Index No: ES-18-50

Techno-Economic Assessment of Struvite Phosphorus Recovery from Sewage Sludge Treatment in Sri Lanka

Thejanie Jayasekara (1st Author)
Department of Chemical and Process Engineering
University of Moratuwa
Katubedda, Sri Lanka
thejaniej@uom.lk

Mahinsasa Rathnayake (2nd Author)
Department of Chemical and Process Engineering
University of Moratuwa
Katubedda, Sri Lanka
mratnayake@uom.lk

***Abstract* — Phosphorous is a nutrient that is considerably available in treated sludge coming out from municipal sewage treatment. In conventional sewage treatment plants, a larger portion of phosphorous remains unrecovered in the treated sludge. In this study, the techno-economic feasibility of phosphorous recovery in the form of struvite from treated sewage sludge is assessed for an already functioning sewage treatment plant in Sri Lanka. For comparative assessment between possible struvite phosphorous recovery technologies, two scenarios are considered, i.e., Scenario (A): wet chemical method with incineration and Scenario (B): wet chemical method without incineration. Composition data of treated sewage sludge is obtained from an existing sewage treatment plant, and design data for conceptualized struvite phosphorous recovery processes are retrieved from the published literature. According to the assessment results, scenario (A) provides a greater phosphorous recovery of 16.2 kg/day. However, the total energy consumption of 50,907.04 MJ/day in Scenario (A) is approximately six times higher than that of Scenario (B). The economic parameters, as well as the freshwater eutrophication impact reduction potentials for both scenarios are further analyzed. The most appropriate struvite phosphorous recovery technology for an existing or future sewage treatment plant in terms of techno-economic aspects are discussed.**

Keywords* — *Struvite phosphorous recovery, Sewage sludge treatment, Techno-economic assessment

I. INTRODUCTION

Phosphorous is an essential element for food production and agricultural industry which cannot be replaced by other elements. Phosphorous is generally produced from natural phosphate rocks that exist in the form of P_2O_5, corresponding to almost 7,000 million tonnes of world reserves [1]. The major application of globally mined phosphate rocks (accounting for 80% in quantity) is fertilizer production [2]. Even though global phosphorous demand is rapidly increasing due to the expansion of agri-food production, it is arguab about the existence of phosphorous reserves as it is estimated that currently minable phosphorous resources only last for

next 50-100 years [3]. With this resources limitation, agricultural industry and food production would be in a huge risk that enforces the inevitable requirement of alternative phosphorous-based sources for fertilizer production. Thus, it is essential to develop sustainable methodologies for phosphorous recovery from possible waste materials that do not induce excessive resources depletion.

Sewage sludge is defined as a semi-solid fluid with around 20% of solids and 80% of water content, which is produced in large quantities as a by-product from municipal wastewater treatment processes [4]. Further, sewage sludge is a rich organic source of phosphorous and other nutrients, such as calcium, aluminum, potassium, and sodium. Therefore, proper nutrient recovery is required due to the possibility of eutrophication if treated sewage sludge is disposed of without nutrient recovery. Moreover, the recovered phosphorous and other nutrients from sewage sludge can be converted to value added products, including fertilizers and organic acids which could create business opportunities with additional revenue generation from waste. Around 90% of phosphorous composition available in sewage sludge is in the solid part of the sludge. Hence, the sludge solid is required to process before converting into valuable products and releasing the treated sludge into the environment [5].

Recovery of phosphorous as struvite from sewage sludge provides a sustainable phosphorous source as other available waste sources of phosphorous, including bone meal, animal manure, etc. are insufficient in available quantities to cater the current phosphorous demand [6]. Struvite is magnesium ammonium phosphate ($MgNH_4PO_4$), and it forms a hard crystalline deposit when the molar ratio of Mg: NH_4: PO_4 becomes greater than 1: 1: 1 [7]. Several methods are available to treat sewage sludge and to recover phosphorous from sludge solids, including biological treatment method, wet-chemical treatment method, and incineration method [8]. Even though these technologies have been practiced all around the world, no such study is reported or a real phosphorous recovery plant is unavailable in the Sri Lankan context. Thus, it is necessary to evaluate the applicability of such technologies in Sri Lanka concerning the techno-economic approach before implementing struvite phosphorous recovery for sewage sludge treatment.

Hence, this paper focuses on the technical and economic feasibility assessment for application of struvite phosphorous recovery technologies by selecting an already functioning sewage treatment plant in Sri Lanka as the case study. This study would support future policy decision making for the implementation of possible struvite phosphorous recovery plant facilities for sewage treatment plants that improve sustainable waste management in the country.

II. OBJECTIVES

This study aims at the goals and objectives as follows.

- Determination of the level of phosphorous availability in thickened sewage sludge from a selected sewage treatment plant in Sri Lanka.
- Theoretical evaluation of the phosphorous recovery potential from a selected sewage treatment plant in Sri Lanka and related techno-economic feasibility.
- Evaluation of eutrophication impact reduction potential by struvite phosphate recovery from sewage sludge.

III. METHODOLOGY

A. Raw data collection from sewage sludge treatment

An already functioning sewage treatment plant in Sri Lanka was selected as the sampling location to obtain quality parameters of influent (raw sewage) and effluent (wastewater). This plant has a capacity of 17,000 m^3/day with 6000 m^3 of generated wastewater per day. Parameters, including Biological Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), total phosphorous, and total nitrogen were basically considered as the raw data to be collected considering a reasonable time period to include parameter variations.

Table 1 lists the obtained quality parameters of influent and effluent flows of the selected sewage treatment plant. The corresponding influent and effluent quality parameter values were utilized for calculations as necessary.

Table 1. Influent and effluent quality parameters of sewage treatment

Parameter	Unit	Influent (Raw sewage)	Effluent (Treated water)
BOD_5	mg/l	99	3.6
COD	mg/l	260	42
Total phosphorus	mg/l	2.7	0.71
Total nitrogen	mg/l	54	12
Total suspended solid	mg/l	340	6.3

B. Conceptual design of struvite recovery

A process flow diagram with the conceptual design of a struvite recovery plant was developed studying the existing process of sewage treatment. According to the current practice, raw sewage is first subjected to a primary treatment process applying gravity separation, then biologically treated by the activated sludge process as the secondary treatment. Therefore, to evaluate the feasibility of the use of phosphorous recovery, the conceptually designed struvite recovery plant was placed in between the secondary treatment process and discharge of sludge into the environment. For identification of the most suitable conceptual design, a qualitative comparison was carried out among the currently practicing methodologies for the struvite phosphorous recovery in the published literature concerning its suitability to establish for the Sri Lankan context. Accordingly, the wet chemical treatment method was identified as the widely applied struvite recovery method from sewage sludge [8]. Moreover, the effect of incineration before the wet chemical treatment method was also identified as important to study. Hence, a scenario-based conceptual design and techno-economic assessment was conducted in this study.

C. Scenario description

Two scenarios were developed for struvite recovery from the wet chemical treatment method with and without incineration, i.e., Scenario (A): wet-chemical treatment of secondary sewage sludge after thickening and incineration, Scenario (B): wet-chemical treatment of secondary sewage sludge without incineration.

Material and energy flow calculations were performed for the selected two scenarios, including detailed calculations for individual unit processes, i.e., sewage sludge thickening decanter, precipitation reactor, and struvite dryer units. Each unit process is considered to be operated under the ambient conditions.

In the considered two scenarios, dewatered sludge undergoes wet chemical treatment and incineration according to the stoichiometrically balanced chemical reactions given by Equation (1) and Equation (2), respectively.

$$\text{Dewatered sludge} \rightarrow Mg^{2+} + NH_4^+ + PO_4^{3+} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O \text{ (struvite)} \quad (1)$$

$$\text{Dewatered sludge} \rightarrow \text{Ash} \rightarrow Mg^{2+} + NH_4^+ + PO_4^{3+} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O \text{ (struvite)} \quad (2)$$

The initial design parameter values were considered for mass and energy flow calculations of unit processes in the conceptual struvite recovery process based on the published literature. Table 2 lists the considered design parameters for the struvite recovery process.

Table 2. Design parameters for struvite recovery process

Parameter	Unit	Value	Reference
Phosphate concentration	mg/l	190	[9]
pH value	-	8.7	[10]
Magnesium concentration	mg/l	67	[9]
Conversion (%)	-	90	[10]
Reaction time	hours	7.9	[10]
Moisture content of filtered struvite	g water /g dry solids	1.5	[10]

All the detailed calculations were carried out with the aid of a MS excel model. Equipment sizing was also computed and obtained resultant values are presented under the Results and Discussion.

D. Freshwater eutrophication impact assessment

The freshwater eutrophication impact due to unrecovered phosphorous that could be released to the environment from conventional sewage sludge treatment without struvite recovery was evaluated. The eutrophication impact reduction through struvite phosphorous recovery in sewage sludge treatment was calculated by comparison of the eutrophication impact due to unrecovered phosphorous in the scenario A and B with respect to that of conventional sewage sludge treatment. Freshwater eutrophication impact was calculated with the aid of Equation (3), and results are given by the unit of kg P equivalents.

$$\text{Freshwater eutrophication impact} = EP_i \times m_i \quad (3)$$

Where, m_i = Eutrophication potential of substance i.

The ReCiPe world (H) V1.12 impact assessment method in the SimaPro Life Cycle Assessment (LCA) software was used to retrieve the mid-point characterization factors required for the freshwater eutrophication impact calculations.

E. Economic assessment

In the economic assessment of the conceptual struvite recovery process, capital expenditure for the integration (CAPEX), operating expenditure (OPEX), revenue from struvite production (revenue) were considered to evaluate the economic feasibility of the considered two scenarios, in a comparative manner. Equations (4), (5), and (6) were applied to calculate CAPEX, OPEX, and revenue, respectively.

CAPEX=(Property, plant, and equipment at the end of the year – Property, plant, and equipment at the Beginning of year) + Depreciation expense (4)

OPEX=Operating Expense = Salaries + Sales Commissions +Promotional & Advertising Cost + Rental Expense + Utilities (5)

Revenue from struvite production=Sales ×Average price of sales (6)

Table 3 lists the selected economic data and parameter values for the economic assessment of the two considered scenarios. One US Dollar (USD) was considered to be equivalent to 200 Sri Lankan Rupees (LKR) in the economic calculations.

Table 3. Economic data and parameter values required for economic assessment

Parameter	Unit	Value	Reference
Cost of land	USD per square rod	3,303.96	Estimated
Monthly labor wages	USD per person	165.2	Estimated
Tariff rate	USD/kWh	0.074	[11]
Magnesium Chloride price	USD/kg	0.22	[12]
Ammonium Chloride price	USD/kg	0.14	[13]
Market price of Kerosine	USD/l	0.86	[14]
Market price of struvite	USD/tonne	1061.11	[15]

IV. RESULTS AND DISCUSSION

A. Mass and energy flow results

Table 4 indicates the mass and energy flow results obtained for the individual unit processes in Scenario (A) and Scenario (B) of the conceptualized struvite recovery process.

Table 4. Mass and energy flow results of unit processes in Scenario (A) and Scenario (B)

Unit process	Mass/energy flow parameter	Unit	Scenario (A)	Scenario (B)
Sewage sludge thickening decanter	Phosphate concentration in the output	mg/l	1,080	190
	Wastewater flow rate	m^3/day	15	63.08
	Power consumption	kW	12.45	1.9
Precipitation reactor unit	Struvite production	kg/day	55.4	38.81
	Ammonia requirement	kg/day	4.28	3.17
	Magnesium requirement	kg/day	5.71	4.22
	Design flow rate	m^3/day	90	70
	Phosphorous availability	kg/day	16.2	11.98
	Power consumption of agitators	kW	1.1	0.81
Struvite dryer unit	Output flow rate of sewage sludge	m^3/day	4.26	3.15
	Power consumption	kW	126.88	93.83

According to the material flow results listed in Table 4, struvite production in Scenario (A) (i.e., 55.4 kg/day) is greater than that of Scenario (B) (i.e., 38.81 kg/day). In Scenario (A), incineration of treated sewage sludge before struvite recovery helps to get rid of harmful substances, such as pharmaceutical residues, multi-resistant bacteria, microplastics, and harmful organic substances that would inhibit phosphorous recovery [16]. This could be the main reason for the considerable increase of struvite production capability of incinerated sewage sludge in Scenario (A) than non-incinerated sewage sludge in Scenario (B). In contrast, total energy consumption of the unit processes in Scenario (A) is far greater than that of Scenario (B). Table 5 reports the energy flow results of each unit process in the conceptualized struvite recovery process.

Table 5. Energy consumption of unit processes in Scenario (A) and Scenario (B)

Unit Process	Unit	Scenario (A)	Scenario (B)
Sludge thickening decanter	MJ/day	1,075.68	164.16
Precipitation reactor unit	MJ/day	95.04	69.98
Struvite dryer	MJ/day	11,165.32	8,270.84
Incinerator	MJ/day	38,571.00	0.00
Total	MJ/day	50,907.04	8,504.98

According to the energy consumption results indicated in Table 5, sludge thickening decanter in Scenario (A) consumes 1,075.68 MJ/day which is around seven times greater than that of Scenario (B) (i.e., 164.16 MJ/day). Further, energy consumption of the precipitation reactor unit in Scenario (A) (i.e., 95.04 MJ/day) is slightly greater for that of the same unit process in Scenario (B) (i.e., 69.98 MJ/day). Similarly, struvite dryer in Scenario (A) also consumes more energy (i.e., 11,165.32 MJ/day) than the struvite dryer in Scenario (B) (i.e., 8.270.84 MJ). Thus, Scenario (A) exhibits a clear increase in energy consumption in all unit processes compared with energy consumption of Scenario (B). The requirement of sludge thickening at a higher level in the decanter, high extent of reaction in the precipitation reactor, and the lowered dry matter content for the struvite dryer in Scenario (A) would be the potential reasons for the increment of energy consumption than of Scenario (B) [17]. Moreover, energy requirement for the incineration process in Scenario (A) is significantly higher which is not applicable for Scenario (B). Therefore, the total energy consumption of the conceptualized struvite recovery process in Scenario (A) is extensively higher than the total energy consumption of Scenario (B).

Fig. 1 illustrates the contribution of unit processes for the total energy consumption in Scenario (A) and Scenario (B).

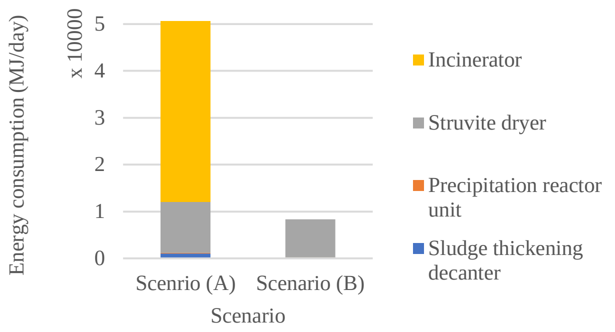

Fig. 1. Contribution of unit processes for total energy consumption in Scenario (A) and Scenario (B)

Fig.1 clearly depicts the huge difference in total energy consumption in Scenario (A) compared with Scenario (B). In consideration of energy consumption by each unit process, the sludge thickening decanter and precipitation reactor units have very low share of energy consumption. However, energy consumptions of drying units in both scenarios are significant and almost contributes to the total energy consumption of Scenario (B). In addition, energy consumption of the incineration unit in Scenario (A) is far greater compared to the other unit processes in the conceptualized struvite recovery plant. Elevated process energy consumption implies a higher quantity of associated environmental emissions as well as increased operating cost that would affect the sustainability of a process. Therefore, Scenario (B) with significantly lower energy consumption is preferrable for struvite recovery from sewage sludge even though the amount of struvite recovery is comparatively higher in Scenario (A).

B. *Economic assessment results*

Table 5 shows the results obtained for the economic parameters, including CAPEX, OPEX, and revenue of Scenario (A) and Scenario (B).

Table 5. Economic assessment results of Scenario (A) and Scenario (B)

Economic parameter	Unit	Scenario A	Scenario B
CAPEX	USD/year	256,085.18	76,332.28
OPEX	USD/year	188,730.55	13,859.05
Revenue	USD/year	21,458.35	15,030.70

According to the economic parameter results, it is obvious that the annual revenue from the struvite recovery in Scenario (A) (i.e., USD 21,458.35) is around one-third greater than the annual revenue from struvite phosphorous recovery in Scenario (B) (i.e., USD 15,030.70). The significant increase in revenue is due to the enhancement of phosphorous recovery in Scenario (A) compared to that of Scenario (B). Nevertheless, other economic parameters including, CAPEX and OPEX are tremendously higher in Scenario (A). CAPEX of Scenario (A) is USD 256,085.18 per year which is almost three times that of Scenario (B) (i.e., USD 76,332.28 per year).

Similarly, OPEX in Scenario (A) shows a drastic rise indicating USD 188,730.55 per year which is nearly thirteen times greater than that in Scenario (B) (i.e., USD 13,859.05 per year). This is resulted mainly because of the cost of capital equipment required and the operating expenses associated with the greater energy consumption for the incineration process and other unit processes in Scenario (A).

Fig. 2 illustrates comparison of economic parameters in Scenario (A) and Scenario (B) in graphical mode.

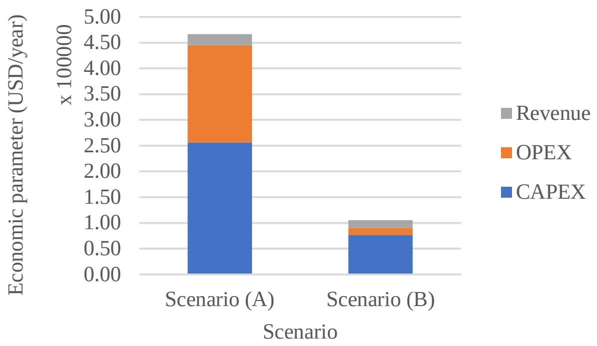

Fig. 2. Economic parameters of Scenario (A) and Scenario (B)

According to the graph, the greatness of CAPEX and OPEX with respect to revenue in Scenario A is obvious in comparison to Scenario B. Therefore, Scenario B is preferable for struvite phosphorous recovery from sewage sludge in terms of techno-economic perspective.

C. Freshwater eutrophication impact assessment results

Table 6 shows the calculated freshwater eutrophication impact results for the case of conventional sewage treatment, and struvite phosphorous recovery scenarios, i.e., Scenario (A) and Scenario (B). In conventional sewage treatment, there is no phosphorous recovery from treated sewage sludge that would cause freshwater eutrophication impact when discharged to the environment. In Scenarios (A) and (B) with struvite phosphorous recovery, the unrecovered phosphorous due to the recovery efficiency of the respective technology can cause the freshwater eutrophication impact.

Table 6. Freshwater eutrophication impact results

Description	Freshwater eutrophication impact (kg of P eq.)
Conventional sewage treatment	17.10
Scenario (A)	0.90
Scenario (B)	5.12

According to the results in Table 6, both scenarios (A) and (B) with struvite phosphorous recovery have significantly reduced freshwater eutrophication impact values compared with the impact of the conventional sewage treatment without phosphorous recovery. Fig.3 illustrates the freshwater eutrophication impact reduction potentials of Scenarios (A) and (B) in graphical form.

As depicted in Fig.3, Scenario (A) has the highest freshwater eutrophication impact reduction potential that corresponds to nearly 95%. However, Scenario (B) is also capable of reducing freshwater eutrophication impact by around 70% via struvite phosphorous recovery. In overall consideration of trade-off among material and energy consumption, revenue/expenses difference, and environmental impact reduction, Scenario (B) surpasses Scenario (A) in this techno-economic assessment. Therefore, struvite phosphorous recovery using the wet chemical method without incineration (i.e., Scenario (B)) could be suggested as the most appropriate technology scenario for future phosphorous recovery integrated sewage treatment plants in Sri Lanka.

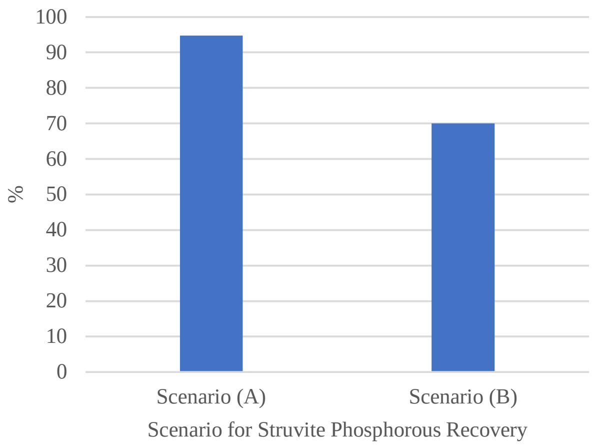

Fig.3. Freshwater eutrophication impact reduction potentials of Scenarios (A) and (B)

V. CONCLUSION

In this study, a techno-economic assessment was conducted considering material and energy utilization, economic analysis, and environmental benefit of two technology scenarios for struvite phosphorous recovery from treated sewage sludge. The findings from this study reveal that the wet chemical method with incineration provides enhanced struvite phosphorous recovery. In contrast, overall comparison of techno-economic aspects demonstrates the appropriateness of the wet chemical method without incineration for struvite phosphorous recovery. Accordingly, the results from this assessment conclude that further treatment of conventionally treated sewage sludge for struvite phosphorous recovery is feasible and beneficial for existing sewage treatment plants. Thus, this assessment would support future decision making for implementation of new sewage treatment plants or modification of existing sewage treatment plants with struvite phosphorous recovery.

REFERENCES

[1] D. B. Colleti, B. Chavel, and W. J. Gatti, “Challenges of skew in D. Seyhan, "Country-scale phosphorus balancing as a base for resources conservation", *Resources, Conservation and Recycling*, vol. 53, no. 12, pp. 698-709, 2009. Available: 10.1016/j.resconrec.2009.05.001.

[2] L. Shu, P. Schneider, V. Jegatheesan and J. Johnson, "An economic evaluation of phosphorus recovery as struvite from digester supernatant", *Bioresource Technology*, vol. 97, no. 17, pp. 2211-2216, 2006. Available: 10.1016/j.biortech.2005.11.005.

[3] Y. Liu, J. Chen, A. Mol and R. Ayres, "Comparative analysis of phosphorus use within national and local economies in China", *Resources, Conservation and Recycling*, vol. 51, no. 2, pp. 454-474, 2007. Available: 10.1016/j.resconrec.2006.10.012.

[4] S. Baroutian, N. Eshtiaghi and D. Gapes, "Rheology of a primary and secondary sewage sludge mixture: Dependency on temperature and solid concentration", *Bioresource Technology*, vol. 140, pp. 227-233, 2013. Available: 10.1016/j.biortech.2013.04.114.

[5] C. Blöcher, C. Niewersch and T. Melin, "Phosphorus recovery from sewage sludge with a hybrid process of low pressure wet oxidation and nanofiltration", *Water Research*, vol. 46, no. 6, pp. 2009-2019, 2012. Available: 10.1016/j.watres.2012.01.022.

[6] "Scientists Warn of Lack of Vital Phosphorus as Biofuels Raise Demand - Schwartzreport", *Schwartzreport*, 2021. [Online]. Available: https://www.schwartzreport.net/2008/06/24/scientists-warn-of-lack-of-vital-phosphorus-as-biofuels-raise-demand/. [Accessed: 10- Nov-2021].

[7] Y. Jaffer, T. Clark, P. Pearce and S. Parsons, "Potential phosphorus recovery by struvite formation", *Water Research*, vol. 36, no. 7, pp. 1834-1842, 2002. Available: 10.1016/s0043-1354(01)00391-8.

[8] M. Sikosana, D. Randall and H. Von Blottnitz, "A technological and economic exploration of phosphate recovery from centralised sewage treatment in a transitioning economy context", *Water SA*, vol. 43, no. 2, p. 343, 2017. Available: 10.4314/wsa.v43i2.17.

[9] P. van Rensburg, E. Musvoto, M. Wentzel and G. Ekama, "Modelling multiple mineral precipitation in anaerobic digester liquor", *Water Research*, vol. 37, no. 13, pp. 3087-3097, 2003. Available: 10.1016/s0043-1354(03)00173-8.

[10] M. Rahman, M. Salleh, U. Rashid, A. Ahsan, M. Hossain and C. Ra, "Production of slow release crystal fertilizer from wastewaters through struvite crystallization – A review", *Arabian Journal of Chemistry*, vol. 7, no. 1, pp. 139-155, 2014. Available: 10.1016/j.arabjc.2013.10.007.

[11] A. Dzyuba and I. Solovyeva, "PRICE-BASED DEMAND-SIDE MANAGEMENT MODEL FOR INDUSTRIAL AND LARGE ELECTRICITY CONSUMERS", *International Journal of Energy Economics and Policy*, vol. 10, no. 4, pp. 135-149, 2020. Available: 10.32479/ijeep.8982.

[12] "Buy 99 Anhydrous Magnesium chloride mgcl2 white in China on Alibaba.com", *Alibaba.com*, 2021. [Online]. Available: https://www.alibaba.com/product-detail/99-Anhydrous-Magnesium-chloride-mgcl2-white_62459136551.html. [Accessed: 10- Nov- 2021].

[13] "Buy Ammonium Chloride 99 5 min in China on Alibaba.com", *Alibaba.com*, 2021. [Online]. Available: https://www.alibaba.com/product-detail/Ammonium-Chloride-99-5-min_62152385558.html. [Accessed: 10- Nov- 2021].

[14] "Kerosene prices around the world, 08-Nov-2021 | GlobalPetrolPrices.com", *GlobalPetrolPrices.com*, 2021. [Online]. Available: https://www.globalpetrolprices.com/kerosene_prices/. [Accessed: 10- Nov- 2021].

[15] D. Kok, S. Pande, J. van Lier, A. Ortigara, H. Savenije and S. Uhlenbrook, "Global phosphorus recovery from wastewater for agricultural reuse", *Hydrology and Earth System Sciences*, vol. 22, no. 11, pp. 5781-5799, 2018. Available: 10.5194/hess-22-5781-2018.

[16] A. Bhasin, "Recovery of Phosphorus from Incineration of Sewage Sludge", Degree project in Chemical Science and Engineering, second cycle, KTH Royal Institute of Technology School of Chemical Science and Engineering, 2017.

[17] D. Đurđević, P. Blecich and Ž. Jurić, "Energy Recovery from Sewage Sludge: The Case Study of Croatia", *Energies*, vol. 12, no. 10, p. 1927, 2019. Available: 10.3390/en12101927.