SEWAGE SLUDGE AND MUNICIPAL WASTE: POTENTIAL SOURCES OF PHOSPHORUS FOR LAND RESTORATION

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ABSTRACT
Waste disposal is one of the environmental challenges facing city authorities. Waste contains nutrients and organic matter required for plant growth that can, in many cases, be recovered and put to use. Quantifying the amount of waste generated and nutrients that can be recovered from it is important. Further, cost of applying the waste on land should be evaluated in order to make wise investment decisions. Globally much of the waste generated is disposed without resource recovery. Therefore, the objectives of this study were to 1) quantify the amount waste generated in the Reykjavík capital area in Iceland, 2) determine the quantity of phosphorus contained in waste and 3) evaluate the cost of transporting the waste to nearby restoration sites and spreading it on the field. Operational data were collected from operators of wastewater and municipal waste treatment in the capital area. The capital area generated 722 tons/year of sewage sludge, 98,890 tons/year of solid waste and 82 million m³/year of wastewater in 2015. Wastewater treatment and municipal waste contributed 68% and 32% phosphorus, respectively. Phosphorus disposed in waste was 435% higher than the phosphorus used by the Soil Conservation Service in 2015. If all this phosphorus were recovered, it would most likely meet all the phosphorus requirements for land restoration in Iceland. The cost of utilizing phosphorus from waste is higher than using inorganic fertilizers. However, for highly degraded soils, such as those with an erosion scale of 3-5, application of waste would quicken soil recovery as it is rich in organic matter and nutrients. Further, utilizing waste reduces environmental pollution and conserves the non-renewable phosphorus reserves. The study recommends that waste be utilized in restoration as a means of recovering and reusing phosphorus. Legislation should be put in place to encourage waste utilization in land restoration.
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1. INTRODUCTION

1.1 The waste management challenge

Waste is a man-made resource that is considered of no beneficial use to the owner or is not able to perform with respect to its desired function (Pongrácz & Pohjola 2004). This definition of waste implies that it depends on the functionality of the material, whether it is waste or not. Waste can be categorized based on its origin, i.e. industrial, municipal or agricultural waste. Industrial waste originates from industries and its composition depends on the activities of the industry. Municipal waste includes waste originating from residences and businesses. This waste is highly organic (Hargreaves et al. 2008; Cesaro et al. 2015) due to the nature of activities that lead to its generation. Agricultural waste includes waste originating from agricultural activities such as crop and livestock production and agro-processing (Jana & De 2015). Waste can also be categorized by grouping it according to form, i.e. liquid, gaseous or solid waste. Waste management is the control of waste-related activities with the aim of protecting the environment, public health and resource conservation (Pongrácz & Pohjola 2004). Among other activities, waste management is concerned with the control of waste generation, collection, processing and disposal. Waste management is one of the major environmental challenges facing municipalities (Odlare et al. 2011) but varies with the economy and environmental regulations of the country (Desmidt et al. 2015). Most households in developed countries are connected to the main sewer and dispose of solid waste through landfilling, incineration or composting (Gentil et al. 2009). On the other hand, most countries in Africa do not have adequate waste management infrastructure (Couth & Trois 2010, 2011) such as wastewater treatment systems and solid waste management facilities. Malawi, for example, still disposes of municipal solid waste in uncontrolled open dumps and discharges partially treated wastewater effluent into urban streams (Sajidu et al. 2007; Kumwenda et al. 2012; Wanda et al. 2015; Mdolo 2016). Consequently, untreated or partially treated waste is often discharged into the environment causing environmental pollution such as eutrophication (Wang et al. 2014).

1.2 Application of sewage sludge and organic waste in agriculture and land restoration

Wastewater, sewage sludge and municipal solid waste are among the waste that is generated in urban areas. Such waste has potential application in agriculture and land restoration due to its organic and nutrient content. Wastewater, also known as sewage, is used water collected from residences, institutions, businesses and industrial establishments together with ground water, surface water or storm water, as may be present (Raynolds & Richards 1996; Metcalf & Eddy 2003), and conveyed to a treatment plant for processing (Malawi Government 2008). The main product of wastewater treatment is the treated effluent which is mostly discharged into receiving water bodies. Sewage sludge is a by-product of wastewater treatment (Song & Lee 2010) and is a complex of mixed semisolids comprising organic materials, microorganisms and inorganic materials that settle at the bottom of wastewater treatment ponds/tanks (Tyagi & Lo 2013) while the liquid supernatant proceeds to the next treatment process. Figure 1 shows the layout of a conventional wastewater treatment system.
In such systems, sewage sludge is generated in the primary treatment stage. This stage involves primary sedimentation. It is also generated in the secondary treatment process involving an activated sludge system. Consequently, sewage sludge generated in the primary and secondary stages is known as primary and secondary/activated sludge, respectively. Activated sludge contains active microorganisms utilized in wastewater treatment (Saunders et al. 2016).

Sewage sludge is rich in organic matter, nutrients and other essential elements required for plant growth, hence its potential for soil conditioning and nutrient addition (Antolín et al. 2005; Alvarenga et al. 2015). However, sewage sludge also contains considerable amounts of toxic substances such as heavy metals (Usman et al. 2012; Bruun et al. 2016) which have the potential of causing soil contamination (Bravo-Martín-Consuegra et al. 2016). In addition, heavy metals can be taken up by plants together with nutrients and become available to grazers and human beings. It is, therefore, desirable to properly treat sewage sludge and analyse its chemical composition (Council of the European Communities 1986; Withers et al. 2016) before applying it to land. Treatment of sewage sludge may include digestion, stabilization (liming), dewatering and drying (Water UK 2010) or composting to reduce the risk of heavy metal contamination (Smith 2009). Composting also reduces the volume of waste (Hargreaves et al. 2008) and hence reduces the transportation cost of the product. Sewage sludge can be co-composted with other waste such as municipal waste to improve the quality of compost before application. Composts produced from co-composting of sewage sludge and other waste tend to have higher metal contents (Hargreaves et al. 2008) than composts produced from municipal solid waste alone, due to the high metal content in the sewage sludge. Increasing the maturity period of co-composts increases the humic material in the compost which binds heavy metals (Hargreaves et al. 2008) and hence greatly reduces their bioavailability to plants, animals and human beings. Co-composting of sewage sludge can be advantageous in situations where the final product will be applied on restoration fields and not on fields where food crops will be grown. Composting facilities include windrowing, aerated static piles and horizontal agitated solids beds (Wei et al. 2001). The choice of the composting facility depends on the moisture content of the input raw material (Wei et al. 2001). Compared with

Figure 1. Schematic diagram of a wastewater treatment plant showing stages where sewage sludge is generated (Source: Modified from Water UK 2010).
Municipal solid waste, especially food and yard waste, is another potential source of organic matter and nutrients. The need for recycling and re-using municipal solid waste is increasing due to restrictions placed on land disposal of such waste. Restrictions on land disposal of waste could be linked to 1) increasing human populations which lead to less land available for waste disposal and 2) uncertainty with phosphate reserves for the production of inorganic fertilizer (Reijnders 2014). As governments struggle to provide settlements and food for growing populations, more stringent regulations will be placed on waste management practices (Tyagi & Lo 2013; Desmidt et al. 2015). Therefore, the design of future waste treatment facilities should encourage nutrient recovery (Wahlberg 2014), shifting from the current focus of protecting the environment and public health to resource recovery (Pongrácza & Pohjola 2004). Failing to do so will have profound effects on the existence of life (Sverdrup & Ragnarsdottir 2011) if phosphorus reserves are depleted.

Land application of waste adds organic matter to soil, which improves its biological and physicochemical characteristics such as improving aggregate stability and decreasing bulk density (Diacono & Montemurro 2010). Organic matter increases soil organic carbon and nitrogen (Diacono & Montemurro 2010) and can reduce plant parasitic nematodes (Treonis et al. 2010). Higher yields can be realized for crops grown on soils with applied waste (Antolín et al. 2005). However, crops can also accumulate toxic metals if the waste is applied excessively, given that the waste is rich in toxic metals (Antolín et al. 2005). Therefore, use of sewage sludge compost and other composts on non-food plants is a potential alternative. Regulations on land application of sewage sludge and other composts on non-food plants are less restrictive than those regulating application on food crops. For example, land application of sewage sludge in the EU is regulated by the EU sewage sludge directive 86/278/EEC (Council of the European Communities 1986). Within this regulation, grazing animals can be allowed to graze in sewage sludge amended fields after three weeks of application (Council of the European Communities 1986). Iceland has adjusted the directive 86/278/EEC by developing regulation 799/1999 on the handling of sewage sludge (Ministry for the Environment 1999). In accordance with this regulation, untreated sewage can be applied to restoration fields if it is ploughed into the soil (Ministry for the Environment 1999). Further, the Ministry allows a one-year period to elapse after application of treated sewage sludge before the land can be put to beneficial use again (Ministry for the Environment 1999). Therefore, for land restoration purposes, application of sewage sludge and other composts could be ideal and the restored fields could be used for grazing in future. In Malawi, national standards regulating land application of sewage sludge and other composts do not exist. Consequently, untreated sewage sludge is often applied on home gardens and lawns. Members of the public often manually excavate the sludge from wastewater treatment ponds and transport it to their homes or gardens for application. Environmental monitoring is usually not undertaken in areas where the sludge has been applied to assess the environmental risk to public health and the receiving soils. Analysis of the physico-chemical characteristics of sewage sludge is most often not performed by the operators.

In Iceland, land application of sewage sludge and other composts would be ideal and in line with the ongoing land restoration efforts. The practice, if adopted, would reduce the amount of waste landfilled or discharged into the ocean and consequently reduce the use of inorganic fertilizer for restoration. Since Icelandic soils are predominantly basic (Arnalds 2015), application of composted sewage sludge and municipal solid waste is expected to have minimal impact on heavy metal
contamination. The pH value plays a major role in the sorption of heavy metals since there is low heavy metal uptake by plants at pH values above 7 (Smith 2009). At such pH values, the soluble form of heavy metals is converted into insoluble metal hydroxides or oxides which cannot be taken up by plants (Brady & Weil 2008). However, in Iceland, as vegetation is established in restored areas, the pH values tend to decrease (Arnalds 2015), which could lead to sorption of heavy metals, making them available to plants and hence grazing animals. Therefore, continued application of compost and sewage sludge should be followed by periodic monitoring of the soils and plants (Singh & Agrawal 2008) for heavy metal toxicity.

1.3 Importance of waste as a source of phosphorus

The cost of inorganic fertilizers is increasing due to increasing production costs (Cordell & White 2011) and uncertainty concerning the size of phosphate reserves (Reijnders 2014). It is argued that the current phosphorus reserves will last for the next 30 to 300 years (Cordell & White 2011). Regardless of when the reserves will be depleted, it is clear that the sustainability of inorganic fertilizers is uncertain. This is compounded by the fact that the accessibility and quality of the reserves is decreasing; hence the high cost of production (Cordell & White 2011; Desmidt et al. 2015). Research has shown that waste contains a considerable amount of organic matter and nutrients (Antolín et al. 2005; Alvarenga et al. 2015). These resources are however often left untapped in landfills and wastewater effluents (Mayer et al. 2016), as illustrated in Figure 2.

Figure 2. A flow diagram showing how phosphorus is managed from mined phosphate rock to waste after consumption. (Source: Modified from Desmidt 2015).

This practice not only causes eutrophication, as the waste ends up in natural water bodies (Desmidt et al. 2015), but also waste the precious resource needed for plant growth and soil conditioning. The current phosphorus use is, therefore, unsustainable and wasteful (Sverdrup & Ragnarsdottir 2011), especially given that it can be recycled from waste (Fig. 3). Management of phosphorus should be sustainable, with recycling it within the system (Fig. 3) rather than discharging it into the environment (Fig. 2) (Dawson & Hilton 2011).
Figure 3. A flow diagram showing how phosphorus should be managed from waste back to agricultural land or industry. (Source: Modified from Desmidt 2015).

It is important to recycle and reuse phosphorus from waste streams (Dawson & Hilton 2011) in order to reduce pressure on the non-renewable reserves. If used in restoration fields, the organic matter and nutrients can improve soil microbial activity (Odlare et al. 2011), soil fertility, soil water retention and soil carbon accumulation (Song & Lee 2010). There has been progress in many parts of the world to recycle waste back into the environment as long as the application rates do not pose a risk to the environment and public health. Consequently, treated and untreated waste has been applied in agriculture, forestry and land restoration. In the European Union, for example, 41% of the sludge produced is used in agriculture (Dawson & Hilton 2011; Kelessidis et al. 2012). On a country basis, Finland reuses almost 100% of its sludge (97% after composting) in agriculture or other land application while Luxembourg, Cyprus and Portugal apply 87% of sludge in agriculture (Kelessidis & Stasinakis 2012), either directly or composted. England, on the other hand, recycles almost 80% of sewage sludge to agriculture (Water UK 2010). Western Australia applies 80% of the sludge generated in agriculture and forestry (Pritchard et al. 2010) while the US applies about 60% of sewage sludge in agriculture, land restoration or other land applications (North East Biosolids and Residuals Association 2007; Lu et al. 2012).

Data on beneficial use of sewage sludge and other organic waste for Iceland are lacking, but small trials are under way (MH Jóhannsson, 12 May 2016, Soil Conservation Service of Iceland, Gunnarsholt, Iceland, personal communication) in which different types of waste are applied in restoration fields and vegetative growth monitored. In Sub-Saharan Africa, especially Malawi, data on waste generation and land application of composts are also lacking. If these data were available, they would form a basis for lobbying governments to invest in construction of composting facilities and land application of composted waste. If waste were collected and properly treated and applied on land, the demand for inorganic fertilizers would considerably decrease and hence conserve the declining non-renewable phosphorus resource.
This study was carried out in the Reykjavík capital area partly because I was in the area at the time and could not get data for such research from Malawi. On the other hand, the study in Iceland could raise awareness on the benefits of utilizing waste in land restoration. While other developed countries are struggling with agricultural application of waste, Iceland could utilize it in restoration work other than mainstream agriculture. The results of this study will help in the design of similar studies in Malawi, profiting from lessons learnt here in Iceland.

The objectives of this research were:
   i) To quantify the amount of waste generated in the Reykjavík capital area in 2015, including: wastewater, sewage sludge and municipal waste
   ii) To determine the quantity of phosphorus in the amount of waste generated in the capital area for 2015
   iii) To evaluate the cost of transporting the waste to nearby restoration sites and spreading it on the field.

2. METHODOLOGY

2.1 Description of the study area

This study was conducted in the Reykjavík capital area in Iceland, which comprises seven municipalities. The population of the capital region in 2015 was 211,282 (Statistics Iceland 2015) which was 64% of the national population. The names and distribution of the population in the seven municipalities making up the capital region are shown in Table 1.

Table 1. Population in the Reykjavík capital region (Statistics Iceland 2015)

<table>
<thead>
<tr>
<th>Municipality</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reykjavík</td>
<td>121,822</td>
</tr>
<tr>
<td>Kópavogur</td>
<td>33,205</td>
</tr>
<tr>
<td>Hafnarfjörður</td>
<td>27,875</td>
</tr>
<tr>
<td>Garðabær</td>
<td>14,453</td>
</tr>
<tr>
<td>Mosfellsbær</td>
<td>9,300</td>
</tr>
<tr>
<td>Seltjarnarmes</td>
<td>4,411</td>
</tr>
<tr>
<td>Kjósarhreppur</td>
<td>216</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>211,282</strong></td>
</tr>
</tbody>
</table>

Waste management regulations in Iceland are based on European Union regulations and each municipality develops its own waste management plans. The Environmental Agency of Iceland (Umhverfisstofnun) is responsible for developing the national waste management plan. Local authorities are supposed to develop their own local waste management plans based on the national waste management plan. In the Reykjavík capital region, solid waste management is coordinated and handled by SORPA, a company jointly owned by municipalities in the area. Wastewater treatment and sewage sludge management is operated by Reykjavík Energy.
2.2 Data collection and phosphorus quantification

This study focused on waste which could be readily composted and utilized in land restoration. Hazardous waste, textiles, metals and plastics were not considered. Timber, wood, packaging waste, paper and cardboard were also not included in the analysis due to their low phosphorus content. Furthermore, these waste fractions are already exported to Sweden for recycling (Saltiola 2014). Therefore, to quantify the amount of phosphorus available in the three major waste streams (wastewater, sewage sludge and municipal solid waste), operational data from wastewater and municipal solid waste operators in the Reykjavík capital region were used. Data collected was on waste generation rates for the year 2015. The operator sampled the effluent wastewater in March, June, September and December 2015 for monitoring nutrient content of the effluent. Phosphorus content in sewage sludge and municipal solid waste was calculated based on phosphorus content values (Table 2) and their moisture content (Table 3) reported in the literature.

**Table 2. Typical phosphorus content in different waste fractions.**

<table>
<thead>
<tr>
<th>Item</th>
<th>P content (g P/kg DS)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sewage sludge (% P₂O₅, TS)</td>
<td>2.5</td>
<td>Metcalf &amp; Eddy 2003</td>
</tr>
<tr>
<td>Timber/wood</td>
<td>0.31</td>
<td>Sokka et al. 2004</td>
</tr>
<tr>
<td>Paper and cardboard</td>
<td>0.24</td>
<td>Sokka et al. 2004</td>
</tr>
</tbody>
</table>

TS= Total solids, DS= Dry solids, P= phosphorus

The amount of phosphorus in sewage sludge and municipal solid waste was, therefore, calculated from annual data acquired, using typical phosphorus values (Table 2). Calculations of phosphorus content were based on the dry matter of the waste fraction. Moisture content (% wet weight) values for each waste fraction (Table 3) were used to determine the dry matter content of the waste.

**Table 3. Moisture content in different waste fractions (Kalmykova et al. 2012)**

<table>
<thead>
<tr>
<th>Waste fraction</th>
<th>Moisture content (% wet weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper &amp; cardboard</td>
<td>0</td>
</tr>
<tr>
<td>Timber/wood</td>
<td>19</td>
</tr>
<tr>
<td>Kitchen waste</td>
<td>65</td>
</tr>
<tr>
<td>Garden waste</td>
<td>65</td>
</tr>
<tr>
<td>Other organic waste</td>
<td>65</td>
</tr>
</tbody>
</table>

Phosphorus content in wastewater was calculated from the wastewater flow rate \(Q, \text{L/sec}\) and phosphorus concentration (mg/L) data acquired from the operator (Reykjavík Energy), using the following equation;

\[
C = \frac{m}{Q}
\]

where \(C\) = concentration of phosphorus (mg/L), \(m\) = mass of phosphorus (mg), \(Q\) = wastewater flow rate (L/sec).

The amount of waste generated, cost of composting the waste, average distance to nearest restoration sites and recommended application rates formed the basis for calculating the cost of utilizing the waste in restoration. The cost of composting was based on values reported in the literature for such operations. The figures used to calculate the cost of transporting and spreading the waste on the field were acquired from the Soil Conservation Service of Iceland based on typical
operational costs for such activities. Figure 4 shows a map of the study area with possible restoration sites within a radius of 30 km to 50 km from the Reykjavík capital area with an erosion scale of 3-5. Erosion severity is based on a scale of 0-5 where point 0 on the scale represents no erosion while 5 indicates extremely severe erosion (Table 4) (Arnalds et al. 2001).

**Table 4.** Erosion severity scale, colour codes and suggested management actions (Source: Modified from Arnalds et al. 2001)

<table>
<thead>
<tr>
<th>Erosion scale</th>
<th>Description</th>
<th>Colour code</th>
<th>Suggested management action</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No erosion</td>
<td>Green</td>
<td>No suggestion</td>
</tr>
<tr>
<td>1</td>
<td>Little erosion</td>
<td>Green</td>
<td>No suggestion</td>
</tr>
<tr>
<td>2</td>
<td>Slight erosion</td>
<td>Green</td>
<td>Care needed when grazing</td>
</tr>
<tr>
<td>3</td>
<td>Considerable erosion</td>
<td>Yellow</td>
<td>Reduce and manage grazing</td>
</tr>
<tr>
<td>4</td>
<td>Severe erosion</td>
<td>Orange</td>
<td>Protected (no grazing)</td>
</tr>
<tr>
<td>5</td>
<td>Extremely severe erosion</td>
<td>Red</td>
<td>Protected (no grazing)</td>
</tr>
</tbody>
</table>

Figure 4. Map showing possible restoration sites within a radius of 30-50 km from the capital area with erosion scale of 3-5 (Source: Guðný H. Indriðadóttir, Soil Conservation Service of Iceland 2016).
3. RESULTS

3.1 Waste generation rates and phosphorus content in sewage sludge, municipal solid waste and wastewater

Results for waste generation rates and associated phosphorus content in each waste fraction of sewage sludge, paper and cardboard, timber/wood, kitchen waste, garden waste, organic waste and wastewater are presented in Table 5. The average wastewater flow rate and phosphorus concentration was 2,601 L/sec and 2.4 mg/L, respectively. The percent phosphorus contribution of each waste fraction is further presented in Figure 5.

Table 5. Amount and different types of waste generated annually in the Reykjavík capital region and their phosphorus content.

<table>
<thead>
<tr>
<th>Waste fraction</th>
<th>Units/year</th>
<th>Amount</th>
<th>Dry matter (%)</th>
<th>Dry matter (tons)</th>
<th>Total P (tons/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sewage sludge</td>
<td>tons</td>
<td>722</td>
<td>-</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>Paper &amp; cardboard</td>
<td>tons</td>
<td>18,852</td>
<td>100</td>
<td>18,852</td>
<td>5</td>
</tr>
<tr>
<td>Timber/wood</td>
<td>tons</td>
<td>11,275</td>
<td>81</td>
<td>9,132</td>
<td>3</td>
</tr>
<tr>
<td>Kitchen waste</td>
<td>tons</td>
<td>65,721</td>
<td>35</td>
<td>23,000</td>
<td>92</td>
</tr>
<tr>
<td>Garden waste</td>
<td>tons</td>
<td>3,015</td>
<td>35</td>
<td>1,055</td>
<td>4</td>
</tr>
<tr>
<td>Other organic waste</td>
<td>tons</td>
<td>27</td>
<td>35</td>
<td>9</td>
<td>0.04</td>
</tr>
<tr>
<td>Wastewater</td>
<td>m³</td>
<td>82,249,862</td>
<td>-</td>
<td>-</td>
<td>195</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>306</strong></td>
</tr>
</tbody>
</table>

Wastewater contained the highest phosphorus (Fig. 5) of all waste fractions studied. Kitchen waste was the highest solid waste generated of all the municipal solid waste (Table 5). Despite being about 25 times smaller in the quantity generated for paper and cardboard, sewage sludge contributes 3% phosphorus while paper and cardboard contribute 1%. Timber/wood and garden waste both contribute 1% phosphorus.

Figure 5. Percent (%) contribution of phosphorus from each waste fraction.
3.2 Cost of utilizing sewage sludge and municipal solid waste in land restoration

The cost of loading, transporting and spreading the waste in land restoration fields is presented in Table 6. Calculations were based on loading the waste in a trailer, transporting it to the nearest restoration field (50 km) and spreading it on the field at an application rate of 30 tons/ha. Therefore, one round trip to the nearest restoration field using a trailer which can take 30 tons of waste would be 100 km.

Table 6. Breakdown of the cost associated with applying 30 tons of waste on a 1 ha of restoration field.

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Quantity</th>
<th>Cost (ISK/unit)</th>
<th>Total Cost (ISK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading</td>
<td>hour</td>
<td>2</td>
<td>5,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Transport</td>
<td>km</td>
<td>100</td>
<td>480</td>
<td>48,000</td>
</tr>
<tr>
<td>Spreading</td>
<td>hour</td>
<td>2</td>
<td>27,000</td>
<td>54,000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>112,000</td>
</tr>
</tbody>
</table>

According to these calculations, the cost of utilizing waste on a restoration field would be around 112,000 ISK/ha. With value added tax (VAT) included at 24%, the cost of utilizing waste would be around 140,000 ISK/ha. This is, however, likely to be an upper estimate. The cost of producing 30 tons of compost would be around 60,000 ISK (Wei et al. 2001; Song & Lee 2010).

4. DISCUSSION

4.1 Waste generation and phosphorus content

The contribution of timber, paper and cardboard to phosphorus was almost negligible. Therefore, in cases where the waste management objective is to recover phosphorus from waste, it is important to consider the phosphorus content of the waste fraction rather than the amount of waste generated. It has been shown in this research that sewage sludge contributed more to the amount of phosphorus than paper and cardboard. The amount of paper and cardboard generated was higher than that of sewage sludge. In the Reykjavík capital area, sewage sludge and kitchen waste should be preferred for phosphorus recycling to timber, paper and cardboard.

A little over 82 million m³/year of wastewater were generated in the Reykjavík capital area in 2015. This wastewater contained 195 tons/year of phosphorus. In comparison, this amount of phosphorus in wastewater effluent was four times higher than the amount in wastewater treatment plants in Gothenburg in Sweden (Kalmykova et al. 2012), a city with a population almost double that of the capital region in Iceland. This observation can be explained by the different treatment systems employed in these two cities. In Gothenburg, advanced wastewater treatment systems are employed to remove phosphorus from effluent before final disposal (Kalmykova et al. 2012; Wu et al. 2016). In the Reykjavík capital area, sewage sludge and wastewater, combined, contributed 67% of the phosphorus. This amount shows that most of the phosphorus in urban areas is contained in wastewater and sewage sludge (Chowdhury et al. 2014; Wu et al. 2016). However, most of this phosphorus is discharged as unproductive outflow into water bodies (Chowdhury et al. 2014) or landfilled (Villarroel et al. 2014).
4.2 Economic evaluation of transporting and spreading the waste in restoration field

There are many sites within a 30-50 km radius from the capital area with erosion levels of 3-5. However, not all of them would be suitable for applying waste. Some of them are grazed and only a few are fenced off from grazing. In addition, there are restrictions on such water protection areas and issues of land ownership that need to be sorted out before restoration activities are undertaken. Also, these sites may be inaccessible due to slope, height and rocks on the surface. Based on the map (Fig. 4), potential sites for waste application might be Krýsuvík in Hafnarfjörður, or Hafnarmelar in Borgarfjörður, all of which are active reclamation sites. If results of a stakeholder analysis were positive (Mackenzie 2011), grazing and fencing were in order and participants agreed on all terms of the operation, these three sites would be ideal for compost and sewage sludge application.

In 2015, about 2,500 tons of chemical fertilizer were used for land restoration with an average phosphorus content (P<sub>2</sub>O<sub>5</sub>) of 4.5% (MH Jóhannsson, 26 July 2016, Soil Conservation Service of Iceland, Gunnarsholt, Iceland, personal communication). The amount of phosphorus used as P<sub>2</sub>O<sub>5</sub> was 113 tons. Since P<sub>2</sub>O<sub>5</sub> contains 43.6% P, the amount of phosphorus as P used in 2015 was 49 tons. If sewage sludge generated in the Reykjavík capital area in 2015 was properly treated, the phosphorus it contained would be enough to provide 16% of the phosphorus used for restoration by the Soil Conservation Service of Iceland. If all kitchen waste were composted and applied in land restoration, it would exceed the phosphorus budget for land restoration in 2015. Phosphorus from kitchen waste alone was almost twice (95 tons) the amount of phosphorus used (49 tons) for land restoration by the Soil Conservation Service of Iceland in 2015. If a biological phosphorus removal wastewater treatment system was employed (Cornel & Schaum 2009) in the treatment of wastewater generated in the Reykjavík capital area, 98 tons of phosphorus would be recovered in the effluent. Just as was the case with phosphorus in kitchen waste, this amount was almost twice the amount which was used for restoration by the Soil Conservation Service of Iceland. Combining all these phosphorus values, the amount of phosphorus wasted through waste disposal from the Reykjavík capital area alone exceeded the phosphorus used for land restoration by the Soil Conservation Service of Iceland in 2015 by over 435%. On a national scale, the phosphorus contained in waste would have met 18% of the total amount of phosphorus imported into Iceland in 2015. With the ongoing efforts in land restoration in Iceland, application of sewage sludge and municipal waste in land restoration could be a sustainable waste management option. As many other countries are struggling to meet stringent regulations on agricultural use of waste, Iceland could take this as an opportunity since the waste generated would be applied in restoration fields where nonfood plants grow.

Utilizing waste on the nearest restoration field from the Reykjavík capital area would cost around 140,000 ISK/ha, VAT of 24% inclusive. using an application rate of 30 tons/ha (United States Environmental Protection Agency 2007). This application rate is recommended by the United States Environmental Protection Agency (USEPA) on highly degraded land (USEPA 2007) like the ones in the restoration fields nearest to the capital area. The cost of utilizing waste could be higher than using inorganic fertilizer, considering that recovery and reuse of phosphorus from waste is currently expensive (Cornel & Schaum 2009). However, this amount could be reduced, if the service were to be tendered. Again, the cost of electricity in Iceland is comparatively low compared to other European countries, which could further reduce the cost of producing the compost. It is also worth noting that land application of waste not only provides nutrients, but also
other benefits such as organic matter and elements required for plant growth (Mayer et al. 2016). On the other hand, other technologies of managing waste such as the scrubbing cost of product gas after incineration, pyrolysis, wet oxidation and gasification are high (Fytili & Zabaniotou 2008) and they emit greenhouse gases, dioxins, fumes and heavy metals. In comparison to such technologies, agricultural application of waste is economical (Lundin et al. 2004). Long term application of waste to agricultural fields can cause heavy metal accumulation in crops. Application of waste in land restoration would be a viable alternative as it could be cheaper and pose a lower public health risk. Composting of the waste would reduce the odour and flies associated with its land application, which could eventually increase its social acceptance. Furthermore, land application of waste is a way of conserving resources, especially phosphorus, which is nonrenewable. In addition, recovery of nutrients from waste reduces the need for importing inorganic fertilizers. Consequently, foreign currency is conserved as a result of reduced importation costs and the country’s carbon footprint is reduced.

4.3 Limitations of the study

This study relied on waste generation data collected by operators. It would have been better if the researcher had had enough time to collect and analyse these data. The time for doing this kind of research was enough to collect and analyse the data properly. The phosphorus and moisture content of the waste used in calculations were based on values reported in the literature. These parameters could have been determined for the waste in the study area since they can vary from region to region.

5. CONCLUSION

The results of the study suggest that municipal waste contains enough phosphorus that could definitely meet the phosphorus requirement for restoration works in Iceland. If proper phosphorus recovery treatment systems were employed, the amount recovered could surpass that used for operations like land restoration. Costs associated with composting, transporting and spreading the waste are higher than those associated with inorganic fertilizer use, however. On the other hand, these costs could be reduced if the service were to be tendered. There are other benefits of waste utilization that must be considered, such as pollution control and improvement of soil quality, among others, when evaluating the total value of utilizing waste-produced phosphorus in land restoration.

Proper care should be taken when applying waste to land to minimize the harmful effects that can ensue to soil and plants, especially should the restored land could be used for grazing in future. For example, a detailed physico-chemical analysis of the waste (sewage sludge and municipal waste) and soil where the waste will be applied should be undertaken. Plants and their tendency to heavy metal accumulation should be studied before growing them on waste-amended soils. Therefore, studies are required to understand the waste-soil-plant-metal interaction and nutrient mineralization, especially in Iceland with its unique soils and vegetation.
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LITERATURE CITED


