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Evaluation of Sewage Sludge for Incineration (Case study: Arak Wastewater Treatment Plant)

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Abstract
Sewage sludge treatment has become a primary subject in wastewater treatment and energy production. This paper aims to study the feasibility of power generation by incineration from sewage sludge enriched with impurities like heavy metals. For this purpose, we chose Arak wastewater treatment plant (AWWTP) and used calorific bomb test for examination. The experimental results showed that the heating values of sewage sludge are much less than the predicted records. This relates to the heavy metal and impurities content of sludge. These totally involved 5 to 18% of dried biomass. Therefore, we modified the predicting equation of heating value with respect to both water and impurities content of excess sludge. Finally, regarding the sludge characteristics of AWWTP, an annealing hierarchy programming (AHP) was used to find optimal technologies for dewatering and sludge minimization. Here, 21 criteria are classified in three main categories to rank the technologies regarding their costs, risks and performance. By all these means, a practical solution is introduced for optimal sludge management.

Keywords: Annealing Hierarchy Programming (AHP), heavy metal, heating value, incineration, sludge, wastewater treatment plant

Introduction

Sewage sludge management and its related technologies have recently found an increasing interest in both scientific and practical issues (Tyagi and Lo, 2011). This can be due to the fact that environmental protection standards have become more vigilant over land disposals as well as greenhouse gas and air pollution missions by incinerators (Snyman and Herselman, 2006; USEPA, 2011).
Various technologies have been studied for dewatering, treatment, disposal, and minimization of sludge as well as energy and material recovery (Christodoulou and Stamatelatou, 2016). For instance, Piao et al. (2016) evaluated different wastewater treatment plants (WWTPs) and

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sludge management systems to assess their life cycle. They found that incinerators have the lowest adverse effects in large cities. These include fewer effects with respect to the eutrophication, global warming, acidification and human toxicity. In addition, they require 33% lower operating costs. Martins et al. (2016) examined oxic-settling-anaerobic (OSA) process using folic acid for sludge minimization in conventional activated sludge systems. They verified that these approaches can reduce the challenges of sludge management without imposing any adverse effects on its digestion in further units. Ultrasonic were examined to disintegrate the sludge prior to anaerobic digesters (Huan et al. 2009; Kim and Lee, 2012) while ozonation could disintegrate and disinfect the sludge (Perez-Elvira et al. 2006). Likewise, electrochemical cells were introduced as promising technology for dewatering and increasing the ratio of food to microorganisms prior to anaerobic digestion (Mahmoud et al. 2011; Azizi et al. 2015). Moreover, Zhang et al. (2012) used high pressure homogenizers (HPH) to disintegrate the returning sludge and reduce its volume. Here, pressure and total solids of sludge were termed as influential parameters. Rai and Rao (2009) confirmed that HPH can well minimize and prepare the sludge for anaerobic digestion regarding its microbial analysis. Collard et al. (2016) compared three sludge drying methods. They concluded that smooth systems like solar drying or reed-beds are effective when some amendments are considered. Nonetheless, thermal drying is recommended when fuel production is aimed in which pellets with high lipid content can become useful. Murakami et al. (2009) proposed the application of a turbocharger driven by flue gas design. This advancement could increase energy recovery and decrease environmental impact. Gianico et al. (2016) has recently compared the conventional and upgraded anaerobic sludge treatment units with technical and economical points of view. They used reliability and complexity criteria for performance evaluation and found that ultrasonic pretreated anaerobic digesters could lead into more biogas production and disinfection rather than conventional methods.

However, there is always a question that which strategy fits better for sludge management. Finding proper solution for this purpose mainly relies on sludge specifications, capital and operating costs, operational challenges and conditions, and the possible application of by-products. For example, Bertanza et al. (2016) has recently ranked sewage sludge management strategies. They came into the idea that finding appropriate solution for sludge management should be performed by a comprehensive decision support system in which economical, social, environmental and technical issues should be included. Here, sludge incineration for energy production and using digested biomass for agriculture were nominated as two efficient alternatives for WWTP with half a million inhabitants. This paper re-evaluates these approaches in condition that sewage sludge is enriched with impurities, like heavy metals. Therefore, we chose Arak wastewater treatment plant (AWWTP) to find proper solutions for sludge management. However, prior to decision making and finding theoretical solution, we analyzed the specifications of sludge in first step. This is focused on assessment of the heavy metal content of sludge in different water contents.

Materials and Methods

Case study

Arak is located on 34°, 5', 30" N and 49°, 41', 30" E with 1740 meters height from the sea level. Here, the annual average precipitation is 340mm while the relative humidity reaches 46%. This city contains more than half a million residents and a few industrial facilities that use the sewers for effluent discharges. AWWTP is a centralized facility and consists of screening and grit removal as pretreatment units. Its third module is constructed in 2010 based on conventional activated sludge with overall volume of 13000m^3. The secondary sedimentation tanks have 40m diameters (Figure 1). Currently, the excess sludge is dewatered by filter press (FP) and sludge drying beds (SDB) and finally disposed in landfills nearby. However, by limiting the standards of land disposals, the question remains whether this facility should be equipped with sludge incinerators or anaerobic digesters in the next module. In order to answer this question, it is necessary to analyze the quality of the disposed sludge. This can probably predict the potential of incinerators for producing energy. The overall influent and effluent characteristics of AWWTP is depicted in Table 1.

Figure 1. View of AWWTP with its unit processes

Table 1. Annual average influent and effluent characteristics of Arak WWTP

Parameter	Concentration (mg/L)		Removal Efficiency (%)
	Influent	Effluent	
Soluble BOD	73	3	95.9
Total BOD	175	9	94.8
Soluble COD	88	9	89.8
Total COD	300	25	91.7
TSS	121	6	95

Table 2. Analysis parameters and their weights used in AHP

Class	Weight	Subclass parameters	Weight
Costs	0.33	Capital costs	0.298
		Operating costs	0.192
		Land	0.063
		Energy	0.192
		Chemicals	0.063
		Labour	0.192
Performance	0.33	Disinfection	0.128
		Solids reduction	0.191
		Toxicity reduction	0.128
		Reclamation potential and its revenues	0.191
		Upgrading and retrofitting potential	0.043
		Compatibility to the case study	0.128
		Energy production	0.191
Risks	0.33	Operational risks and process failure	0.188
		Low flexibility for process control	0.063
		Dependency on pre/post treatment units	0.063
		Not availability of instruments	0.094
		Odor emission	0.063
		Vulnerability to climate conditions	0.125
		Vulnerability to influent characteristics	0.125
		Environmental risks	0.281

Annealing hierarchy programming (AHP)

In order to find the optimal solution for sludge management in AWWTP, we used Annealing Hierarchy Programming (AHP) method carried out by the Expert Choice 11 software. For the first time, the influential parameters on sludge management are categorized in three main classes. These are termed here as costs, performance, and risks. These classes respectively include 6, 7 and 8 criteria as described in Table 2. The risks consider different aspects that may threaten the overall performance or the environment. For instance, high concentrations of heavy metals in the excess sludge have impact on the operation of sludge management systems. However, it differs from incinerators to digesters. In order to find the weights of each parameter for scoring the technologies in sludge management, the comments of operators, specialists, and teachers were obtained by questioners regarding AWWTP conditions. Final subclass parameters and their weights are depicted in Table 2. It is obvious that capital and operating costs (Feizi Ashtiani et al. 2015a, b), environmental risks (Jamshidi and Niksokhan, 2016), energy consumption and production, and the reclamation potential and its revenues (Jamshidi et al. 2014a, b; Jamshidi et al. 2016a, b, c) are declared as the most influential parameters for process selection.

Sampling and test

In order to analyze the heat value (*HV*) of the disposed sludge, samples were taken weekly from the effluent of the thickener (TK), filter press (FP) and by the surface of sludge drying beds (SDB) for 10 months. In laboratory, these samples were centrifuged and thermally dried to reduce their water content to 50, 30 and 5% respectively. Afterwards, the required mass for three replications was introduced in bomb calorimeter set to analyze the gross calorific value of sludge (ASTM D240). The remaining was totally dried and weighted. Here, the dried samples were prepared initially in laboratory by Aqua regia and digested via Anton-Paar. The concentration of heavy metals including zinc, copper, lead, cobalt, cadmium, nickel, chromium and aluminum were measured in this solution by ICP Variant 710 (APHA, 2005). The reported values of impurities are the aggregate of these constituents per total volume (%) of the disposed sludge sampled as above.

Results and discussions

Regarding the experimental results, it is realized that the water content and sludge impurities, like heavy metals, are effective on the calorific value of sludge for incineration. If the biomass is not dry enough for incineration, high fraction of fuel would be required for water evaporation and thermal drying. Therefore, dewatering play a key role to make incinerators cost-effective. This was previously discussed by Ducharme (2010) who proposed Equation 1 to calculate *HV* (KJ) per kg excess sludge.

$$HV = 185X - 26.4W \tag{1}$$

Where X refers to the organic content of sludge (%) while W is the water content (%). As shown in Figure 2, decreasing the water content of sludge from samples type S1 to S3 could develop *HV* to 9.7 MJ/Kg. This can possibly produce power equal to 170 kwh per tones of dry solids. However, with respect to Equation 1, it was expected that sludge with 95% dewatering has *HV* at least 17 MJ/kg (Ducharme, 2010). In addition, Gezer Gorgec et al. (2000) found that sewage sludge has the potential of recovering energy about 9 to 23 MJ/kg of sludge. They predicted that 675 to 1240 kwh can be achieved per tones of dry solids. This disparity between the literatures and experimental results can be due to the high content of impurities and heavy metals of the excess sludge of AWWTP.

The experimental analysis showed that the thickened and dewatered sludge to 50% (S1), 70% (S2) and 95% (S3) respectively contain 5.17, 8.61 and 17.89% impurities on average as heavy metals and cationic ions. It is obvious that *HV* is reliant on the proportion of carbon source of sludge for incineration and energy production. These impurities develop the dry weights (DW) of solids and reduce the potential of sludge for combustion. It means that heavy metals and impurities can reduce the ratio of potential *HV* per kg biomass by decreasing the inflammable proportion of dry solids. Therefore, we proposed Equation 2 as a modified version for Equation 1 to predict the *HV* of sludge whenever industrial discharges and heavy metal content of sludge are considerable. Provided that the manager of AWWTP uses sludge incinerators, it has to mix other biosolids, like manure, to increase the profitability of incineration (Morrin et al. 2010).

$$HV = 185(X - I) - 26.4W - 125000(\frac{\sqrt{I}}{X}) \quad (2)$$

In Equation 2, *I* refers the impurities of sludge (%) while other parameters are defined as before. The predictions by this equation have shown perfect compatibility with the observed data in this case. This equation is also testified for the dewatered sludge of Mahallati domestic wastewater treatment plant in Tehran. For instance, the average observed data (four samples) of sludge incinerated by 50, 60 and 95% solids content had respectively 8.4, 10.1 and 16.2 *HV* (MJ/kg $_{\text{biomass}}$). Equation 2 predicts the *HV* respectively as 7.3, 11.6 and 16.9 MJ/kg. In this regard, the heavy metal constituents of biomass (*I*) were respectively 0.061, 0.088 and 0.163% which is considerably lower than AWWTP.

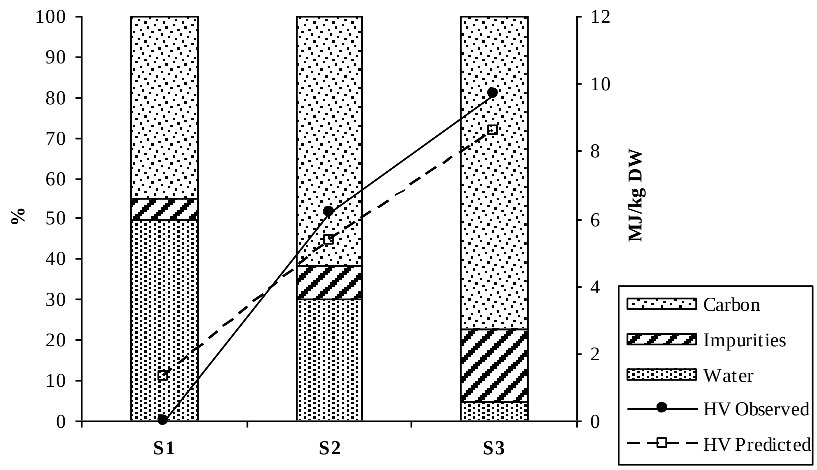

Figure 2. Predicted and observed heating values of dewatered sludge (MJ/kg) of AWWTP with respect to water and heavy metal content of biomass.

The impurities and heavy metals of AWWTP are mostly originated by industrial effluents. The concentrations of zinc, lead, copper, nickel, chromium, and aluminum were considerable in AWWTP. Other impurities are cobalt, cadmium, barium, iron, calcium and magnesium (Figure 3). It is noteworthy that Arak is an industrial city where different aluminum and metal factories working. The high concentration of aluminum, nickel and lead show that their discharges and heavy metals are finally reach the sludge biomass and condensed as it dewatered. Therefore, sludge drying bed (SDB) shows more impurities than filer press (FP) or thickener (TK) in relevant samples (Figure 3).

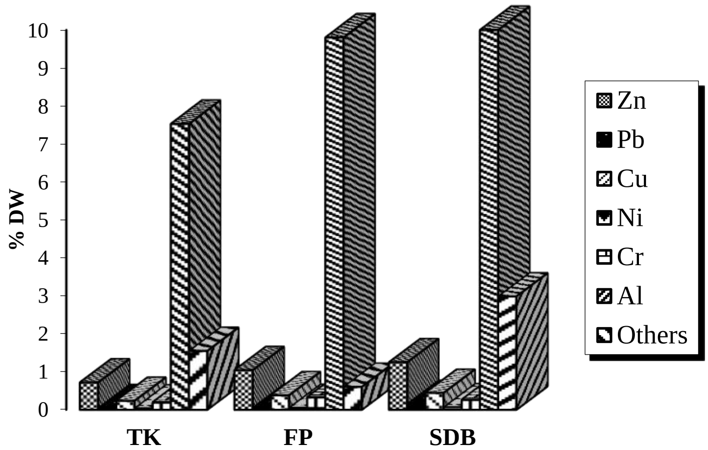

Figure 3. Average heavy metal contents of sludge in dry weight samples taken from Thickener (TK), Filter Press (FP), and Sludge Drying Bed (SDB) of AWWTP

This research showed that the concentrations of heavy metal in addition to the water content of sludge have direct influence on its heating values. This consequently reduces the potential of energy production in incinerators. With respect to the capital and operating cost of using incinerators, it is realized that using these strategies for sludge treatment may not be economically efficient (IRENA, 2012). Therefore, the excess sludge of AWWTP is more cost effective to use primary thickening, mesophilic anaerobic digestion, and sludge composting in final step instead of incineration. This can bring more income that using costly incinerators with limited power generation (Milieu Ltd, 2010). However, it is still risky to operate anaerobic digesters or use the composted sludge having high dosages of heavy metals. Therefore, it seems inevitable to use pretreatment units for heavy metals precipitation prior to wastewater or sludge treatment. The latter can be combined with increasing the ratio of food to microorganisms of digesters in electrolysis cells (Azizi et al. 2015). Both can consequently develop the income rate of WWTP (Figure 4). However, it is rather complicated which type of technology fits more for sludge dewatering or sludge minimization with respect to the characteristics of Arak sewage sludge. For this purpose, various parameters were defined for scoring each technology.

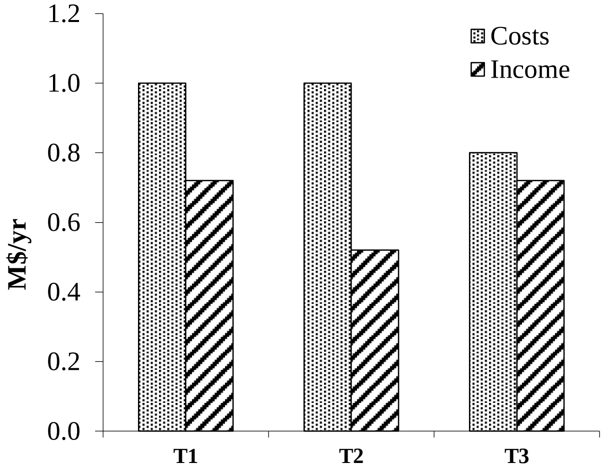

Figure 4. Cost analysis of three main strategies for sludge management in AWWTP

With respect to the results of the questionnaires used for scoring, weighting and comparing the technologies prior to the decision making analysis by AHP, it was concluded that chemical and mechanical approaches like electrochemical pretreatment by electrolysis (Yuan et al. 2011; Gholikandi et al. 2013), and using high pressure homogenizers (HPH) can well be suited as pretreatment units for anaerobic digestion to respectively reduce heavy metals and increase F/M ratio of the reactor. In contrary, ozonation and bio-augmentation are ranked with the lowest scores (Figure 5). In addition, the application of belt filters; filter press or centrifuges are recommended for dewatering as thermal drying is completely rejected by the lowest score (Figure 6). These types of technologies are recommended to be applied with anaerobic digesters. Here, composting the digested sludge can be considered as the main source for WWTP income.

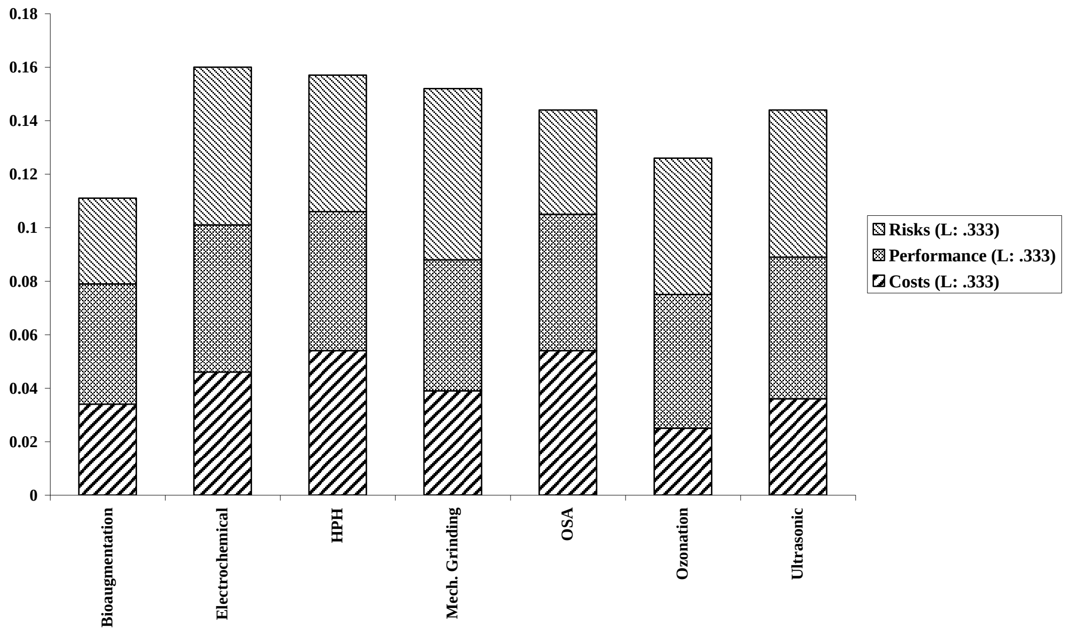

Figure 5. Comparative results of sludge minimization technologies

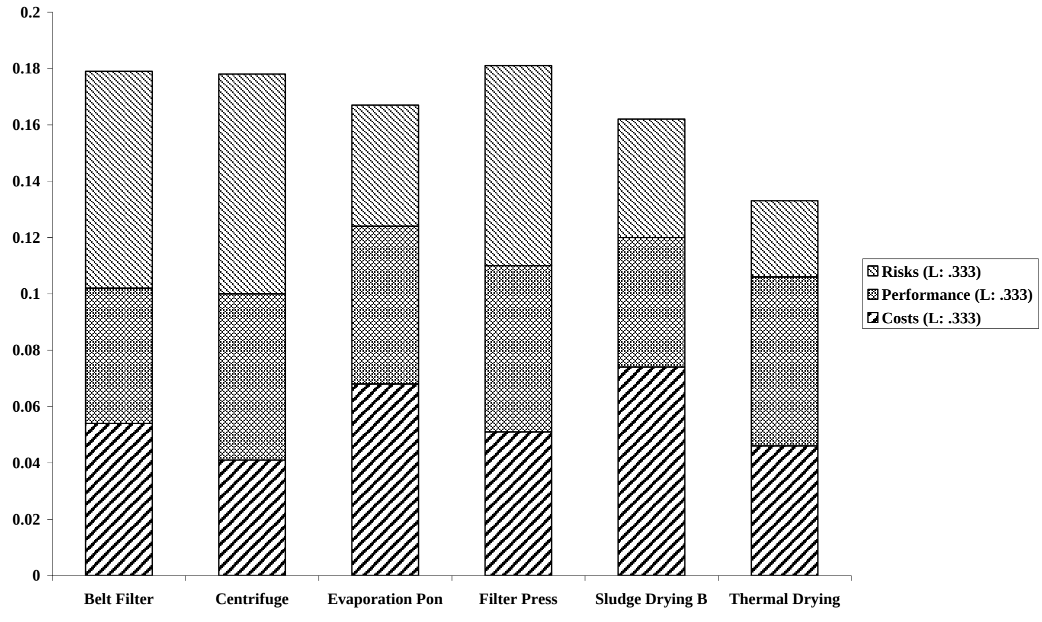

Figure 6. Comparative results of sludge dewatering technologies

Conclusion

In order to assess power generation from sewage sludge enriched with heavy metals, we used a set of examinations to analyze its characteristics and heating values prior to any decision making or investment. The experimental results revealed that the excess sludge of AWWTP has considerable amounts of impurities as heavy metals. As these constituents involve significant proportions of dry solids, it could reduce the calorific value of sludge. Therefore, the potential of incinerators for power generation are dramatically influenced and stood far behind typical predictions. Thus, the equation for estimating the heating value of sludge is modified with respect to its water and impurities content.
This study also pointed to a set of criteria for ranking different dewatering and sludge minimization technologies that partitioned in three main categories. Total costs, total risks and performance of technologies are these classes. Based on these criteria, it is realized that pre-treated anaerobic digestion and composting is more cost effective than sludge incineration for AWWTP. This is obviously due to the lower income of the incinerators in this facility.
AHP results showed that prior to any sludge digestion, using electrochemical pretreatments are required to precipitate heavy metals and disintegrate its compounds for more rapid digestion. The operation of filter press was also confirmed to gain the highest score in sludge dewatering.

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