height of each potted plant was measured soon after transplantation in May and their final height and biomass were measured before harvesting in October. Six random plants were used for the measurements.

2.3. Statistical analyses

Statistical significance ($P < 0.05$) of the differences was determined by one-way ANOVA and Duncan's multiple range test was used for post hoc comparison.

3. Results and discussion

3.1. Composting performance and characteristics

The temperature of the compost increased to 80 °C (Fig. 1) during composting. The water content of the sludge dropped from 64.5% to 57%. The OM/N ratio was 25.3 at the beginning of composting, 32.3 after 1 week, 26.0 after 2 weeks, and 25.3 after 3 weeks. The temperature was more than 70 °C for 16 days.

These values are slightly higher than those observed in other sewage sludge composting processes (Gómez et al., 2003; Grube et al., 2006). Because a big fermenter (30 m^3) was used in this study, the heat loss would be less, resulting in the higher composting temperature. The overall production cost of 1 ton of compost was

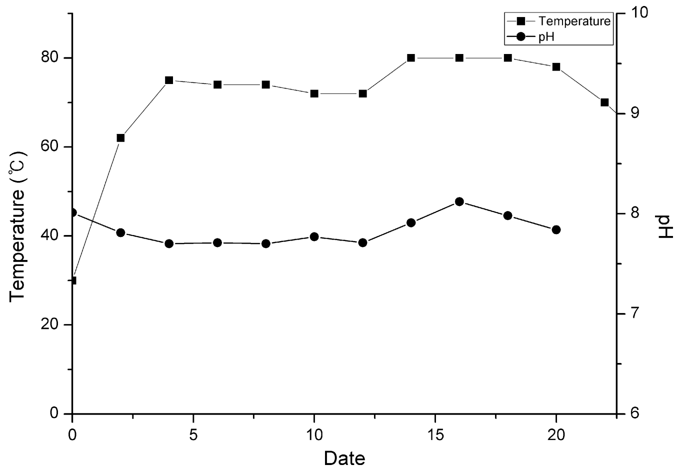

Fig. 1. Changes in the pH and temperature during the sewage sludge composting.

Table 1
Characteristics of sewage sludge compost and reclaimed soil in a waste landfill, Korea.

Parameter	Reclaimed soil	Sewage sludge	Compost
pH	8.01	8.7	7.8
EC (μs cm^{-1})	142	1444	3200
Water (%)	18.5	82.1	50.5
OM (%)	0.3	10.4	35.4
TN (%)	0.006	1.0	1.6
OM/N (%)	0.001	10.8	26.1
Available P (%)	0.001	0.22	0.29
Pb (mg/kg)	97	132.5	123.9
Cd (mg/kg)	3.8	1.3	1.2
As (mg/kg)	0.8	0.1	0.1
Cr (mg/kg)	14.5	28.7	19.1
Cu (mg/kg)	17.4	97.7	84.6
Hg (mg/kg)	ND	0.8	0.2
NaCl (%)	0.02	0.1	0.4

The properties of the compost and soil in the pot experiments were examined by Korea Testing & Research Institute. The data are presented as the means of 3 replicates. ND: not detected.

62,000 won (~US$ 52) excluding the cost of the equipment. Purchase of sawdust and bark amounted to about 80% of the total cost of composting (including personnel and operating expenses).

Sewage sludge compost contained less than 10% of the national standards for the heavy metal contents of compost (KEI, 2003) except in the case of Cu (<20%) and salt (Table 1). These values are also lower than the standards for compost (Hogg et al., 2002) set by the US EPA CFR40/503 Sludge Rule. Because of segregated garbage collection and reclamation, the levels of heavy metals and other toxic materials are very low in sewage sludge. As waste segregation is introduced in developing countries recently, sewage sludge management will become more effective and the environmental risk will reduce. The reclaimed landfill soil showed relatively high heavy metal contents and low OM and N contents (Table 1) because of the mining process for reclaimed soil. Poor nutrient conditions (low OM, N, and P) and low moisture in the reclaimed soil would restrict plant growth on landfills (Lee et al., 2004). Therefore, landfill soil will need conditioner or fertilizer (with water holding capacity) treatment before reclamation.

3.2. Soil characteristics after treatment

As three types of trees were used in this study, the effects of the plants on the soil would differ by species. The soil-only pots were established to examine the effects of compost on soil and exclude the effects of the plants. The properties of the reclaimed soil improved following the compost treatments (Table 2). As the reclaimed soil was dug from an area adjacent to the landfill from a depth of up to 100 m, it had poor nutrient contents (~0.01% N) and low moisture, which might limit plant growth (Lee et al., 2004) after reclamation. However, sewage sludge compost and bark greatly improved the soil characteristics. Sewage sludge compost can be used as a soil conditioner (Korboulewsky et al., 2002). In the pot experiments (soil-only pots), the 50% compost-treated soil (Treatment 1) had an average Total–N (T–N) content of 0.37% and the soil in Treatment 3 contained 0.23% T–N. The T–N content of the soil mixed with bark and sawdust (50%) increased to 0.28% because of sawdust and bark decomposition. Further, the available forms of N (NH_4^+, NO_3^-) were significantly increased. The C/N ratio dropped from 43 (control) to 17 (Treatment 1). The soil physical characteristics improved after the compost and sawdust treatments (Table 2). Usually, landfill soil has low porosity and low moisture content; however, these parameters also greatly improved after the compost and sawdust (bark) treatments. In the control pots (reclaimed soil only), low soil porosity (<50%) and high bulk density (average of 1.46 g cm^{-3}) restricted plant growth. These soil conditions result in poor drainage and low oxygen supply as well as root growth restriction. The reclaimed soil in the pots was not hardened with heavy rollers as in the landfill reclamation site; therefore, the soil density of 1.46 g cm^{-3} would increase to beyond 1.6 g cm^{-3} in the reclamation site, known as the hazardous point after reclaiming process in the landfill (Lee et al., 2005). However, after the compost and sawdust treatment, the bulk density dropped to below 1.0 g cm^{-3}.

Table 2
Soil properties after 5 months of the various compost treatments in the soil-only pots.

Parameter	Treatment 1	Treatment 2	Treatment 3	Control
Moisture (%)	46.9 ± 3.97^{a}	32.6 ± 1.36^{b}	44.16 ± 4.89^{ab}	14.29 ± 3.26^{c}
OM (%)	12.4 ± 0.25^{a}	6.55 ± 0.27^{c}	8.43 ± 0.74^{b}	0.81 ± 0.01^{d}
C (%)	6.27 ± 0.51^{a}	2.88 ± 0.67^{b}	3.45 ± 0.26^{b}	0.42 ± 0.15^{c}
N (%)	0.37 ± 0.01^{a}	0.28 ± 0.09^{a}	0.23 ± 0.02^{a}	0.01 ± 0.001^{b}
H (%)	1.22 ± 0.09^{a}	0.78 ± 0.06	0.92 ± 0.04^{b}	0.59 ± 0.04^{c}
NH_4^+–N (mg/kg)	23.3 ± 3.82^{a}	NM	NM	0.08 ± 0.003^{b}
NO_3^-–N (mg/kg)	28.3 ± 6.54^{a}	NM	NM	5.21 ± 1.264^{b}
Cr (mg/kg)	19.3 ± 1.46^{a}	NM	14.7 ± 0.8^{b}	12.9 ± 0.28^{b}
Cu (mg/kg)	39.4 ± 0.69^{a}	NM	38.4 ± 1.08^{a}	23.4 ± 1.25^{b}
Cd (mg/kg)	4.0 ± 0.09	NM	4.1 ± 0.2	3.97 ± 0.14
Pb (mg/kg)	69.7 ± 4.0^{b}	NM	103.2 ± 10.48^{a}	86.56 ± 5.56^{ab}
As (mg/kg)	ND	NM	ND	ND
Bulk density (g cm^{-3})	0.68 ± 0.03^{c}	0.85 ± 0.01^{b}	0.79 ± 0.01^{b}	1.46 ± 0.04 ^{a}
Porosity (%)	0.73 ± 0.02^{a}	0.67 ± 0.01^{ab}	0.69 ± 0.02^{b}	0.46 ± 0.01 ^{c}
Respiration (g m^{-2} h^{-1})	1.3 ± 0.012^{a}	0.56 ± 0.083^{c}	1.04 ± 0.072^{b}	0.04 ± 0.01 ^{d}

The data are presented as the mean ± SE of 3 replicates. The means within a row followed by the same letter are not significantly different at $p < 0.05$ (Duncan's multiple range test). ND: not detected; NM: not measured.

Table 3
Soil properties after 5 months of the various compost treatments in the planted pots.

	Treatment 3			Control		
	L. tulipifera	*B. schmidtii*	*Q .acutissima*	*L. tulipifera*	*B. schmidtii*	*Q. acutissima*
Moisture (%)	40.2 ± 9.5	38.7 ± 0.1	31.9 ± 3.9	16.8 ± 0.5[b]	19.4 ± 0.1[a]	15.3 ± 0.1[c]
OM (%)	11.0 ± 1.6	12.3 ± 0.3	7.43 ± 1.5	4.06 ± 0.0	4.21 ± 0.0	4.23 ± 0.0
C (%)	3.15 ± 0.03[a]	3.319 ± 0.33[a]	2.81 ± 0.12[b]	0.69 ± 0.11[b]	0.63 ± 0.02[b]	0.96 ± 0.05[a]
N (%)	0.28 ± 0.00	0.25 ± 0.02	0.24 ± 0.00	0.04 ± 0.00[a]	0.02 ± 0.00[b]	0.02 ± 0.03[b]
H (%)	0.73 ± 0.18	0.925 ± 0.00	0.92 ± 0.03	0.58 ± 0.05[b]	0.55 ± 0.07[b]	0.76 ± 0.05[a]
Cr (mg/kg)	15.62 ± 0.59[b]	18.33 ± 0.62[a]	17.13 ± 0.53[ab]	12.18 ± 0.94	12.01 ± 0.14	12.86 ± 0.22
Cu (mg/kg)	36.25 ± 2.41	38.33 ± 0.54	39.68 ± 1.25	29.53 ± 0.37	29.85 ± 0.09	29.9 ± 0.15
Cd (mg/kg)	3.37 ± 0.27[b]	4.43 ± 0.40[a]	4.42 ± 0.04[a]	4.46 ± 0.28	4.1 ± 0.10	4.266 ± 0.02
Pb (mg/kg)	94.18 ± 11.55[b]	114.67 ± 9.20[a]	115.22 ± 0.91[a]	114.53 ± 8.47	104.83 ± 5.00	115.98 ± 3.16
As (mg/kg)	ND	ND	ND	ND	ND	ND
Respiration ($g\,m^{-2}\,h^{-1}$)	3.02 ± 1.28	2.73 ± 0.94	2.89 ± 0.38	0.80 ± 0.18	0.58 ± 0.15	0.69 ± 0.23

The data are presented as the mean ± SE of 3 replicates. The means within a row followed by the same letter are not significantly different at $p < 0.05$ (Duncan's multiple range test). ND: not detected.

Respiration of the reclaimed soil decreased because of the low OM content, low soil moisture, and absence of a source of microorganisms. Compost with microbial-nutrient sources improved the soil moisture and respiration (Table 2).

The application methods to mix compost (and bark) with reclaimed soil, not to use scattering methods, would be more effective to reduce soil density. Scattering compost on landfill could be economic methods to fertilize landfill areas. However, scattering could not be effective to decrease soil density of landfill because this method can only affect surface layers of the soil. And scattering compost on sloped landfill areas could have a limited impact because wind and rainfall may spread the compost to the non-composted areas. Since metals of the compost will remain in the surface soil layer for a very long time (McGrath and Lane, 1989), concentrated compost on surface soil could have negative effects for plants such as germination. Mulched layers of the compost would decrease germination of plants (Ozores-Hampton, 1998) by covering light, moisture, O_2 and concentrating phytotoxic substances. So mixing compost with reclaimed soil for formation of top soil in landfills would have some merits compared to scattering compost after top soil formation. Since our experiment used this (mixing) method, heavy metal accumulations of the top soil after compost treatment can be lightened.

The accumulations of five heavy metals, known to be the major toxic heavy metals in sewage sludge compost (KME, 1999), were investigated. The accumulations of Cu and Cr significantly increased in the pot experiments, although their values were still less than 20% of the national standards for heavy metal contamination concern levels (screening levels) in soil (Lee et al., 2004). Only the Cr content exceeded the standard level (4 mg/kg) set by the Korean Ministry of Environment. However, the Cr content of compost was only 30% higher than that of the reclaimed soil and lower than the mean value reported by the US Environmental Protection Agency (EPA; 47.5 mg/kg). As the US EPA has not established the Ecological Soil Screening Levels (Eco-SSLs) of Cr in plants, average values of Cr toxicity levels for plants in this document were used (US EPA, 2003). The Cu content of sewage sludge compost was much higher than that of the reclaimed soil; however, as the level after the compost treatments was lower than the heavy metal contamination concern level, the Cu content would not be an obstacle in the use of sewage sludge compost. Overall, all the heavy metal contents in the compost were lower than the US EPA-recommended Eco-SSLs for plants (US EPA, 2003).

Table 3 shows that the soil moisture content after Treatment 3 (planted pots) was significantly less than that of the soil-only pots (44%), probably because of plant evaporation activities. The soil C, N, and OM contents in the planted pots were significantly higher than those of the soil-only pots (Table 2) due to the root activity and foliage. In Treatment 3, the heavy metal accumulation in the planted pots was not significantly different except for the Cd and Pb contents in the *L. tulipifera*-planted pots. As the tulip trees showed sensitive reactions to the compost treatments, absorption in *L. tulipifera* could be more active, resulting in the low heavy metal concentration. Pb accumulation in the tulip tree leaves was significantly higher than that in the other species; therefore, active metal absorption would cause these differences. The Cd content in *L. tulipifera* was also high, possibly causing the low Cd concentration in the soil. None of the control pots with plants showed a significant difference in the soil heavy metal contents. Soil respiration in the planted pots was significantly increased by root respiration (Table 3). As the value for Treatment 3 is much higher than that for the control treatment, the compost-treated pots had more root and microbial activity than the soil-only pots.

3.3. Tree growth after the compost treatments

3.3.1. Early responses

Withering in the early stage was found only among the tulip trees in Treatment 1 (completely withered). Withering by compost occurs because of two reasons. The first is related to Cr, which was the only heavy metal exceeding the dangerous level. Cr interferes with several metabolic processes, causing toxicity to plants, as exhibited by reduced growth and phytomass, chlorosis, impaired photosynthesis, stunting, and finally, plant death (Sharma et al., 1995). However, compared with the previous studies (Grant and Dobbs, 1977; Vajpayee et al., 2000), Cr accumulation in the soil and plants in this study seems to be at a nontoxic level considering plant sensitivity. However, though Cr was the only heavy metal (which) exceeding the dangerous level, un-analyzed substances could affect plants. Although the compost was used after temperature has been stabled and piled up for storage before application, fresh compost can have characteristics of immature compost. Phytotoxic substances of fresh compost can injure plant, as fresh compost can have acids such as acetic, propionic and isovaleric acids (Ozores-Hampton et al., 2002). Therefore, to obtain more mature compost, providing more time before application (after composting) would decrease these risks and show better performances of plants. And pretreatment methods of composting can also reduce the contents of toxic materials. Physico-chemical treatments such as sequential extraction (Amir et al., 2005) and radiation technology (Wang and Wang, 2007) are known as effective methods to reduce heavy metal concentrations and organic pollutants. And co-composting materials such as zeolite can reduce heavy metal concentrations in compost including Cr (Zorpas et al., 2000). Coal ash is also known as useful co-composting materials for reducing heavy metal concentrations (Wong et al., 1997). By developing and using pretreatment methods and co-composting materials, toxic materials in sewage sludge would be more alleviated for use as compost form.

Table 4
Growth variations[a] in the trees after the assorted compost treatments.

Experiment	Measure	*L. tulipifera*	*B. schmidtii*	*Q. acutissima*
Treatment 1	Leaf (g)	NM	3.9 ± 0.72^{a}	5.1 ± 0.83^{a}
	Height (cm)	NM	10.7 ± 1.98^{b}	8.6 ± 1.47^{b}
Treatment 2	Leaf (g)	0.9 ± 0.19^{b}	0.3 ± 0.03^{b}	1.2 ± 0.27^{b}
	Height (cm)	4.0 ± 0.64^{b}	4.1 ± 1.35^{bc}	3.4 ± 1.02^{c}
Treatment 3	Leaf (g)	2.2 ± 0.73^{a}	5.4 ± 0.48^{a}	8.3 ± 1.51^{a}
	Height (cm)	1.5 ± 0.50^{c}	31.7 ± 2.93^{a}	16.2 ± 1.89^{a}
Control	Leaf (g)	2.1 ± 0.45^{a}	0.2 ± 0.00^{b}	1.4 ± 0.26^{b}
	Height (cm)	6.9 ± 2.03^{a}	2.9 ± 0.96^{c}	3.1 ± 1.17^{c}

The data are presented as the mean ± SE of 6 replicates. The means within a column followed by the same letter are not significantly different at $p < 0.05$ (Duncan's multiple range test). The leaf weights are their dry weight. NM: not measured.

[a] The height values indicate increased values for the trees.

Table 5
Chlorophyll contents of the leaves.

Experiment	Period	*L. tulipifera*	*B. schmidtii*	*Q. acutissima*
Treatment 1	July	NM	42.2 ± 3.36^{a}	30.1 ± 2.95^{a}
	October	NM	31.6 ± 2.87^{a}	37.7 ± 1.03^{a}
Treatment 2	July	27.0 ± 0.75^{b}	21.1 ± 0.86^{c}	33.2 ± 1.52^{a}
	October	7.9 ± 3.02^{b}	23.1 ± 0.82^{b}	12.1 ± 1.09^{c}
Treatment 3	July	31.0 ± 1.31^{a}	31.4 ± 0.79^{b}	28.6 ± 3.09^{a}
	October	32.8 ± 6.76^{a}	28.5 ± 3.13^{a}	34.5 ± 0.84^{b}
Control	July	24.7 ± 0.98^{b}	25.4 ± 1.21^{c}	18.9 ± 0.97^{b}
	October	0.4 ± 0.12^{b}	14.1 ± 0.45^{c}	8.2 ± 1.19^{d}

The data are presented as the mean ± SE of 6 replicates. The means within a column followed by the same letter are not significantly different at $p < 0.05$ (Duncan's multiple range test). Unit: SPAD unit. NM: not measured.

The other possible reason involves overfertilization. Overfertilization is a condition that results from excessive application of fertilizers. As fertilizers contain ions, an early symptom of overfertilization is the wilting of leaves, attributable to inadequate water uptake by roots through reverse osmosis (Weinbaum et al., 1992). Generally, 50% compost in the soil might lead to excessive fertilization. However, as another study (Han et al., 2004) using sludge has shown that plants can survive following 50% compost treatment, this amount was considered practical. Nevertheless, differences in plant plasticity might have caused the differences among the tree species. Generally, sawtooth oak and Schmidt birch are found in forests where the average OM content of the soil is 10% (Mun and Joo, 1994). Therefore, these trees might be more suitable for soil with higher OM content. Moreover, the oak (*Quercus*) species can readily adjust to rapid changes in the soil conditions (Kim et al., 2008). However, as tulip trees are quite sensitive to the soil conditions (Ryu et al., 2003), the high OM content might have caused stress in these plants. The rapid withering indicates that reverse osmosis by overfertilization is the major factor. Overall, treatment using a proper compost ratio (25%, Treatment 3) improved the plant performance in all the tested tree species.

3.3.2. Growth patterns

The biomass of the shoots and leaves was measured in October (Table 4). After the compost treatments, all the tree species showed significant increases in the leaf biomass and height. These differences in yield could be explained by improvements in the soil structure, OM content, and nutrient supply (Hachicha et al., 2008). Although *L. tulipifera* did not set roots well in Treatment 1, the height and leaf biomass were significantly increased in Treatment 3 (25% sewage sludge compost). *B. schmidtii* and *Q. acutissima* also showed the best performance in Treatment 3, with significantly higher biomass and greater height increase than in the control treatment and Treatment 2 (50% bark and sawdust). Woody plants tend to grow slowly and the major height increase in our experiments was not due to trunk growth but from new branch formation for leaves. Therefore, shoot increase was determined by the formation of new branches, and the compost treatments showed better formation of new branches. Nonlignified Schmidt birch showed the greatest difference among the treatments. The increased branches and height affected the numbers and biomass of the leaves. Treatment 3 (25% compost) demonstrated the highest leaf biomass increase in all the tree species. Except *L. tulipifera* (in Treatment 1 due to early withering), the other species showed a significant increase in the leaf biomass in Treatment 1 than in the control treatment. Overall, Treatment 3 (25% sewage sludge compost) had the best performance in terms of both height increase and leaf biomass.

3.3.3. Physiological responses

Because the numbers of tree leaves were limited in the pot experiments, only a nonsampling chlorophyll surveying method with a SPAD-502 unit was used to reduce stress and conserve the leaf biomass. The treatments with compost demonstrated higher chlorophyll contents as fertilization increases the chlorophyll contents (Tam and Magistad, 1935). Treatment 1 showed significantly increased chlorophyll contents (Table 5) in Schmidt birch and sawtooth oak compared with the control treatment. Treatment 3 also showed significantly increased chlorophyll contents compared with the control treatment, and this tendency became clearer as fall approached. The trees in the reclaimed soil tended to lose their chlorophyll contents faster than those in the other treatments. Trees with more N have greater leaf longevity (Escudero et al., 1992). Reclaimed soil is considerably poor in nutrients and has limited available N; therefore, fertilization with compost positively affects the chlorophyll contents and photosynthesis rates of trees.

Although the tulip trees were sensitive to compost treatments, they showed the highest photosynthesis rate in Treatment 3 (Fig. 2). Schmidt birch also demonstrated the highest rate in Treatment 3. Both species showed weak photosynthesis rates in the control treatment. Trees in the landfill soil had a low maximum photosynthesis rate because of the low nutrient and moisture levels, reducing their ability to manage high-intensity light (Kim et al., 2002). However, the increased soil nutrients and moisture following the compost treatments significantly increased the photosynthesis rates. N-supplied conditions increase the net photosynthesis rate per unit (Makoto and Koike, 2007), and increased soil N in the compost and bark treatment will be effective for plant performance. If it is not oversaturated, increased moisture in the soil (Table 3) will also increase the photosynthesis rate (Wei et al., 2008) of plants (about 36% soil moisture showed the maximum rate for the *Quercus* species). Therefore, sewage sludge compost increased the plant photosynthesis rates by increasing either soil N or the moisture content.

3.3.4. Chemical contents and heavy metal accumulation in leaves

Table 6 shows that the N contents in the leaves increased significantly with the compost treatments. As the control soil had poor N contents, the nutrients in the compost would be quite useful for trees. Treatment 1 showed the highest N contents in the leaves. *L. tulipifera* exhibited the most dramatic N increase, the most sensitive reactions to compost, and the highest heavy metal accumulation. The other species also showed significantly increased N contents in the leaves after the compost treatments.

The heavy metal accumulations in the leaves were relatively low compared with those measured in the previous studies (Wei and Liu, 2005; Casado-Vela et al., 2007; Chiu et al., 2006). As (arsenic) were not detected in all the leaf samples. One similar study using sewage sludge compost as a fertilizer (Moreno et al., 1996) found

Table 6
Chemical contents and heavy metal accumulation in the leaves with different compost treatments.

	L. tulipifera		*B. schmidtii*			*Q. acutissima*		
	Treatment 3	Control	Treatment 1	Treatment 3	Control	Treatment 1	Treatment 3	Control
C (%)	44.71 ± 0.27[b]	45.49 ± 0.09[a]	43.33 ± 0.61	43.80 ± 0.26	42.64 ± 0.11	42.02 ± 0.47	41.93 ± 0.32	42.44 ± 0.29
N (%)	1.46 ± 0.07[a]	0.48 ± 0.02[b]	1.23 ± 0.04[a]	1.16 ± 0.08[a]	0.86 ± 0.02[b]	1.33 ± 0.04[a]	1.23 ± 0.03[a]	0.80 ± 0.06[b]
Cr (mg/kg)	1.86 ± 0.09	2.00 ± 0.07	2.89 ± 0.26[a]	2.03 ± 0.01[b]	1.76 ± 0.04[b]	1.50 ± 0.04[b]	1.72 ± 0.06[a]	1.58 ± 0.03[ab]
Cu (mg/kg)	4.78 ± 0.27	4.60 ± 0.46	5.55 ± 0.32	4.96 ± 0.15	4.61 ± 0.19	2.45 ± 0.17[c]	3.62 ± 0.09[a]	3.13 ± 0.15[b]
Cd (mg/kg)	0.57 ± 0.03	0.52 ± 0.02	0.65 ± 0.04[a]	0.56 ± 0.01[ab]	0.49 ± 0.03[b]	0.21 ± 0.04[b]	0.38 ± 0.03[a]	0.34 ± 0.01[a]
Pb (mg/kg)	9.82 ± 0.47	8.58 ± 0.49	10.24 ± 0.42[a]	8.78 ± 0.21[b]	5.95 ± 0.05[b]	3.42 ± 0.80[b]	5.87 ± 0.38[a]	5.72 ± 0.20[a]

The data are presented as the mean ± SE of 4 replicates. The means within a row followed by the same letter are not significantly different at $p < 0.05$ (Duncan's multiple range test). The chemical contents of *L. tulipifera* following Treatment 1 were not measured because of complete withering. As is not detected.

higher heavy metal accumulation in plants. Although the total accumulation was greater, the per-weight accumulation might be insignificant because of the dilution effect, as fertilized plants grow faster (Korboulewsky et al., 2002). However, Cr contents of leaves were relatively higher compared to other heavy metals. As Cr was the only heavy metal that has exceeded the standard level in compost, might be over accumulated in plant leaves. But as Cr contents of reclaimed soil was higher itself, Cr contents of compost would not be a matter. And some species in control even has higher Cr accumulation than compost treatments. And as wagner pots (no drainage holes on bottom) were used in this experiment, leached heavy metals from soil and compost would not drain and fully uptake by plants during evaporation (despite of this demerit, wagner pot was used to prevent leaching from the pot. As coarse reclaimed soil and bark are used with compost, serious leaching of compost particles would occur and effects of compost could be mistaken. Wagner pots with hole on the side could prevent excessive leaching from the pot). *B. schmidtii* showed a significant increase in the heavy metals mostly following Treatment 1. As *B. schmidtii* was not lignified, the trees showed a rapid increase in biomass with the compost treatments. This species showed greater performance in Treatment 1 and Treatment 3, both of which resulted in high levels of N and heavy metals. *Q. acutissima* showed significantly high heavy metal accumulation but the best height and biomass increase in Treatment 3, suggesting that vigorous activity of trees stimulates more plant uptake. Although direct comparison was not possible, the accumulation of heavy metals in our study was not high by itself or in comparison with the controls (Table 6). As reclaimed soil itself has high heavy metal contents, application of sewage sludge on landfill soils would not cause side effects. According to data from the Sudokwon Landfill Management Corporation, the heavy metal concentration of sewage sludge is not high because of the separate reclamation and leachate-purifying processes. Therefore, sewage sludge from sanitary landfills would be useful because of the low heavy metal concentration in the leachate. Sewage sludge compost made from sanitary landfill waste could be a usable resource for improving the soil conditions and revegetation after landfill reclamation.

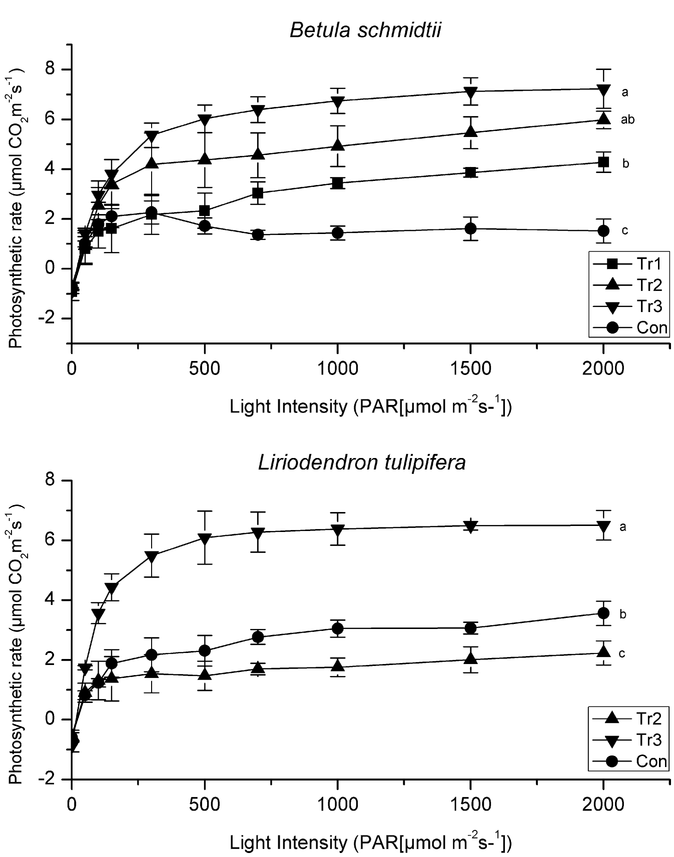

Fig. 2. Photosynthetic performance of the trees with the various compost treatments. The error bars represent the mean ± SE of 3 replicates. Symbols having the same letter are not significantly different at the 0.05 level.

4. Feasibility study for using sewage sludge compost

The cost of producing 120 tons of sewage sludge compost included using a fermenter (rental fee: US$ 20), operating fee including electric charges (US$ 420), heavy machinery operating fee (including excavator: US$ 500), the material cost (almost sawdust: US$ 4500) and US$ 720 for personal expenses (the rental fee of a fermenter was much less expensive than expected because it was government facility). The final cost of producing sewage sludge compost was about US$ 52 per ton in this study and this was almost same as the lowest production cost of 1 ton of sewage sludge compost (Wei and Fan, 2001). However, as some rental fee was supported by government policy fund and transport cost was zero (composting was operated in a landfill itself), low production cost of compost was not surprising. As the cost of sewage sludge reclamation was US$ 17 per ton (Shin, 2004), about US$ 35 more per ton was expended. However, the overall cost could be offset by the use of sewage sludge compost as a soil conditioner or fertilizer in landfills. Fertilizers like urea is low priced, but fertilizers like compost which has water holding capacity is essential in semi-arid area such as landfills. The most inexpensive fertilizer of compost form for landscape architecture costs US$ 250 per ton in Korea (Korea Price Research Center, 2004). So overall cost savings by using sewage sludge compost in landfill are about US$ 198 per ton. As a landfill covers total about 20,000,000 m^2 and 80% of this area is planning to cover with vegetation, areas of 16,000,000 m^2 is required for fertilization. Since optimal fertilization rate is about 10 g of nitrogen per square meter (Kim, 2001), about 8000 tons of compost fertilizer will be needed for the landfill (estimating 2% of nitrogen in compost). So use of sewage sludge compost as a soil conditioner will save about US$ 158,400 just in the study landfill. Since the cost of fermenter construction is about US$ 5000, mass production of sewage sludge compost will cover enough for the construction fee. With recent increase of fertilizer price (price increase of anhydrous ammonia and urea (45–46% N) was over 70% between 2004 and 2008; USDA, 2009), recycling of sewage sludge as compost will have an economic benefit. Our results suggest that composting of sewage sludge can be an economical and environment-friendly solution for sewage sludge recycling and fertilizing for landfill revegetation.

5. Conclusions

Treatment with sewage sludge compost significantly improved the chemical and physical properties of the reclaimed soil in the landfill. It also improved the nitrogen content, porosity, moisture, organic matter content, and respiration of the reclaimed soil. Consequently, trees treated with sewage sludge compost had better performance in terms of growth and leaf biomass as well as in the physiological characteristics, such as higher chlorophyll contents and photosynthetic rates. The soil heavy metal contents did not increase largely except in the case of Cu, but all the values were lower than the Eco-SSLs for plants recommended by the US EPA. Compost-treated tree leaves did not show significantly increased heavy metal accumulation compared with the trees grown on reclaimed soil only.

The cost of producing sewage sludge compost was about US$ 52 per ton, saving about US$ 198 per ton by replacing commercial fertilizers. Therefore, sewage sludge composting and recycling can be an environment-friendly solution to disposal problems and an economical strategy for improving the soil conditions in landfills.

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