



Research Article

Investigation of energy costs for sludge management: a case study from dairy industry

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ABSTRACT

Sludge management has been regarded as an environmental challenge to deal with due to high energy costs for wastewater treatment plants. From this perspective, energy costs of sludge management should be defined and calculated in order to obtain an effective energy management in wastewater treatment plants. Energy consumption of sludge management is the major constituent of the operational costs. Especially, dewatering processes have led to high electricity consumption at industrial wastewater treatment plants. This paper aimed to define the role of design and operational parameters on energy costs of sludge treatment process in terms of total organic carbon (TOC) and sludge volume index (SVI) considering water-energy nexus. Dissolved Air Flotation (DAF) sludge and centrifuge decanter were used for sludge dewatering process in a dairy wastewater treatment plant. Lime is used for sludge stabilization. Energy cost index has been figured out using a new derived numerical method. This study proposed a new developed methodology for energy cost assessment of sludge management. This paper revealed that energy costs would be lower if the wastewater treatment plant was operated under design conditions. If the plant was operated at design conditions, nearly 63% of reduction on energy costs of sludge handling process could be ensured. It has been recommended this plant could be operated under design conditions.

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INTRODUCTION

Dissolved air flotation (DAF) process has been used since early years for industrial wastewater treatment. DAF process has been applied in order to treat the types of wastewater such as dairy wastewater which has high concentrations of organic substances [1, 2]. Dissolved air flotation process is a type of flotation process that separates fats, oils and grease (FOG) and the other organic substances from

wastewater [3]. Contaminant substances have been disposed with the use of dissolved air in a wastewater system generated by injecting air under high pressure into a recycle stream of purified DAF effluent by a blower. A coagulant chemical such as ferric chloride or aluminum sulfate should be used in order to agglomerate the colloidal particles, and a flocculant material should be added (polyelectrolyte) in order to conglomerate the particles into heavier flocks [1].

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Chemical substances accumulate at DAF tank and form the chemical treatment sludge. DAF process leads to the large amount of sludge.

Sludge has originated as a byproduct of wastewater treatment processes, and sludge management is a significant challenge at the operation of wastewater treatment plants (WWTPs) from both economic and environmental perspectives of view [4]. A typical industrial sludge contains approximately 90–98% of water [5]. It should be dewatered before the final disposal. Also, dairy wastewater sludge contains huge amounts of pathogens due to the feedstocks used in the production step such as raw milk. So this chemical sludge has very highly organic content and large concentrations of carbonaceous material. The main sludge treatment techniques have been considered as thickening, aerobic or anaerobic stabilization, conditioning and dewatering [4, 5]. There are many technologies have been carried out as sludge treatment processes. Lime use is a widespread and economical technique for sludge stabilization process [6]. Stabilization process is applied for the removal of organic materials and pathogens from treatment sludge. Filter press, belt filter and centrifuge decanter are majorly used for sludge dewatering process. Dewatering processes have been carried out to separate water from sludge and to reduce sludge volume [5]. Industrial sludge has a high volume and low settleability [5]. Sludge handling and disposal activities can account for 25–65% of the total operational costs of WWTPs [7]. For many authorities and scientists regard that sludge management is a crucial environmental challenge due to the investment and operational costs for WWTPs [6].

Sludge handling units lead to intensely higher operational costs which are estimated to be 50–60% of the total costs of WWTPs [8, 9]. Energy costs of sludge management have the highest ratio on operational costs. Particularly, sludge dewatering processes need large amount of energy. Sludge is occurred in the result of wastewater treatment processes. So, a correspondence could be considered between water and energy in terms of sludge handling process. The water-energy nexus is a recently used type of systematic approach that underlines the linkages between water and energy [10]. It is clear that energy is a necessity in order to treat and distribute water [10]. Furthermore, energy is used directly for water generation, distribution, and treatment, and is depleted by heating, cooling and pumping processes [11]. According to many researchers, wastewater and sludge treatment processes are negligible for the water-energy nexus; they focus more on water consumption in the energy sector. In fact, energy consumption of the wastewater treatment plants (WWTPs) should be a significant consideration of the water-energy nexus. This study determines the energy costs of an industrial wastewater treatment plant in terms of sludge management process using water-energy nexus. High energy consumption leads to the high operational costs of the WWTPs. Energy cost constitutes a high-

er ratio of total operational costs of a wastewater treatment plant. Energy demand of a sludge handling process is based on the volume of treated sludge (sludge flow), sludge settleability and organic and water content. In order to obtain energy efficiency and to reduce the energy costs, it should be focused on these operational parameters.

Operational parameters of the industrial wastewater treatment plants do not match the design parameters for many factors such as the inaccurate estimation of the employees or production capacity [12]. This mismatch has an unfavorable effect on sludge management and energy costs [12, 13]. This study aimed to reveal the role of design and operating conditions on energy costs of sludge management related to DAF tank using centrifuge decanter. The aim of this paper is also in order to develop a new estimation method for energy costs of sludge management in the wastewater treatment plants. This paper recommended a new estimation method for energy management of sludge handling units. The originality of this study is that a new developed model for energy cost assessment of sludge management was carried out. Also, the novelty of this paper was that effect of design and operating sludge parameters in terms of total organic carbon (TOC) and sludge volume index (SVI) were investigated and benchmarked with each other. The other objectives of this study are to determine the effect of TOC and SVI on operational costs of sludge management. Also, energy costs of electricity consumption of decanter were figured out. From this purpose, a new estimation model was developed. In the literature, several researchers have focused on environmental and economic assessment of waste activated sludge using life cycle assessment (LCA) method. Uggetti et al. (2011) [14] reported the economic costs of sludge treatment wetland using LCA approach. Nielsen (2015) [15] investigated on chemical use, energy, and greenhouse gas emissions of a sludge reed bed. Sid et al. (2017) [16] researched how energy was consumed throughout the whole plant and how operating conditions affected this energy requirement for an activated sludge system. Apart from previous studies, a new estimation model was developed for energy cost assessment of sludge management processes in this paper.

MATERIALS AND METHODS

Description of the Industrial WWTP

The dairy industry has been located in Turkey. In this study, a full-scale dairy wastewater treatment plant was selected as the pilot plant. The main wastewater accumulation points of the dairy industry are the clarification, pasteurization and homogenization processes. The wastewater and sludge analyses were performed using Standard Methods [17]. This industrial plant is a kind of small-scale WWTPs. Figure 1 showed the wastewater treatment and sludge handling flow diagrams. Table 1 demonstrated the influent and sludge characterization.

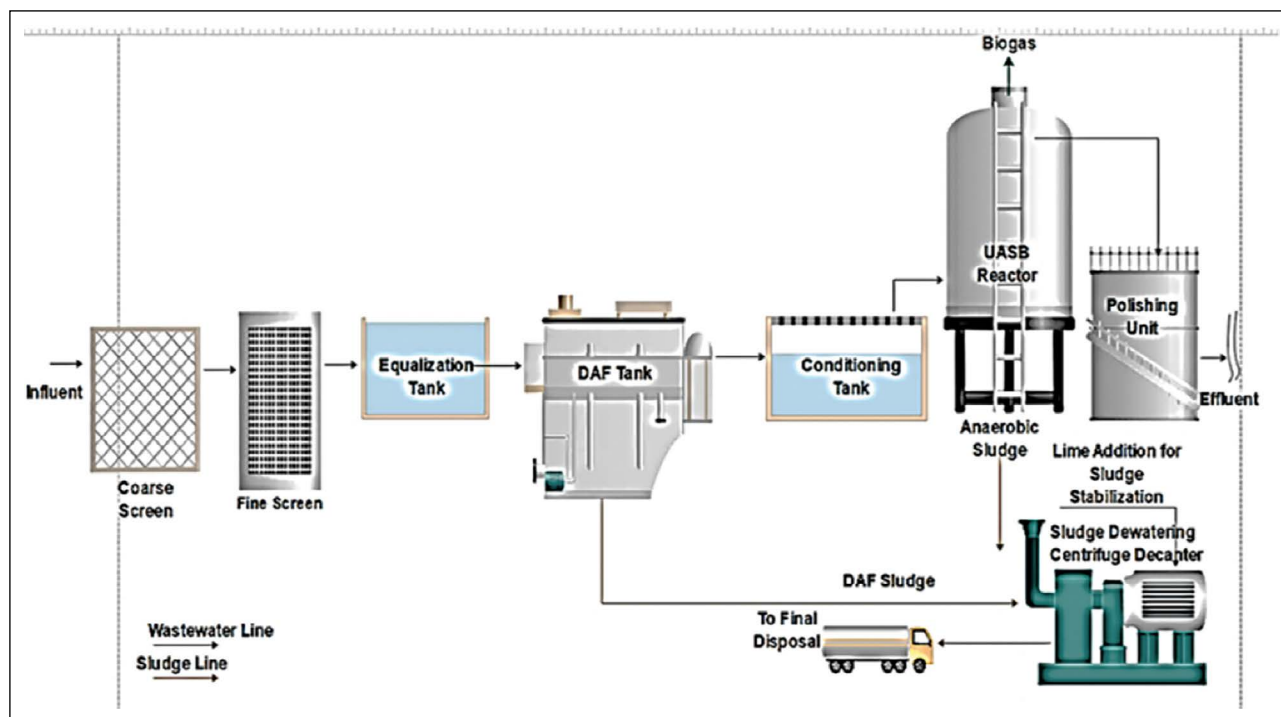


Figure 1. Wastewater treatment and sludge handling flow diagram.

Table 1. Wastewater and sludge characterization

Parameter	Value
COD (mg L ⁻¹)	12000
FOG (mg L ⁻¹)	350
TSS (mg L ⁻¹)	425
pH	6
Flow Rate (Q) (m ³ d ⁻¹)	2100
Raw Sludge Water Content (%)	95.5
Dewatered Sludge Water Content (%)	13
Raw Sludge Solids Content (%)	4.5
Dewatered Sludge Solids Content (%)	87

* Standard deviations of COD, FOG, TSS, pH and flow rate were 8.21, 7.64, 6.45, 4.21 and 8.13 respectively.

In this paper, a DAF unit was continually operated under specific operational conditions to ensure the highest removal efficiency. DAF tank is a kind of crossflow plate pack tanks. At DAF tank, polyaluminum chloride (PAC) was used as the coagulant substance and polyelectrolyte (PE) was used as the flocculant material. In this study, powder form of PAC was used. AC 100 S particular type of PAC was prepared as the aqueous solution. As seen from Figure 1, sludge is generated from DAF tank and up flow anaerobic sludge bed (UASB) reactor. Anaerobic sludge is stabilized so there is no need to stabilize it with lime. Sludge generated in wastewater treatment processes typically contains

very small amounts of solids distributed throughout a large volume of water. Besides, anaerobic sludge has no require to be dewatered due to low water content and stability. DAF sludge has low solid content (4.5%) and high organic content. This sludge could be dewatered in order to reduce its volume and decrease the water content in the sludge. Dewatering aimed to decrease the water content and to reduce the water content to 25%, nearly. In this WWTP, centrifuge decanter was used as sludge dewatering technology. Sludge dewatering technology needs huge amount of electricity. It could be considered that large amount of energy costs in WWTPs is corresponded to sludge dewatering processes. So, energy costs of sludge dewatering processes should be evaluated at WWTPs.

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Table 2. Wastewater and sludge characterization

Parameter	Value
q_s ($m^3 d^{-1}$)	100
Q_s ($m^3 d^{-1}$)	42
V_s ($m^3 year^{-1}$)	15330
TOC_d ($mg kg^{-1}$)	80000
TOC_o ($mg kg^{-1}$)	50600
SVI_d ($mL g^{-1}$)	150
SVI_o ($mL g^{-1}$)	100
μ ($kWh m^{-3} sludge^{-1}$)	100000
Ω ($TL kWh^{-1}$)	1.05
PD (kW)	200

*At all abbreviations, “d” defines the design parameters and “o” defines the operational parameters.

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Determination of Energy Costs

There are several methods could be defined in the literature depending on the variables used for energy costs assessment of WWTPs. Many investigations demonstrated that it was possible to use operational parameters such as the volume of wastewater treated, the volume of sludge, and the other parameters based on wastewater and sludge characterization [18] in order to estimate the energy costs. In this study, energy cost assessment methodology was modified based on the model developed by Hernandez-Sancho et al. (2011a) [18].

Energy cost indicator (ECI) is the meaning of the energy cost index of a sludge dewatering process based on sludge volume, organic content and settleability of sludge. In this model, energy cost indicator (ECI) which was derived from the performance index (PI) has been figured out for design and operational conditions. The performance index (PI) constitutes of operational flow rate (Q) ($m^3 d^{-1}$) and the design flow rate (q) ($m^3 d^{-1}$) of the WWTP.

The performance index (PI) was adapted from a study by Castellet-Viciano et al., (2018) [13] for sludge management in this study. It comprises of operational sludge flow (Q_s) ($m^3 d^{-1}$) and the design sludge flow (q_s) ($m^3 d^{-1}$). Eq. 1 demonstrated the estimation of the adapted performance index for sludge management processes.

$$PI = [(q_s - Q_s) / Q_s] \times 100 \quad (1)$$

Energy cost indicator (ECI) was derived from the performance index (PI); the model included the volume of treated wastewater per year (V) ($m^3 year^{-1}$) and biochemical oxygen demand (BOD) ($g m^{-3}$). The basic equation model for small-scale plants was given in Eq.2 [13].

$$ECI = 1983.106 V^{0.717} e^{(-14.327 BOD + 0.660 PI)} \quad (2)$$

In this study, energy cost indicator (ECI) was derived from this equation tool (Eq.2.) for sludge management and the model constituents of the volume of sludge per year (V_s) ($m^3 year^{-1}$) and total organic carbon of sludge (TOC) ($mg kg^{-1}$) or sludge volume index. TOC shows the organic content of sludge and SVI shows the settleability of sludge. The derived estimation model of ECI for small scale WWTPs was shown in Eq.3. The values of ECI were figured out both design and operational parameters.

$$ECI = 1983.10^6 V_s^{0.717} e^{(-14.327 TOC, SVI + 0.660 PI)} \quad (3)$$

A new model was developed for the estimation of energy costs of sludge management in this paper. Energy costs (ε) ($\text{€ } m^{-3} sludge^{-1}$) could be estimated with the help of Eq. 4.

$$\varepsilon = ECI \times \mu \times \Omega \times 1000 \quad (4)$$

Where:

ECI: Energy cost index

μ : electricity consumption for dewatering of per $1 m^3$ sludge ($kWh m^{-3} sludge$)

Ω : specific cost per 1 kWh energy of the plant ($TL kWh^{-1}$)

Electricity consumption of the plant was ensured from the electricity counters and bills of the centrifuge decanter. Ω is used as the specific cost related to Turkey [19]. Energy costs corresponded to design and operational conditions were figured out and benchmarked using a new developed estimation model in this paper. The data set used in this study was shown in Table 2.

Energy costs for decanter also calculated using sludge amount (V) $m^3 year^{-1}$, the design power of decanter (PD) ($kWh m^{-3} sludge^{-1}$) and Ω ($TL kWh^{-1}$). Eq. (5) shows the calculation term.

$$\varepsilon = PD \times V \times \Omega / 10000 \quad (5)$$

RESULTS AND DISCUSSION

Benchmarking of Energy Cost Indicators

The results revealed that energy cost indicators of sludge management in terms of TOC and SVI corresponded to design parameter were lower than operational parameter for both two types of sludge parameter. The values of energy cost indicators related to design and operational TOC parameter were 0.657 and 1.08, respectively. Similarly, energy cost indicators corresponded to design and operational SVI parameter were 0.686 and 2.51, respectively. It could

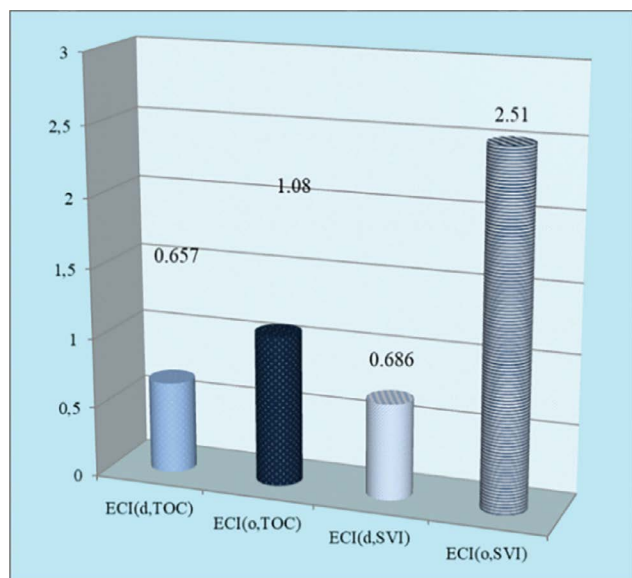


Figure 2. Benchmarking of energy cost indicators.

be considered that energy cost indicators related to SVI parameter were higher than TOC parameter. Figure 2 shows the benchmarking of the energy cost indicators of sludge dewatering process.

PI is very significant variable in the model. When the sludge is dewatered under design conditions, it could be said that the value of PI will be zero. If the gap between the operational and the design sludge volumes increase, the value of PI will be higher. According to the basic model, as PI is low, energy cost index reduces. In this study, PI was calculated out as 1.38. If WWTPs are operated at design sludge flow, energy cost index of the plants could be lower. There are many studies related to this topic. Using of cost functions was carried out, in the previous studies. Most of developed models for WWTPs have been focused on determination of the operational costs and the costs of maintenance activities of the treatment and pumping equipment. Hernandez-Sancho et al. (2011b) [20] applied an energy cost modelling using statistical method for 341 WWTPs in Spain. Castellet-Viciano et al. (2018) [13] investigated the impact of design flow on energy costs for small, middle and large scales of WWTPs. They reported that PI was 0.20, 0.40, 0.60 and 0.80 for the small-scale WWTPs [13]. The value of PI was calculated as 1.38. Apart from the previous studies, the energy costs of sludge management were focused in this paper.

Energy cost Assessment

According to findings, energy costs corresponded to design parameters were lower than operational parameter for both 2 sludge parameters. If the plant is operated under design conditions, energy costs would be lower. Energy costs of design and operational parameters in terms of TOC of sludge dewatering process were 69.0 and 113.4 TL

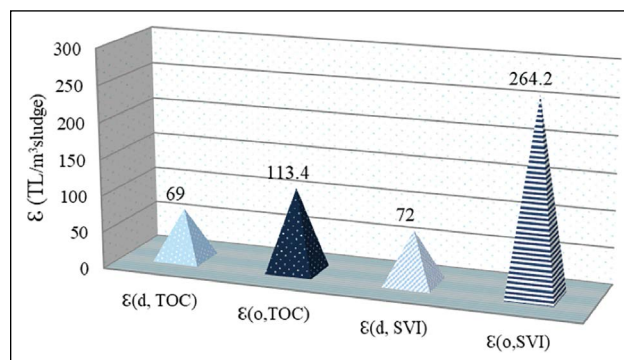


Figure 3. Energy costs of sludge dewatering process.

m^{-3} sludge, respectively. Energy costs of design and operational parameters related to SVI were 72.0 and 264.2 TL m^{-3} sludge. Energy costs of SVI parameter were higher than TOC parameter. It could be said energy consumption was higher for settling of sludge than for sludge stabilization process. TOC defines the organic content of sludge and is used as stabilization indicator. Figure 3 shows the energy costs of sludge dewatering process.

Energy costs of decanter was calculated as 321.93 TL m^{-3} sludge considering only energy consumption. It is obvious that operational costs were lower than energy costs of electricity consumption.

Molinos-Senante et al. (2013) [21] used a cost function model to describe the costs of sludge and waste management for a wastewater treatment plant. In a study by Plumlee et al. (2014) [22] the costs of advanced wastewater treatment processes which were microfiltration, ultrafiltration, nanofiltration, reverse osmosis, ozone, ultraviolet (UV) treatment with H_2O_2 and biological activated carbon were investigated. They found that membrane treatment led to the highest costs and ozone led to the lowest costs. Yumin et al. (2016) [23] determined the operational costs of WWTPs in rural areas using cost functions which membrane bioreactor technology, sequencing batch reactor, purification tank, biological filter and artificial wetland were used at 221 different WWTPs. In the literature, the investigations corresponded to energy costs of sludge management are limited. Many studies focused on technical, economic and environmental evaluation of sludge management using life cycle assessment (LCA) method. In a study by Uggetti et al. (2011) [14] economic performances of sludge treatment wetlands were applied using LCA method. They found that sludge treatment wetlands were the most appropriate technology for decentralized sludge management in small regions. Ushani et al. (2018) [24] performed a similar study. They carried out energy and cost benefit analysis for scalability of a sludge disintegration process to be applied at pilot scale. They observed bacterial disintegration in terms of energy analysis. They reported that sodium thiosulphate induced immobilized protease secreting bacterial disintegration was a feasible process

with net profit of 2.6 USD Ton⁻¹ of sludge. Yapıcıoğlu and Yeşilnacar (2020) [25] used the similar assessment method to determine the energy costs of a dairy wastewater treatment plant in terms of wastewater treatment process. They found that energy cost indicator of the existing treatment process was lower than optimum operating conditions.

CONCLUSIONS

The results revealed that energy cost indicators of sludge dewatering process related to design parameter were lower than operational parameter in terms of TOC and SVI.

Energy costs of design and operational parameters in terms of TOC were 69.0 and 113.4 TL m⁻³ sludge, respectively. Energy costs of design and operational parameters related to SVI were 72.0 and 264.2 TL m⁻³ sludge. Energy costs of SVI parameter were higher than TOC parameter. It could be said energy consumption was higher for settling of sludge than for sludge stabilization process.

If the plant is operated at design conditions, energy costs of sludge management could be lower. According to this study, if the sludge management is carried out under design conditions, approximately 63% of reduction on energy costs could be ensured.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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