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Importance of biomass management acts and policies after phytoremediation

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Abstract

Background: Although phytoremediation is a promising method for pollution control, biomass produced by the remediation process must be managed; otherwise, it will eventually return to the environment and cause secondary pollution. Therefore, research and policy development for the post-remediation management of biomass are both required.

Results: While there are many published studies of phytoremediation, research into post-remediation management is very limited. Therefore, a new study using biomass as a co-composting material was conducted and showed positive effects on soil characteristics and plant performance. However, despite its potential, research and policies to promote this form of management are still lacking.

Conclusions: We suggest public engagement in support of "Post-phytoremediation management" legislation that stipulates management of biomass after phytoremediation, promotes recycling of biomass with known environmental risks, and includes specific policies developed for managers. Further research to support and inform such policies and laws is also required.

Keywords: Phytoremediation, Biomass, Post-remediation, Compost, Pollutants, Legal provisions

Background

Modern civilization inevitably produces large quantities of pollutants through industrialization, intensive agriculture, and urbanization (Eapen and D'Souza 2005). Among these pollutants, chemical wastes including agrichemicals, heavy metals (Lu et al. 2015), nitrogen (N) and phosphorus (P) from fertilizers (Smith and Siciliano 2015), nanomaterials (Song et al. 2013a), and even microplastics (Fendall and Sewell 2009) can all degrade water quality. Such pollutants can directly affect living organisms by their own toxicity but can also indirectly affect whole ecosystems, for example, by eutrophication and effects on trophic cascades (Paerl and Whitall 1999). Pollutant management is therefore very important. However, standard pollutant-removal techniques such as the use of sewage and wastewater treatment plants are constrained by factors such as high cost and unsustainability (Abma et al. 2010). Therefore, the development of other treatment systems to compensate for these disadvantages has been actively pursued (Mohan and Gandhimathi 2009). Among many new methods, phytoremediation and wetland construction for biofiltration have begun to attract interest because of their environmentally friendly and cost-effective traits (Justin and Zupancic 2009). In Korea, phytoremediation studies applied to many streams, rivers, and lakes have received national funding and policy support (Song and Kang 2006, Kim and Yun 2012). However, this form of phytoremediation has associated problems of long-term post-remediation management, for which research and policy development are very limited (Song et al. 2016). Pollutants taken up by plants during phytoremediation can easily be returned to the target environment by post-mortem decomposition, thereby degrading the efficiency of the remediation process (Helfield and Diamond 1997). Effective management of plant biomass after remediation is therefore necessary. The use of plant biomass after phytoremediation is suggested for biofuel (Banuelos 2006), and one comprehensive study suggested incineration after comparing multiple methods of biomass management such as compaction, incineration, ashing, pyrolysis, direct disposal, and liquid extraction (Sas-Nowosielska et al. 2004). However, research into

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this aspect of management is still sparse (Song et al. 2016), and in particular, there is no information about domestic or international policies concerning these problems. Since phytoremediation is being applied widely in Korea and in many other countries, there is a need for a review of methods for biomass management after phytoremediation and of the policies used to promote these systems. At least to the authors' knowledge, no papers have yet been published that suggest relevant policies based on direct evidence utilizing scientific experiments. In this study, therefore, we carried out a literature search on current phytoremediation methods and policies and tested our own method for managing biomass after remediation. From a synthesis of these results, we propose the requirements for an effective biomass management method and highlight the need for policies to address the problem of waste produced by the phytoremediation process.

Methods

Research, case studies, and polices relating to phytoremediation

The Research Information Sharing Service (RISS, http://www.riss.kr) and Google Scholar (http://scholar.google.com) were used to locate published studies of phytoremediation from Korea and other countries. Policies were retrieved from online repositories of regulations. For South Korea, the "National Law Information Center" (http://www.law.go.kr/eng/engMain.do) was the principal source. For the United States, regulations were obtained from Cornell University's "Legal Information Institute" (https://www.law.cornell.edu/). Regulations for the European Union were found at EUR-Lex (http://eur-lex.europa.eu/homepage.html?locale=en).

Field experiment into feasibility of post-remediation management

To test the feasibility of using plant biomass after phytoremediation, an experiment was carried out to convert biomass of plants to compost, a form of fertilizer. The Sudokwon landfill in Incheon, Korea, is one of the biggest sanitary landfills in the world and has approximately 5 km of leachate channel that acts as a remediation and buffer zone before leachate is emitted to the sea. However, the plants growing in the channel, reed (*Phragmites australis*) and cattail (*Typha angustifolia*), are not subject to any management and their decomposition may potentially reduce the remediation capacity of the channel and return pollutants to the environment (Song 2010). *P. australis* and *T. angustifolia* were therefore harvested from the channel in October, at the end of the growing season. Harvested macrophytes (20 kg) were chopped to a length of approximately 5 cm and mixed with 10 L water, 1 L EM (effective microorganism) solution, and 100 g brown sugar for windrow composting (EM-center 2003). The composting materials were covered with several blankets to prevent heat loss. After the composting process, the compost was sealed and left in the shade until the following spring before experimental application.

Compost was applied to the landfill slope in April where, recently, 2-year-old chestnut trees (*Castanea crenata*) were transplanted with either 1400 g macrophyte compost or 150 g commercial fertilizer/m^2 (Osmocote Plus, 13 N + 13 P + 13 K + 2 MgO; Scotts International B.V., Geldermalsen, The Netherlands). The application rates were designed to supply 20 g nitrogen/m^2, which is the optimal fertilizing rate for the landfill slope (Kim 2001). Including the control, four treatments were established and monitored. In summer (August), photosynthetic rates of chestnut trees were analyzed using a portable photosynthesis measurement system (Li-6400, Li-cor Biosciences, USA) to check the condition of the plants. The leaves of the second highest branches were selected for measurement. Every leaves of trees were harvested in the fall and analyzed for nutrition. We collected core samples of soil (5 cm length, 100 cm^3; Eijkelkamp, Giesbeek, The Netherlands). A composite of three cores was made for each sample, and we assessed three samples (nine cores). Nitrogen content of soil and plant leaves was measured using an elemental analyzer (Flash EA 1112, Thermo Electron Co., USA). Heavy metal content of compost and plants was analyzed by ICP emission spectrometry (ICPS-1000IV; Shimadzu, Japan) after acid digestion of samples (Song et al. 2013b).

Statistical analysis

Differences between paired groups were evaluated using either Student's t test for normally distributed variables or the Mann–Whitney U test when normality assumptions were violated (SAS v. 9.1, SAS Institute Inc., USA). For multiple comparisons, data were analyzed using one-way PROC ANOVA. When a significant treatment effect was detected, post hoc comparisons of the means were performed using Tukey's honest significant difference (HSD) test (SAS v. 9.1, SAS Institute Inc., USA). Statistical significance was inferred when $p < 0.05$.

Results and discussion

Research and case studies relating to phytoremediation

There is an extensive literature on phytoremediation. The RISS and Google Scholar retrieved many published case studies, including the use of artificial wetlands and floating islands for remediation. For South Korea alone, the literature search uncovered >100 relevant examples. However, for artificial wetlands, most case studies address their use for educational purposes or for park construction, and research relevant to remediation is more limited. Examples in

South Korea are the Nanji leachate retention wetland in Seoul (Song and Kang 2006), the artificial wetland in the Sihwa development area (No et al. 2002), the Masan wetland in Asan city (Lee et al. 1999), the Jangja stream in Guri city (Lee 2005), the Juam lake in Boseong county (Choi et al. 2012), the artificial wetland in Nonsan city (Kim et al. 2012), and the floating island in Paldang lake, Gangwon province (Choi et al. 2007). Globally, there are too many cases to summarize here but phytoremediation is in wide use because of its cost-effectiveness and efficiency (Salt et al. 1995) for water, soil, and air. In addition, constructed wetlands are employed not only for the pollutant-accumulation capacity of their plants but in holistic systems (Cheng et al. 2002) that maximize provision of ecosystem services. Many studies also report increased remediation capacity through the use of plant-microorganism interactions (Barac et al. 2004) or transgenic plants (Eapen and D'Souza 2005). These examples show the continuing development of techniques in phytoremediation research. For South Korea, Table 1 summarizes published studies reporting pollutant contents of plants (by tissue accumulation) after remediation. Data show that plants after remediation contain high levels of N and/or P and have high biomass. For macrophyte species in particular, tissue decomposition can affect water quality (Asaeda et al. 2000) and reverse the remediation process. Macrophyte tissue decomposes by a factor of >80% within 200 days, returning nutrients to the water (Chimney and Pietro 2006). Furthermore, plant species accumulating heavy metals or toxic wastes would also cause secondary pollution of the remediation site after tissue decomposition. With respect to these problems, we did not locate any South Korean studies involving post-remediation management of plant biomass except research papers written by authors of this manuscript.

Field experiment into feasibility of post-remediation management

The remediation macrophytes in the Sudokwon landfill leachate channel had high biomass and high N content (Table 2). As this is a sanitary landfill, macrophyte metal contents do not exceed the national standards set for agricultural waste (Cd 5.0 mg/kg, Cr 70 mg/kg, Pb 100 mg/kg, Zn 300 mg/kg) (Korea Ministry of Environment KME 2010). However, pollutants released by the decomposition of plant tissues will eventually re-pollute the channel. As the metal contents are within the permitted national standards, the material can be reclaimed as waste. However, the process thereby creates another form of waste and also results in unused biomass. Reuse of biomass will reduce waste production and also save the cost of reclamation. As all metal values in Table 2 are less than 10% of the standards set for sludge recycled compost (Korea Environmental Institute KEI 2003), it will be more efficient to recycle biomass as compost. Otherwise, decomposition of plant tissue will re-contaminate the channel, reducing sustainability of the remediation system. Therefore, we tested a composting method to manage plants after remediation. This method will require harvesting of macrophytes in the channel, thus preventing secondary pollution.

During composting, the temperature of the compost increased and showed 30 °C higher temperature (36 °C) than the surrounding environment (6 °C) after 1 month, before falling to ambient temperature after 2 months. The final product, even after composting with sewage sludge, the macrophyte compost still had less than 10% of the national standards set for sludge recycled compost (Korea Environmental Institute KEI 2003), except Zn contents which does not have standard values (Table 3).

Table 4 shows that soil characteristics were improved more by compost treatment than by commercial fertilizer. As the landfill has very poor soil with low organic matter, low nutrient contents, and semi-arid

Table 1 Location, species, accumulation rate, and biomass of plants after the remediation process

Location	Species	Accumulation rate (mg/g)	Per area biomass (g/m^2)	References
Lake Sihwa	Rees	N 24.9, P 2.5	2515 (DW)	(No et al. 2002)
Masan wetland	Reed, cattail	Reed (cattail)—N 12 (11), P 0.9 (1.7)	Reed 532 cattail 1000	(Lee et al. 1999)
Artificial wetland	Water rice	N 26.9, P 6.8	4032 (DW)	(Kim and Ihm 1998)
Lake Juam	Water-fringe, water-lily	N about* 20 P about 4.0	NA	(Choi et al. 2012)
Artificial wetland	Reed	N 32.1, P 2.4	8100 (FW)	(Kim et al. 2012)
Lake Paldang	Reed, cattail	N 30, P 2.5	NA	(Choi et al. 2007)
Indoor	Duckweed	N 12, P 40.9 Cd 0.2 Cu 0.9	NA	(You 2016)
Indoor	Yellow flag-iris	Cd 0.2	NA	(Lee et al. 2009)

Scientific names of plant species: water rice, *Zizania latifolia*; water-fringe, *Nymphoides peltata*; water-lily, *Nymphaea tetragona*; duckweed, *Spirodela polyrhiza*; flag-iris, *Iris pseudacorus*

*Estimated value from graphs

Table 2 Biomass, nutrient, and metal contents of macrophytes in the leachate channel

Species	Biomass per shoot (g)	N (%)	C (%)	Cd	Cr	Fe	Pb	Zn
T. angustifolia	258	3.53	42.1	0.12	8.1	1021	4.4	184
P. australis	177	2.77	43.1	0.11	6.8	954	3.9	192

The data presented are means of ten replicates for biomass and four replicates for other variables
Metal content is expressed as milligrams per kilogram

condition (Kim 2001, Song 2010), the application of compost with high organic matter and nitrogen contents had huge effect. Also, commercial fertilizer significantly improved soil nitrogen contents but not soil moisture. The N organic matter and moisture contents of soil were all higher than in the Osmocote treatment, as organic matters of compost significantly increased moisture-holding capacity of reclaimed soil (Song and Lee 2010b). As the landfill slope is a semi-arid environment (Song 2010), increased organic matter and moisture content is very important. Also, as compost usually contains more available form of N (NH_4^+ and NO_3^-) by decomposition activities of microorganisms, even supplied with same rate of TN, N sources of compost could be more useful to plants.

The observed improvement was closely related to plant performance. Chestnut trees treated with macrophyte compost showed higher photosynthetic performance (Fig. 1) indicative of improved health (Song and Lee 2010a). Table 5 also shows that N content of leaves from plants treated with compost were higher than control values, indicating that compost-treated plants had more access to nutrients. Nutrient availability is a major obstacle to re-vegetating landfill slopes (Song and Lee 2010b). Therefore, results show that plants after remediation had excellent potential for use as composting materials. The good results for both *P. australis* and *T. angustifolia* imply that the effects are not species specific. The very hard stem of *P. australis* is a partial disadvantage for composting (Song 2010). However, the good results for this species suggest that remediation plants with softer stems and leaves may also be effective. Overall, results show that it is possible to re-use remediation plant biomass, thereby reducing secondary pollution and enhancing production of cost-effective and environmentally friendly fertilizer. Especially when phytoremediation is targeting N and P, the resultant biomass will produce nutrient-rich fertilizer. The post-remediation management and use of biomass therefore justifies further research and policy development.

Table 3 Nitrogen and metal contents of macrophyte compost before application

Compost type	N (%)	Cd	Cr	Fe	Pb	Zn
T. angustifolia compost	3.53	2.0	4.8	1779	3.9	1740
P. australis compost	2.77	1.8	5.2	1521	3.7	1720

The data presented are means of three replicates
Metal content is expressed as milligrams per kilogram

Research and policy relating to post-remediation management

Despite the reported limitations and problems of phytoremediation, effective techniques exist for managing biomass after remediation. Simple harvesting will reduce re-entry of pollutants by up to 75% (Asaeda et al. 2000). Generation of energy by incineration (Brooks et al. 1998) or by production of bio-ethanol has also been suggested (Banuelos 2006). Incineration has been considered the most realistic method (Sas-Nowosielska et al. 2004), although its waste products may pose a problem (Witters et al. 2012). Research into post-remediation techniques is still very limited (Song et al. 2016), and more studies such as ours are needed. Although we focused on phytoremediation, any phytoremediation method will produce biomass requiring post-remediation management. Furthermore, as harvesting remediation may be costly (Song et al. 2016), policies promoting effective management are also required.

Measures for the effective utilization of post-remediation biomass could be implemented in two stages. The first stage is to pre-emptively prohibit the use in compost of biomass containing toxic residues. In South Korea, one regulation relevant to the management of post-remediation biomass can be found in the "Wastes Control Act" (Act Number 13038). Article 13 of the act ordains, "Where the Minister of Environment deems that any products or materials, the hazard criteria of […] which are manufactured by recycling wastes require a certain control, he/she may enter into an agreement with the head of the local government concerned, the manufacturer of the said products or materials, etc. that requires them to disclose the use and quantities of

Table 4 Soil characteristics 3 months after treatment

Items	Moisture (%)	OM (%)	N (%)	C (%)
Control	13.03 ± 0.23^b	0.52 ± 0.01^b	0.02 ± 0.01^c	0.19 ± 0.03^b
Osmocote	12.83 ± 0.33^b	0.54 ± 0.02^b	0.04 ± 0.00^b	0.47 ± 0.04^a
P compost	17.60 ± 0.49^a	0.78 ± 0.03^a	0.05 ± 0.00^{ab}	0.49 ± 0.00^a
T compost	17.37 ± 0.52^a	0.87 ± 0.03^a	0.06 ± 0.00^a	0.62 ± 0.07^a

The data presented are means of three replicates (mean ± SE). Means within a column followed by the same superscript letter are not significantly different at $p = 0.05$
OM organic matter, *P Phragmites australis*, *T Typha angustifolia*

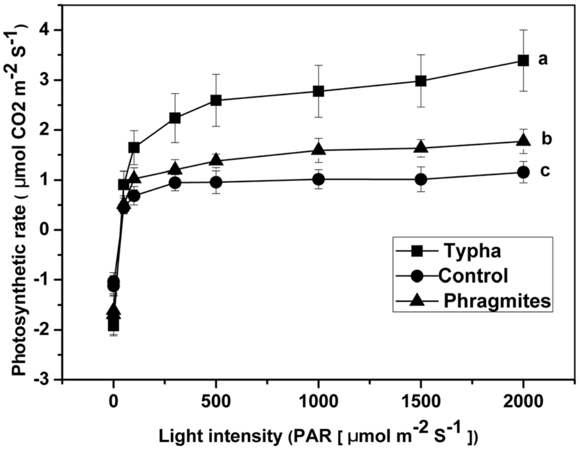

Fig. 1 Photosynthetic rates of chestnut tree (30 °C, 400 ppm CO_2) by treatments. *Symbols* and *bars* represent mean ± SE of four replicates. *Symbols having the same letter* are not significantly different at the 0.05 level. *Typha T. angustifolia*, *Phragmites P. australis*

each type of wastes, the heavy metal contents of such wastes, and other information". At least until a new law is enacted to regulate the safe and efficient use of post-remediation biomass, local governments can utilize the Wastes Control Act by their own local ordinances. The ordinances may have to classify the biomass as a form of recycled material. In other countries also, the use of post-remediation biomass can be governed by currently existing legal instruments for municipal solid or biodegradable waste. For example, the USA's "Solid Waste Disposal Act" (Public law 89-272) and its amendments can direct how the post-remediation biomass is used depending on the concentration levels of toxic elements. Similarly, the European Union's "Urban Waste Water Treatment Directive" (91/271/EEC) and "Sewage Sludge Directive" (86/278/EEC) can be quoted to control toxic elements in post-remediation biomass. However, we did not find any acts or laws specifically concerned with post-remediation biomass. Therefore, to improve the management of biomass (or, at least, to not leave post-remediation biomass as it is), additional legislation should be considered.

The second stage of policy implementation is to enforce or promote the use of post-remediation biomass that is proven safe by the first-stage policy measures. In South Korea, the enforcement decree (Ministry of Environment, No. 2011-64) for the "Wastes Control Act" has a special section titled "Regulations on recycling organic sludge etc. as soil modifier or landfill cover soil." The government may modify the decree and promote the use of composted post-remediation biomass. In the USA, the "Federal Water Pollution Control Act" (Public law 92-500) and its amendments can be consulted for biomass composting. The European Union has a specific law titled "Waste Framework Directive" (2008/98/EC) that requires composting of bio-waste, and which can also be applied to post-remediation biomass. However, these laws are only related to the re-use of post-remediation biomass and are not framed specifically to promote post-remediation management. Therefore, to protect the environment and achieve sustainability, there is a need for the enactment of a "Post-phytoremediation management" or even "Post-bioremediation management" law that sets out the government's obligations to (a) manage biomass after phytoremediation to prevent secondary pollution, (b) ensure that toxic pollutants are not used for recycling, and (c) promote recycling of biomass with environmentally friendly methods.

Table 5 Nutrient contents of chestnut leaves

	N (%)	C (%)
Control	2.81 ± 0.04^{b}	46.48 ± 0.41
P compost	3.16 ± 0.05^{a}	46.62 ± 0.23
T compost	3.12 ± 0.04^{a}	46.62 ± 0.23

The data presented are means of three replicates (mean ± SE). Means within a column followed by the same superscript letter are not significantly different at $p = 0.05$

P Phragmites australis, *T Typha angustifolia*

Conclusions

Post-remediation biomass must be managed; otherwise, it will eventually return to the environment and cause secondary pollution. Research into the post-remediation management of biomass is therefore required. Using biomass as a co-composting material could be one of the best solutions because it is cost-effective and environmentally friendly. In this research, we proved that post-remediation management of biomass is effective by actual experiment, and with this scientific basis, we became more confident of requirements for such policies.

However, despite of its potential, research and policy development to promote this form of management is lacking. There is a need for enactment of a post-phytoremediation management law that stipulates management of biomass after phytoremediation and promotes recycling (using environmentally friendly methods) of biomass known to pose an environmental risk. Specific policies for managers must be developed, and additional research should be carried out to support and inform such policies and laws.

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SU conducted the experiment and partially wrote the manuscript. HP designed the experiment and partially wrote the manuscript. Both authors read and approved the final manuscript.

Competing interests
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