Identifications of Pathways for Phosphorus-based Product Recovery from Sewage Sludge using Multi-Criteria Decision Analysis for Sri Lankan Context

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***Abstract**: This study was carried out to inspect the suitability of 5 methods to produce phosphorus-based products using sewage sludge as an alternative to the rock phosphate demand to produce phosphate fertilizers. The considered methods are supercritical water gasification of sewage sludge, struvite precipitation, thermochemical treatment of sewage sludge, wet chemical treatment of sewage sludge and electrodialysis of sewage sludge. These methods are compared with each other to determine best method using 11 different criteria selected in Sri Lankan context. The comparison was carried out using a multi-criteria decision making (MCDM) technique called TOPSIS under 3 different scenarios which assigned different values to the criteria in environmental, economical and fertilizer suitability aspects. An analysis was carried out regarding results of the MCDM to determine the best method and struvite precipitation was selected as the best method in Sri Lankan context to recover the phosphorus in wastewater.*

***Keywords**: phosphorus, wastewater, multiple criteria decision making, sludge processing*

1. Introduction

Phosphorus is a key component in agriculture. It has to be supplied to cultivations in the form of fertilizers. Phosphorus fertilizers are manufactured using rock phosphate and due to the heavy consumption, rock phosphate reservoirs are depleting in a remarkable rate. According to researches, a half of global rock phosphate reservoirs would deplete within next fifty years (Egle, Rechberger and Zessner, 2015; Cieślik and Konieczka, 2017). Therefore, the search has been widened to find alternatives to rock phosphate and municipal wastewater has been identified as a viable source of phosphorus.

Several methods have been developed to extract phosphorus from wastewater and most of them use the residue of the wastewater treatment process which is called the sewage sludge. The sewage sludge is treated in various methods achieve the maximus extraction of phosphorus. These methods vary from each other in many aspects. Some of them are phosphorus yield, treatment cost, power requirement, carbon footprint, form of the recovered phosphorus and etc. therefore, these methods have to be evaluated using a universal list of criteria to find the method that suits best under a predetermined set of aspects. A literature review was carried out to find necessary data regarding the selected methods of phosphorus extraction. A number of methods have been developed for the objective and some of them are chemical hydrolysis, supercritical water gasification, struvite precipitation, bioleaching of sewage sludge, thermo-reductive treatment, thermochemical treatment, wet chemical treatment and electrodialysis of sewage sludge (Guedes et al., 2014; Egle, Rechberger and Zessner, 2015; Cieślik and Konieczka, 2017; Shiba and Ntuli, 2017; Amrullah and Matsumura, 2018; Gorazda et al., 2018; Semerci, Kunt and Calli, 2019). This study is carried out to check the viability of these methods for Sri Lanka as a sustainable solution for fertilizer crisis.

Eleven criteria have been selected for the evaluation and they have been selected considering the sustainable development goals published by United Nations in 'The 2030 agenda for sustainable development'. A number of MCDM tools and techniques were under consideration for the analysis and some of them were namely PROMETHEE, ELECTRE, DEXI, TOPSIS and etc. (Pohekar and Ramachandran, 2004; Huang, Keisler and Linkov, 2011). TOPSIS was selected as the MCDM technique for the study due to its versatility and applicability in the subject of waste management (Karimi et al., 2011; Yahya et al., 2020). After the mathematical analysis of collected data, they were interpreted graphically as well as numerically to obtain the desired results.

2. Materials and Methods

Methods to recover posphorus

Five methods were selected to recover phosphorus. They are supercritical water gasification (SCWG), struvite precipitation, thermochemical treatment of sewage sludge, wet chemical treatment of sewage sludge and electrodialysis of sewage sludge. The mentioned methods vary from each other in many aspects and they are discussed in the following section.

In the process of supercritical water gasification, dewatered sewage sludge is dried to reduce the water content further. The drying has to be done for 2 hours at 110 0C (Weijin et al., 2019). Then the dried sewage sludge is allowed to cool in air. Then the sludge is mixed with deionized water to acquire optimal solubility and concentration of soluble matter for the gasification process (Weijin et al., 2019). After that, formed slurry is sent into the gasification chamber where the temperature and pressure is maintained at 500 0C and 37 MPa respectively and it is kept in there for about 15 minutes (Weijin et al., 2019). The residue in the chamber after the completion of gasification is collected and it is left to cool. Then sulfuric acid is added to the residue at a solid-liquid ratio of 1:1000 (Acelas et al., 2014). The pH value of the medium is maintained at 2 to ensure the maximum yield of phosphorus as phosphoric acid and it is collected as the product in this process (Acelas et al., 2014). In the process of SCWG, no specific method is used to remove heavy metals from the sewage sludge and this has an impact on the environment.

In the process of struvite precipitation, first of all dewatered sewage sludge is leached using sulfuric acid and the ratio is 100 ml of 1M sulfuric acid for 1g of sewage sludge (Shiba and Ntuli, 2017). Then it is left to settle for 2 hours (Shiba and Ntuli, 2017) and then it has to be filtered. The leachate has to be treated to remove heavy metal content and this is done using Bentonite (Egle et al., 2016; Shiba and Ntuli, 2017; Li et al., 2019). Then magnesium and nitrogen have to be added externally to precipitate struvite which is Mg.NH4.PO4 and magnesium and nitrogen are added as magnesium chloride and ammonium hydroxide respectively (Cieślik and Konieczka, 2017; Shiba and Ntuli, 2017).

In the process of thermochemical treatment, dewatered sewage sludge is incinerated in a muffle furnace at a temperature of 800 - 1000 0C for two hours(Yang et al., 2019). Then the ash is grinded and sieved. Then magnesium chloride is added to the sieved ash as 10g of magnesium chloride per 1kg of ash (Yang et al., 2019) and then the mixture is incinerated again in a muffle furnace again at a temperature of 800 - 1000 0C for two hours to remove heavy metals (Yang et al., 2019). Then again the residue is grinded and sieved to get magnesium phosphate as the product (Jeon and Kim, 2018; Yang et al., 2019). Residue after sieving is again sent to the grinder. This is a costly and complex process compared to other processes. Two incinerations produce a considerable amount of flue gas while second incineration removes heavy metals as chlorides. Even though this is a costly process, it has a high phosphorus yield.

Wet chemical treatment of sewage sludge is another method recover phosphorus from sewage sludge which seems to be suitable for Sri Lanka. In this process, sewage sludge is incinerated in a muffle furnace at a temperature of 800 - 1000 0C for two hours (Yang et al., 2019) and then it is treated with sulfuric acid as 300-500 g of acid per 1kg of ash(Liang et al., 2019). Then the solution is filtered to separate the leachate and the leachate is treated using bentonite to remove heavy metal contamination. After that the leachate is mixed with magnesium chloride and ammonium hydroxide with a molar ratio of 1:1:1 (Liang et al., 2019) to precipitate Struvite (Liang et al., 2019).

In the process of electrodialysis, sewage sludge is incinerated to obtain sewage sludge ash. Sludge is incinerated at a temperature of 800 – 1000 0C for two hours (Guedes et al., 2014). Then it is mixed with 0.08 M sulfuric acid at a mass: volume ratio of 1:10 (Guedes et al., 2014). An electrodialysis cell with two platinum coated electrodes, a stirrer and 0.01 M sodium nitrate mixed with nitric acid at 1:1 ratio has been selected for the experiment (Guedes et al., 2014). Nitric acid is used to fix the pH value at 2 (Guedes et al., 2014). Then the solution is electrolyzed for 14 days with a current of 199 mA (Guedes et al., 2014) and phosphoric acid is the final product of the process.

A. Evaluated criteria

Eleven criteria have been selected according to the UN's sustainable development goals and weights have been assigned to the selected criteria according to the considered scenario. Table 1 shows the list of criteria along with assigned weights. Assignment of the weights for the respective criteria was carried out by considering their importance for the respective scenario. The baseline weight was taken as 1 and it was changed increasing or decreasing according to the scenario. This was done to obtain a better impact from each criterion on various situations.

Table 1- Selected criteria and their weights

Criterion	Equal weight	Environment conservation	Profitability	Fertilizer applicability
P yield	1	0.5	1.7	0.8
Cost to treat 1g of SS	1	0.5	1.7	0.3
Estimated income per 1g of SS	1	0.5	1.7	0.3
Energy consumption	1	1.5	1.3	0.3
Carbon footprint	1	1.8	0.3	0.2
Approximate time for 1 batch	1	0.2	1.3	0.3
Fertilizer suitability	1	1.3	1.0	1.5
Heavy metal content	1	1.4	0.5	1.2
Chance of mechanical failure	1	0.2	1.0	0.1
Noise impact	1	1.0	0.2	0.1
Technical complexity	1	0.2	0.7	0.1

B. Technique of order of preference by similarity to ideal solution (TOPSIS)

TOPSIS has been selected as the tool for the Multi-Criteria Decision Analysis technique. In TOPSIS, the calculations are carried out as shown below and the ranking is done according to the performance scores obtained.

Normalization of matrix.

Table 2- Decision matrix

Criteria	Supercritical water gasification	Precipitation	Incineration with chloride	Wet chemical treatment	Electrodialysis
P yield (mg/1g SS)	32.3	20.4	33.32	29.92	23.7
Cost to treat 1g of SS (LKR)	27.35	2.86	106.10	51.03	49.80
Estimated income per 1g of SS (LKR)	0.005	0.000003	0.02	0.000004	0.004
Energy consumption (kWh/1g SS)	4.68	0.37	10.68	5.18	4.56
Carbon footprint (kg CO2/ 1g SS)	3.32	0.26	8.68	4.78	4.33
Approximate time for 1 batch (hr)	12	7	5	9	336
Fertilizer suitability (5- max 1- least)	1	5	3	5	1
Heavy metal content (1- high 0-low)	1	0	0	0	0
Chance of mechanical failure (3- high 2- medium 1- low)	2	1	3	2	1
Noise impact (2-high 1- medium 0- low)	1	0	2	1	1
Technical complexity (2-high 1- medium 0- low)	2	0	2	1	1

$$\bar{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_1^j {X_{ij}}^2}}$$

where,

$\bar{X}_{ij}$= Normalized value of ith criterion of jth method.

X_{ij}= Value of ith criterion of jth method.

Calculation of Euclidian distances

Two parameters named as ideal best value and ideal worst value is extracted from the matrix after normalizing and weighing. If the considered criterion affects positively on the analysis (i.e profit), the highest value in the row is taken as ideal best value (V_{ij}^+) and the lowest value in the row is taken as ideal worst value (V_{ij}^-). If the considered criterion's effect is negative (i.e cost), lowest value in the row is taken as ideal best value and the highest value in row is taken as the ideal worst value.

After selecting ideal values, respective Euclidean distances are calculated according to following equations.

$$S_j^+ = \sqrt{\sum_1^i (V_{i1} - V_i^+)^2}$$

$$S_j^- = \sqrt{\sum_1^i (V_{i1} - V_i^-)^2}$$

where,

S_j^+- positive Euclidean distance

S_j^-- negative Euclidean distance

Calculation of performance score,

$$P_j = \frac{S_j^-}{S_j^+ + S_j^-}$$

C. *Collected data*

Table 2 shows all the data collected through a literature survey and necessary calculations.

3. Results and Discussion

A. *Results of TOPSIS*

Figure 1 shows the normalized matrix of collected data which provides an idea of the behavior of the selected methods of phosphorus recovery.

Figure 2 shows the performance score variation obtained from the TOPSIS analysis.

B. *Discussion*

As shown in Figure 2, struvite precipitation provides better results over other 4 methods in each scenario. When the environment friendly scenario is considered, precipitation is advantageous over other 4 methods due to negligible energy consumption, noise impact, carbon footprint and heavy metal removal. Due to those reasons, struvite precipitation outperforms other methods in environment friendly scenario. It outperforms other methods in profitability and fertilizer applicability too. However, in those scenarios,

precipitation does not show a massive margin.

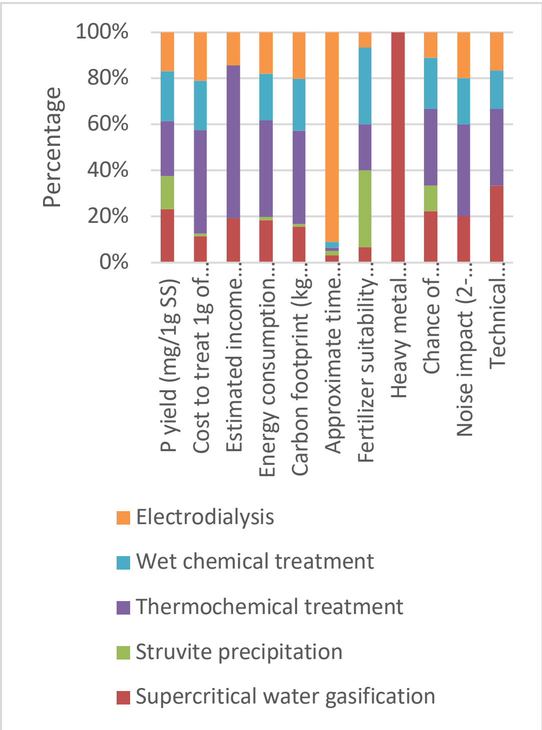

Figure 1- Performance scores comparison

When it comes to fertilizer applicability, precipitation is on par with wet chemical treatment. According to fig. 2, precipitation slightly outperforms other methods in terms of profitability. Even though the expected income per 1g of sewage sludge is very small, this method has the upper hand due negligible cost and power consumption alongside with lower chance of mechanical failures.

When the process of supercritical water gasification is considered, that it provides a strong performance score only in the profitability scenario. When it comes to profitability, SCWG is the second-best option after precipitation. This happens due to the low cost of operation, relatively low energy consumption and relatively high phosphorus yield. The effect of these criteria can be seen from fig. 1.

SCWG underperforms badly in other 3 scenarios while producing worst performance score in the fertilizer applicability scenario. This happens due to the formation of phosphoric acid as the product of process. Phosphoric acid is not used as a fertilizer but it is used to manufacture fertilizers. Therefore, this could be useful if plans are laid to manufacture phosphorus fertilizers using phosphoric acid. When it comes to environment friendly scenario, SCWG can be seen at the bottom position. This happens due to the heavy metal contamination and the energy consumption.

Thermochemical treatment stands at the third place when it comes to the equal weight scenario while underperforms on environment friendly scenario. This happens due to the high-power consumption, high carbon footprint and high noise impact. Even fig. 1 shows that thermochemical treatment has a higher impact on environment related criteria.

When it comes to profitability and fertilizer applicability, thermochemical treatment sits in a strong position. This happens due to high phosphorus yield, high income per 1g of sewage sludge, low time of operation and low heavy metal content. Thermochemical treatment provides magnesium phosphate as the final product. This is used as a fertilizer (Li et al., 2018; Luo et al., 2020) and therefore thermochemical treatment gets placed into a stronger position compare to electrodialysis and SCWG.

When wet chemical treatment is considered, it becomes a strong competitor for struvite precipitation when it comes to fertilizer applicability. This happens due to the heavy metal removal and the production of struvite as the final product. According to fig. 2, wet chemical treatment sits only behind precipitation when it comes to equal weight scenario and environment friendly scenario. Wet chemical treatment outperforms SCWG, thermochemical treatment and electrodialysis in the environment friendly scenario due to substantially lower energy consumption, carbon footprint and noise impact.

When the terms of profitability are considered, wet chemical treatment underperforms due to the lower income, higher chance of mechanical failures and moderate cost, energy consumption and technical complexity.

When electrodialysis is considered, according to fig. 2 the process underperforms in terms of profitability. Major reason for this is the high operating time. Longer operating period has erased the benefit of having moderate cost, phosphorus yield, energy consumption and lower chance of mechanical failure. Electrodialysis sits on 4th place not only in the fertilizer applicability scenario, but also in the unbiased analysis. Even though electrodialysis produces phosphoric acid as the final product, it has gained a significant lead from SCWG in terms of fertilizer applicability due to the removal of heavy metals. Electrodialysis has proved to be a competitor in terms of environment friendly scenario. It sits on the 3rd place after precipitation and wet chemical treatment due to lower noise impact, carbon footprint, energy consumption and heavy metal removal.

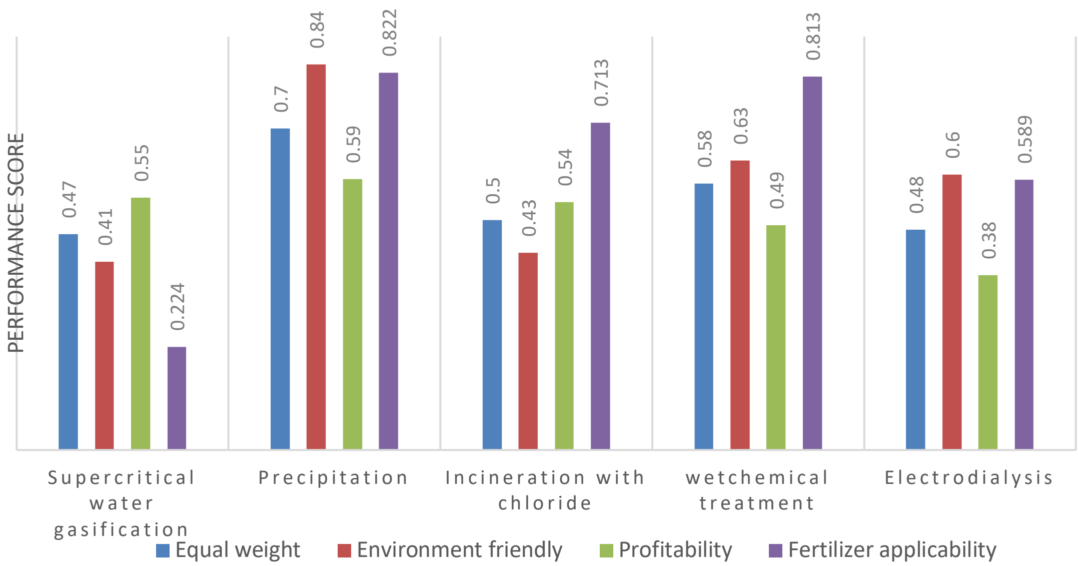

Figure 2- Normalized matrix of data

4. Conclusion

Five methods which were selected from a pool of methods to recover phosphorus from sewage sludge formed during the wastewater treatment process were evaluated using a multi-criteria decision analysis technique to determine the most suitable method to Sri Lanka. 11 criteria were selected according to the sustainable development goals imposed by UN and the analysis was carried out using TOPSIS multicriteria decision-making technique.

Analysis was done considering 4 different scenarios where the weights of the criteria were changed according to the scenario and the results were generated for the comparison to choose the method which is most suitable for Sri Lanka. According to the results, struvite precipitation stood above all other methods in each scenario. This happens due to low energy consumption, heavy metal removal during the process, zero emission of flue gases, relatively low use of machinery and the formation of struvite as the final product.

Even though precipitation stands as the most suitable method, more studies are essential since the requirement of land, uses of alternative products such as phosphoric acid are not included in the multi-criteria analysis. Inclusion of those parameters might provide a more accurate result when it comes to real world feasibility assessment.

After considering results, it is fair to say that the research hypothesis, which is most suitable and feasible method to recover phosphorus fertilizer from sewage sludge which is generated in municipal wastewater treatment plants in Sri Lanka can be selected by considering multiple criteria, is true and acceptable.

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