ENGineering and INdustry Innovative Training for Engineers (ENGINITE)

PROJECT NUMBER
2017-1-CY01-KA202-026728

B2 course

Engineering economics

Prepared by TUC

Co-funded by the Erasmus+ Programme of the European Union

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Contents

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1. Overview

This course emphasizes the economic principles and the analysis of engineering decisions. Thus, the strong relationship between engineering design and manufacturing of products/systems and the evolved economic aspects, along with applied concepts of the time value of money and equivalence, will be highlighted in the course. A real problem regarding the metal recovery from WWTPs sludge will be given to various groups and solutions that will take in to account both technological and economic aspects should be provided

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2. Key learning outcomes

Upon completion of the course, participants should be able to:

- Define, estimate and analyze engineering - industrial project costs.
- Compline creatively knowledge of mathematics, economics, and engineering principles to solve engineering industrial problems.
- Efficiently perform money management and use gained knowledge to make economic assessments of alternative engineering designs, solutions or projects.

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3. Problem-based learning scenario

You are the CEO of an international mining company that extract metals using the technology of hydrometallurgy-electrowinning. However, the company faces many difficulties due to the following reasons:

•The metal % in ore are declining (e.g. 2-3 % in 1950 and 0.3-0.8% in 2018)

•The metal extraction and recovery from ore is becoming more expensive and energy intensive.

•The metal mine resources are confined only in a few countries (and especially in Europe there are very few mines).

A possible source that has been little examined so far is the excess sludge from Wastewater Treatment Plant (WWTP). No excavation or rock processing is needed as it is a ready to be used material.

Your project is to find in which WWTPs from Europe the extraction of specific metal or metals could be beneficial. You should do: 1) An economic analysis, 2) You should specify which metal or metals will you target and 3) Which technologies will you employ.

You should take into account the metal concentration, the current price of metal, the lowest and highest metal price in the last 5 years and the amount of sludge that can be generated.

Find the profits of three different scenarios for small WWTP, medium and large WWTP and take in to account the cost of the organic solvent that you will used for this processes. The metals that can be recovered through hydrometallurgy-electrowinning are Cu, Zn, Ni, Co, Mo.

Investigate the relation between the price of metal, the concentration of metal and the tones of sludge or ash that the recovery could be profitable.

Proposed a strategy for sludge treatment after the metal extraction.

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4. Background information

- Mulchandani, A. & Westerhoff, P. (2016). Recovery opportunities for metals and energy from sewage sludges. *Bioresource technology*, *215*, 215-226.

Abstract

Limitations on current wastewater treatment plant (WWTP) biological processes and solids disposal options present opportunities to implement novel technologies that convert WWTPs into resource recovery facilities. This review considered replacing or augmenting extensive dewatering, anaerobic digestion, and off-site disposal with new thermo-chemical and liquid extraction processes. These technologies may better recover energy and metals while inactivating pathogens and destroying organic pollutants. Because limited direct comparisons between different sludge types exist in the literature for hydrothermal liquefaction, this study augments the findings with experimental data. These experiments demonstrated 50% reduction in sludge mass, with 30% of liquefaction products converted to bio-oil and most metals sequestered within a small mass of solid bio-char residue. Finally, each technology's contribution to the three sustainability pillars is investigated. Although limiting hazardous materials reintroduction to the environment may increase economic cost of sludge treatment, it is balanced by cleaner environment and valuable resource benefits for society.

- Pipi, A. R., Magdalena, A. G., Giafferis, G. P., da Silva, G. H., & Piacenti-Silva, M. (2018). Evaluation of metal removal efficiency and its influence in the physicochemical parameters at two sewage treatment plants. Environmental monitoring and assessment, 190(5), 263.

Abstract

In sewage treatment plants, physicochemical parameters are highly controlled since treated sewage can be returned to water bodies or reused. In addition, pollutants such as heavy metals also deserve attention due to their potential toxicity. In general, these characteristics of sewage and treated water are evaluated independently, with the support of Brazilian legislation that does not require a routine for the analysis of metals as frequent as for the physicochemical

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parameters. In this work, 66 samples of raw sewage, treated sewage, and effluents from two treatment plants in the city of Bauru, São Paulo, Brazil, were evaluated to assess the efficiency of the treatment plants in the removal of metals. In addition, the influence of these pollutants on the quantification of physicochemical parameters was evaluated. The quantification of metals was performed using inductively coupled plasma optical spectroscopy (ICP-OES), and Spearman's test was applied to evaluate correlation between physicochemical parameters and metal content. The main metals found in the samples were Ba, Mn, Zn, Cu, Se, Fe, and Al. The results indicate that concentrations of metals in the aquatic environment can significantly affect the physicochemical parameters, since high concentrations of metals can interfere mainly in the pH, chemical oxygen demand, and dissolved oxygen.

- Westerhoff, P., Lee, S., Yang, Y., Gordon, G. W., Hristovski, K., Halden, R. U., & Herckes, P. (2015). Characterization, recovery opportunities, and valuation of metals in municipal sludges from US wastewater treatment plants nationwide. *Environmental science & technology*, *49*(16), 9479-9488.

Abstract

U.S. sewage sludges were analyzed for 58 regulated and nonregulated elements by ICP-MS and electron microscopy to explore opportunities for removal and recovery. Sludge/water distribution coefficients (K_D, L/kg dry weight) spanned 5 orders of magnitude, indicating significant metal accumulation in biosolids. Rare-earth elements and minor metals (Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) detected in sludges showed enrichment factors (EFs) near unity, suggesting dust or soils as likely dominant sources. In contrast, most platinum group elements (i.e., Ru, Rh, Pd, Pt) showed high EF and K_D values, indicating anthropogenic sources. Numerous metallic and metal oxide colloids (<100–500 nm diameter) were detected; the morphology of abundant aggregates of primary particles measuring <100 nm provided clues to their origin. For a community of 1 million people, metals in biosolids were valued at up to US$13 million annually. A model incorporating a parameter ($K_D \times$ EF × $Value) to capture the *relative potential for economic value from biosolids* revealed the identity of the 13 most lucrative elements (Ag, Cu, Au, P, Fe, Pd, Mn, Zn, Ir, Al, Cd, Ti, Ga, and Cr) with a combined value of US $280/ton of sludge.

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- Kudakwashe K. Shamuyarira and Jabulani R. Gumbo (2014). Assessment of Heavy Metals in Municipal Sewage Sludge: A Case Study of Limpopo Province, South Africa. *Int. J. Environ. Res. Public Health* 11: 2569-2579

Abstract

Heavy metals in high concentrations can cause health and environmental damage. Nanosilver is an emerging heavy metal which has a bright future of use in many applications. Here we report on the levels of silver and other heavy metals in municipal sewage sludge. Five towns in Limpopo province of South Africa were selected and the sludge from their wastewater treatment plants (WWTPs) was collected and analysed. The acid digested sewage sludge samples were analysed using Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) methods. The concentrations of silver found were low, but significant, in the range 0.22 to 21.93 mg/kg dry mass. The highest concentration of silver was found in Louis Trichardt town with a concentration of 21.93 ± 0.38 mg/kg dry mass while the lowest was Thohoyandou with a concentration of 6.13 ±0.12 mg/kg dry mass. A control sludge sample from a pit latrine had trace levels of silver at 0.22 ±0.01 mg/kg dry mass. The result showed that silver was indeed present in the wastewater sewage sludge and at present there is no DWAF guideline standard. The average Cd concentration was 3.10 mg/kg dry mass for Polokwane municipality. Polokwane and Louis Trichardt municipalities exhibited high levels of Pb, in excess DWAF guidelines, in sludge at 102.83 and 171.87 mg/kg respectfully. In all the WWTPs the zinc and copper concentrations were in excess of DWAF guidelines. The presence of heavy metals in the sewage sludge in excess of DWAF guidelines presents environmental hazards should the sludge be applied as a soil ameliorant.

- Teng, T.T. et al. (2012). Heavy Metal Ion Extraction Using Organic Solvents: An Application of the Equilibrium Slope Method. DOI: 10.5772/33199 · Source: InTech
  In book: Stoichiometry and Research - The Importance of Quantity in Biomedicine

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Abstract

The separation procedure of a chemical species from a matrix is essentially based on the transportation of the solute between the two involved phases, generally an organic and an inorganic one. Specifically, solvent extraction uses the concept of unique solute distribution ratios between two immiscible solvents. However, there are several situations where solutes have been observed to completely move from the inorganic to the organic phase (Anthemidis and Ioannou, 2009).

Organic solvent extraction is the transport of solutes, e.g. heavy metal ions, from an inorganic (or aqueous) phase to an organic phase. Solvents used comprise of an extractant + diluent combination. The roles of each are as follows: 1) the extractant, as a specific metal ion extractant; 2) the diluent, as a solvent condition controller, i.e. hydrophobicity, which can affect the molecules extractability (Watson, 1999; Cox, 2004). Occasionally, a phase modifier can be added to solve the problem of emulsion formation, aside from improving the phase demarcation process in an aqueous organic system (Cox, 2008). Solvent extraction is widely applied to processes of metal ions recovery, ranging from aqueous solutions in hydrometallurgical treatment to environmental applications. It is also considered a useful technique to increase the initial concentration of the solute, commonly used in the separation processes of analytical applications (Reddy et al., 2005).

In the biomedical field, supported liquid membrane methodology was used for trace analytes determination by facilitating chromatogram differentiation between samples, water and blood plasma (Jonsson and Mathiasson, 1999). It is also used to enrich human wastes (e.g. urine) with heavy metals prior to concentration determination using atomic absorption spectroscopy (AAS) (Lindegrade et al., 1992; Djane et al., 1997a; Djane et al., 1997b).

OTHER SCIENTIFIC PAPERS

https://www.sciencedirect.com/science/article/pii/S2095495615001102
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OTHER

Eurostat data
http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_ww_spd&lang=en
E.U - Sustainable sewage sludge management fostering phosphorus recovery and energy efficiency.
https://cordis.europa.eu/result/rcn/187939_en.html

Sewerage board limassol
http://www.sbla.com.cy/en/content/sludge-waste-water-quality-and-quantity-control

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5. Case studies

The estimated production of waste sludge in Europe is 2 billion tons per year (Meulepas et al. 2015). Until today, this waste sludge is disposed via incineration, landfilling or ocean disposal as well as reused as soil conditioner in agriculture. Land application represents the most economical way for final disposal of residual sludge and it combines the recycling of plant nutrients and sludge disposal at the same time (Gu et al., 2004). The recent banning of ocean disposal and new stringent European landfilling criteria have opened new prospects for sludge management (Tyagi et al. 2013). There is a general agreement that the long-term goal should be to recycle the nutrients and organic matter present in sludge. Due to the physical-chemical processes involved in sludge generation however, sewage sludge tends to accumulate heavy metals as well as potentially pathogenic organisms (viruses, bacteria, etc.) and poorly biodegradable trace organic compounds. The concentration of heavy metals in sewage sludge is found to be between 0.5 - 2% on a dry weight basis, but may rise to as high as 6% in some cases (Pathak et al., 2009). Several wastewater treatment plants (WWTPs) receive influent not only from residential areas but also from industrial areas. Sludge generated at these plants contains higher heavy metal concentrations, which may vary considerably with time and mostly depend on the specific industrial activities. The application of contaminated sludge over prolonged periods may cause accumulation of heavy metals along the food chain or in the ground and surface water, resulting in negative effects on animal and human health. Removal of heavy metals prior to land application of sludge or reuse of nutrients from sludge and ashes is therefore desired.

Apart from this, rising metal prices and China's tightening grip on supplies on several metals have heightened the appeal of finding other sources of metals supply. Unlike oil, there are no bio-derived alternatives for these metals (e.g Cobalt (Co), Zinc (Zn) and Copper (Cu)). These are unique and finite elements that are quickly dispersed throughout the environment, making their mining more costly and difficult (Carey 2015 and Dosdosn et al., 2012). Westerhoff et al. (2015) attempted to estimate the economic potential of metals in sewage sludge by calculating the monetary value of metal content in sludge from metal concentrations and spot market price of purified metals. The top 13 elements with the highest economical potential to be recovered from biosolids resulting this research are Silver (Ag), Copper (Cu), Gold (Au), Phosphorous (P), Iron (Fe), Palladium (Pd), Manganese (Mn), Zinc (Zn), Iridium (Ir), Aluminium (Al), Cadmium (Cd), Titanium (Ti), Gallium (Ga), and Chromium (Cr). The analysis was performed for a community with a population of 1,000,000 inhabitants (approx. 28,600 dry tons of biosolids per year), and the estimated value of metals in the biosolids could approach

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12,000,000 euro per year (415 €/ton) with greater than 20% of the value accounted (2,300,000 €/year) for Gold (Au) and Silver (Ag). Phosphorus, which is the focus of many wastewater recovery systems, has a relatively low economic potential (51,000€/year). Many studies (Table 16.1) point out that the metals that are usually found in relative high concentrations in sludge are Al and Fe, both resulting from coagulant addition during treatment, and to a less extent Zn, Cu, Ni, Pb and minor traces of Ag. During this study, 5 metals were pre-selected (Cu, Ni, Al, Zn, Ag) to be further analysed based on the sum of the average concentration found in dry weight sludge multiply by their average price.

Table 1 Concentration of heavy metals on dry weight sludge (mg/kg dry sludge).

Sludge type	Zn	Cr	Cu	Ni	Pb	Fe	Mn	Reference
Anaerobically digested sludge	2823	663	255	622	57	72200	nil	[Wong et al., 2004]
Anaerobic sewage sludge	1000	nil	300	200	180	nil	400	[Lombardi et al., 2001]
Anaerobically digested sludge	2306	181	256	47	88	64400	nil	[Wong et al.,2002]
Anaerobically digested sewage sludge	13301 27609	79.2 128	153 111	nil	nil	nil	nil	[Gu et al., 2004]
Anaerobically digested sewage sludge	1690	85.6	242.6	79.6	64	29731	nil	[Chan et al., 2003]
Sewage sludge	3756	nil	296.4	nil	351.3	nil	nil	[Chen et al., 2005]
Tannery sludge	nil	nil	10382	nil	nil	3123	nil	[Wang et al., 2010]
Sewage sludge	812.9	nil	171	nil	118.	nil	nil	[Zhang et al., 2009]
Pig manure	3434	10.3	1408	nil	nil	nil	995	[Zhou et al., 2012]

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Anaerobic sludge	702	10.4	245	nil	nil	nil	nil	[Zhou et al., 2013]
Pig slurry	2710	10.41	871	18.70	0.7	nil	510	[Zhu et al., 2013]
Sewage sludge	1516	nil	545.6	nil	133	nil	nil	[Zhu et al., 2013]

Therefore, an approach similar to the one used by Westerhoff et al. (2015) was used to estimate the economic value of these metals present in a 300,000 p.e. sludge line (~ 8,580 dry tons of sludge per year) (Table 16.2). The aim of this research was to provide a rough indication of average and maximum possible added value. Annual per capita production of biosolids is in the order of 28.6 kg D.M. /person-year (Westerhoff et al. 2015). In addition, a sludge management overview is pointed out based on the concentration of metals in sludge and the possible technologies.

Table 2. Presence of some metals in EU sludge and estimation of their economic potential.

Metal	Average metal content Mg/kg d.m.	Maximum metal content Mg/kg d.m.	Sludge Ton d.m./year	Relative Yearly Profit Potential based on the average metal content and the average price ($) of metal (during 2005-2015)	Relative Yearly Profit Potential based on the maximum metal content and the highest price of metal ($) (during 2005-2015)
Cu	285	1050	8580	18706	108966
Ni	29	66	8580	7962	29446
Al	16885	30500	8580	314946	2170740
Zn	910	2330	8580	23540	88761
Ag	7	108	8580	45516	1162272

**Values of metals was estimated from Fytili, D. and Zabaniotou, A. (2008) and EU Draft Summary Report 1 “Environmental, economic and social impacts of the use of sewage sludge on land.”*

The economic value was evaluated based on the price of scrap metal (01/2015) and the average price for refined metal between 2005 and 2015 (London Stock Exchange). Several studies have pointed out that the recovery of those metals could be between 70-99% (Pathak et al. 2009), being in this case full recovery assumed. The amount of metals present in sludge for a 300,000 p.e. installation is in the order of a few tons/year (except Al) and should be considered as a minor contribution to the industrial metal cycle. For example, the EU's demand for Cu in 2014

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was estimated at around 4.2 million tons whereas yearly Cu mass flow in sewage sludge for the total EU is estimated to 4854 ton or 0.1%. The maximal recoverable “scrap” metal value for the considered metals is estimated to amount to 100-200 kEuro/year for a 300,000 p.e. installation. It is therefore concluded that the main current driver for metal recovery from sludge or ashes remains environmental rather than economic (e.g. facilitating sludge disposal through land application). However, in several cases where the concentrations of metals are high and the metal’s price has relatively high value (e.g. Al and Ag, Table 16.2) then the recovery of metals can be an option for metal recovery and economic profits. However, the net profit has to be estimated having also in consideration the capital and operational costs (for metal extraction and recovery) and the highest metals that can be recovered from sludge. Consequently, metals should be extracted from the sludge only if their concentrations are above certain (national) limits (Figure 16.1) and when extraction is feasible applying best available technologies. In case that the recovery of target metals has economic potential, including avoidance of disposal cost of metal contaminated fractions, and/or ecological benefit, then the effort should be on metal recovery processes and not only on metal removal (Figure 16.1). In case that the extracted metals do not have any economic or ecological benefit for recovery then, after bioleaching, they can be precipitated or adsorbed and subsequently disposed off. The leached sludge can be neutralized and be used for land application or can be directly used for incineration.

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6. Discussion Questions

1. Define the specific problem that you have.
2. In what way(s) can the problem be solved? The knowledge that you have about the new technologies is several? Elaborate each one.
3. What further information would you need in order to accomplish the job well?
4. Where this information can be found? Do you need to make some interviews?
5. Do you think your proposal is economic valuable and affordable for the company??
6. How you or your team would be prepared to present to the company's owner the new plan?
7. You take into account definitions such as “waste-to-energy” “circular economy”, “industrial symbiosis” and “life cycle assessment”?
8. What are the measurable sustainability indicators?

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7. Reflective Questions

- What are my first thoughts about this overall project? Are they mostly positive or negative?
- What were some of my most powerful learning moments and what made them so?
- How do I feel my solution relates to real-world situations and problems?
- How well did I and my team communicate overall?
- What can/should you do with what you know?

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8. Assessment Document

The participants in groups of 4-5 people will have to prepare a small presentation regarding their problem solution in order to present the solution they have chosen explaining the concept and all the factors involved in their solution.

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