Sustainable wastewater management and energy production from sludge incineration process in industrial wastewater treatment plants

Sustainable Wastewater Management and Energy Production from Sludge Incineration Process in Industrial Wastewater Treatment Plants

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ABSTRACT

One major issue in industrial wastewater treatment plants is sludge handling and management with associated significant costs. Furthermore, the accumulated sludge handling such as the American Petroleum Institute (API) process can lead to environmental issues and health challenges such as cancer for workers in the site. This study applies combustion methods to analyse nexus of sludge incineration process and energy production potentials for this solid waste as a by-product of wastewater purification process. The methodology is demonstrated by its application to a real-world case study of petroleum refinery wastewater treatment in Iran. For this purpose, sludge samples were taken from the accumulation site and tested by calorimetry bomb, PARR 1266, Preiser Scientific, USA. In this study, 15 samples were evaluated from different points of the sludge in the case study. Measurements show that the average heat value is equal to 3,100 kcal/kg. The experimental results show that increasing water content in the sludge can lead to decreasing the net heat value. On the other hand, increasing Chemical Oxygen Demand (COD) in wastewater can result in increasing the harvested energy. In total, the sludge accumulation in the plant over the eight past years is around 4,000 tonnes which is equivalent to the thermal value of 12,400 GCal of potential energy that will be otherwise leads to environmental and health problems if not released through incineration process. This can highlight the significance of wastewater-energy-pollution nexus in sludge management of petroleum refineries by converting a threat to an opportunity.

KEYWORDS

Incinerations; refinery plant; sludge; sustainability; wastewater-energy-pollution nexus.

1. INTRODUCTION

Sewage sludge contains significant amounts of organic matter that can be used in energy production [1-2]. In order to use the heat capacity available in organic compounds, there are technological methods of heat conversion, among which the most important ones are the production of solid fuel, incineration, and gasification [3]. Sludge from refinery industries has many problems for reuse due to low Biological Oxygen Demand (BOD) and high Chemical Oxygen Demand (COD). In addition, it usually has significant amounts of oil which cannot be degraded by conventional aerobic and anaerobic digestion processes [4]. Likewise, they are not worth producing biological energy or using as fertiliser in agriculture. Thus, one of their most common management methods is energy production through thermal processes [5].

In the refinery plants, the chemical sludge includes oil and petroleum compounds which is obtained from liquid-solid phase separation with the application of American Petroleum Institute (API) treatment system [6]. The schematic plan of API petroleum wastewater treatment package is demonstrated in Fig. 1. API system is one of the most common devices for removing oil from water, which are widely used in refineries. The design and manufacture of API grease trap is based on the stock law and the difference in density of solid and liquid particles, and it has high efficiency in environments with a temperature of more than 5°C [7]. After trapping the sludge in the API method, the collected sludge can be incinerated with a burner in different stages as per Fig. 2. It can be understood that in the first step, the temperature of the reactor is increased and based on net heat value, after energy production, two other hazardous products contain air pollution and ash are generated [8]. The management of air pollution and generated ash is one of the main aspects of waste to energy system [9].

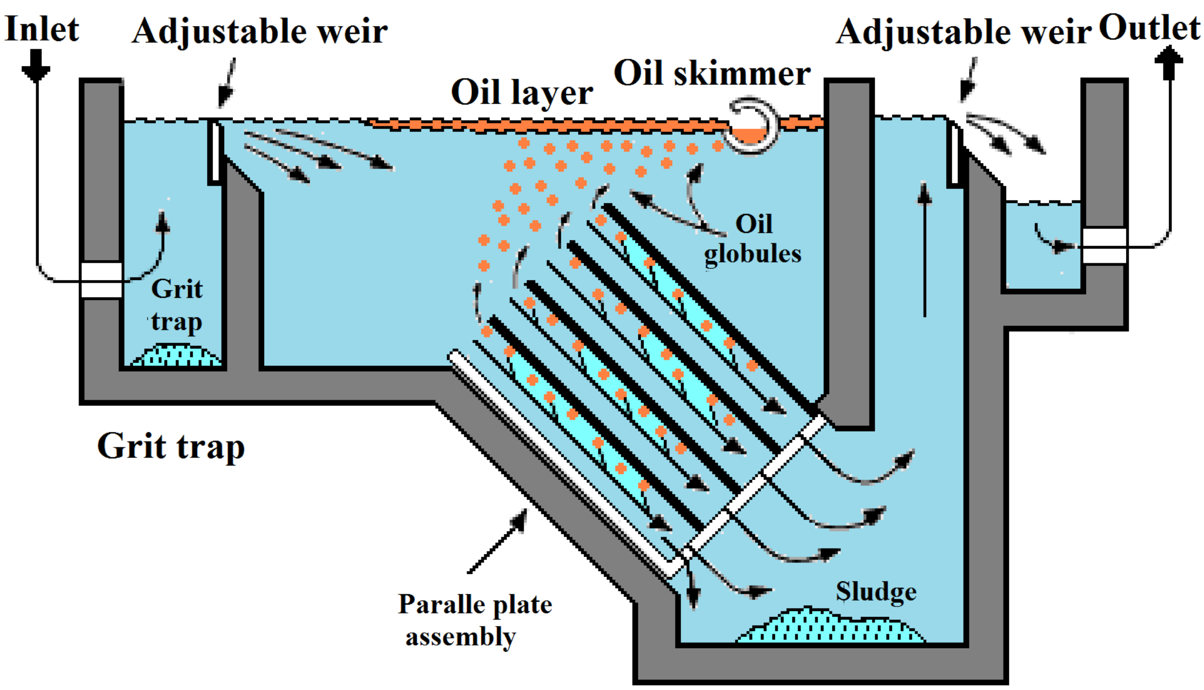


Fig. 1. The schematic plan of the API separator transverse section.

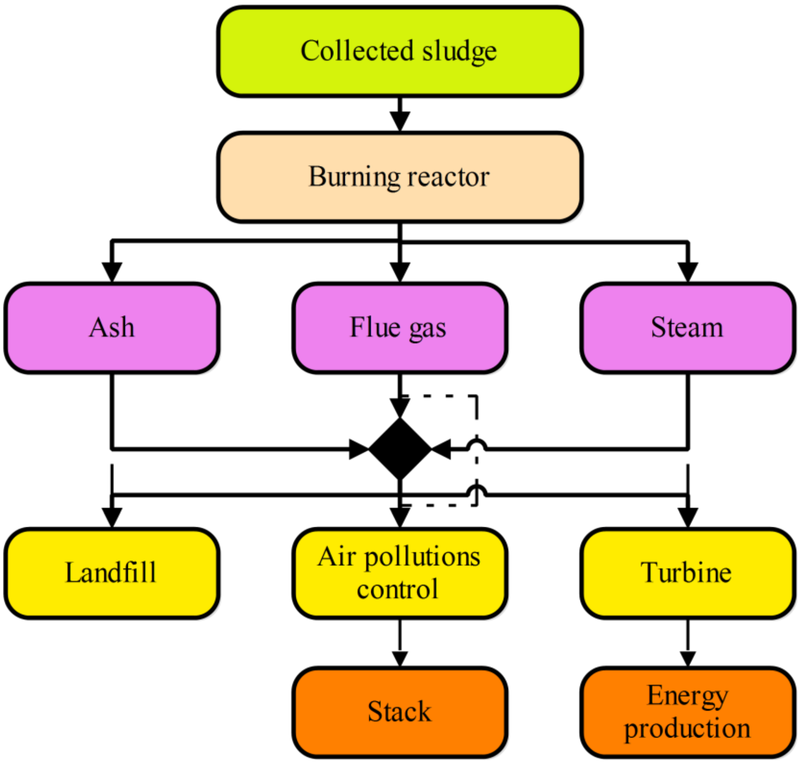


Fig. 2. Different stages of thermal recovery of sludge in waste to energy process.

There are some studies in the field of sludge thermal recovery that are analysed in this study. Thipkhunthod et al. (2005) predicted the calorific value of urban sewage sludge using approximate and supplementary tests and evaluated their models based on the R^2 coefficients and finally the application of their models for sludge containing ash was analysed [10]. Shen et al. (2010) evaluated and predicted the components and elements in sludge using the results of approximate tests related to models for predicting and estimating the calorific value of biomass. Their study used 66 series of data samples to build and create the model, and 20 points were used to validate and reduce related errors [11]. Another similar study presented by Yin (2011) developed regression models for predicting and estimating the heating value of biomass based on the results of approximate and supplementary tests. The initial model of their study was made based on the results of the background research related to the biomass of different areas and regions, and evaluated with the characteristics of the biomass of the case study [12]. In the research conducted by Nhuchhen and Salam (2012), they used a new strategy to predict the values of high calorific values of sludge using approximate analysis methods. They analysed 250 studies based on the calorific value of sludge and an error function based on linear and non-linear correlations was considered to increase the accuracy of predictions [13]. Wzorek (2012) investigated the quality of sludge produced in a sewage treatment plant by activated sludge method and examined its energy production capacity through combination with wastes of high fuel value. In the mentioned research, calorific value, humidity, organic matter and heavy metals were measured in an experiment, the combination of dewatered sludge with meat waste, wood and coal slurry was evaluated in terms of calorific value and energy production, and its results were compared with coal as an alternative fuel for cement factory [14]. Rios et al. (2015) examined the quality of sludge organic matter in sewage treatment plants in Mexico and addressed the electricity supply capacity and presented an empirical formula that expresses the relationship between organic matter, calorific value of methane gas and electricity production

[15]. Ongen et al. (2022) appraised the performance of fixed bed gasifier for energy harvesting from oily sludge and chicken manure in which all dimensions were set in lab scale [16].

Based on the literature review in this study, it is evident that most of the previous studies have been related to experimental practices of conventional wastewater treatment plant and the heat value of refinery plants have not been appraised by scientific communities. This study aims to analyse heat value assessment of the API sludge in a real-world case study and the 3D profiles of heat value for managerial insight creation is also evaluated.

The literature review also shows that the scheduling of refinery plant's sludge seems to be challenging task and importantly in countries with massive crude oil resources with no significant research background by previous researchers. Therefore, this study also aims to (1) evaluate the heat value from refinery plant's sludge by experimental practices, (2) develop; statistical modelling of the experimental outputs in longitudinal and transverse profiles of the sludge storage area, (3) determine the calorific value of sludge accumulated in the depth profile, (4) Schedule the available sludge resources in the storage and presentation of managerial insights. The structure of remaining parts of the paper is as follows: first, materials and methods are presented followed by presenting results and discussion and drawing conclusions by summarising key points and uncertainty.

2. METHODOLOGY

2.1. CASE STUDY

This study is demonstrated on a gas purification and separation refinery in Iran. In the refinery, H_2S gas is separated from the mass of sweet gas as a souring agent. The effluent from the washing of the separating columns is transferred to the API system and the resulting sludge has significant amounts of moisture, acidic compounds, petroleum and organic compounds. The main structure of the sludge management in the refinery is shown in Fig. 3.

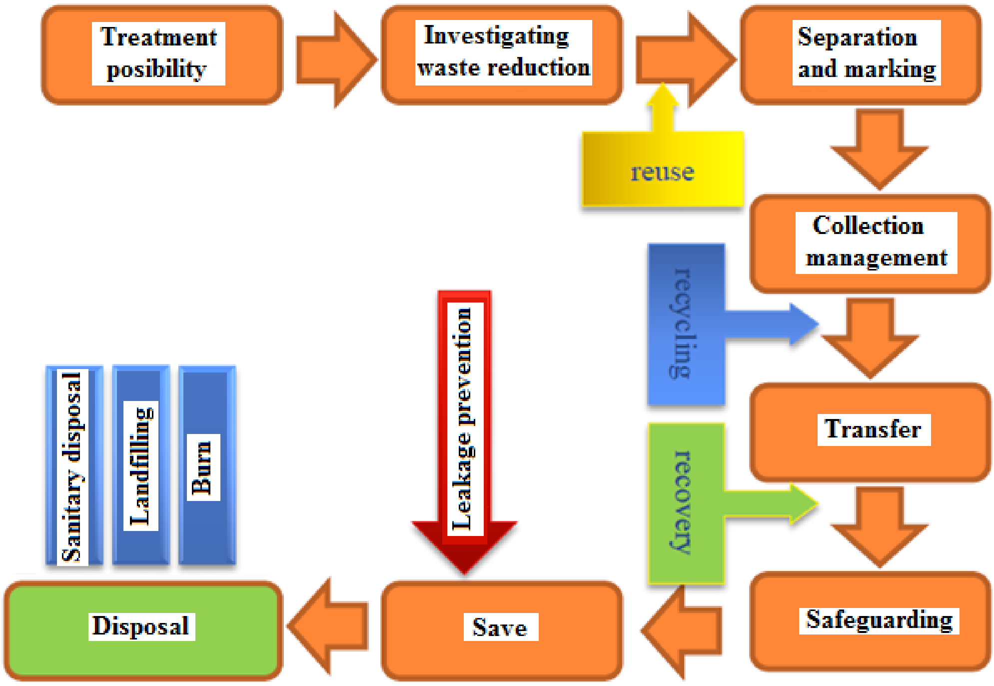


Fig. 3. The stages of sludge management in the case study refinery plant.

2.2. EXPERIMENTAL PRACTICES

Table 1 summarises all the experimental instruments, methods and references for heat value examinations, COD measurement, and moisture content detection used in this study. Likewise, the sampling process is done with the application of valve tube for sludge coring B-10104 made by Raven American company.

Table 1. The applied devices and protocols in the present research.

Measurement item	Instruments	Protocols	Reference
Heat value of sludge	Calorimetry bomb, PARR 1266, Preiser Scientific, USA	ASTM D294 (1995)	[17]
COD measurement	COD analyser, Yatherm Scientific Company, India	Standard methods for water and wastewater examinations	[18]
Moisture content detection	Humimeter FS4.1, Schaller Company	Standard methods for water and wastewater examinations	[18]

3.1.2.3. SCHEDULING AND LARGE-SCALE HEAT VALUE ASSESSMENT

This study considered sampling and evaluation of calorific value and sampling from a circle with a diameter of 200 meters such that the centre of this circle is the first place of sludge accumulation during 5 years of accumulation. Evidently, the volume of the occupied land is more than this amount, but only a diameter of 200 meters was tested to identify the management conditions as the overall process can be examined and evaluated in this situation while the storage process is radial from the innermost point to the outermost point as per shown in Fig. 4. Therefore, the sludge accumulated in the middle points have a longer life than the marginal sludge.

At the same time, the depth of accumulated sludge is one meter, and depth sampling is taken every 30 cm. As can be seen in Fig. 4, there are 5 sampling points (P1-P5) and depth profiles are obtained at 30 cm depths (3 points). At the same time, it can be concluded that a total of 15 points have been subjected to experimental evaluation and numerical analysis. This study defines longitudinal and transverse profiles as follows.

Transverse profile: P4, P1, P5

Longitudinal profile: P2, P1, P3

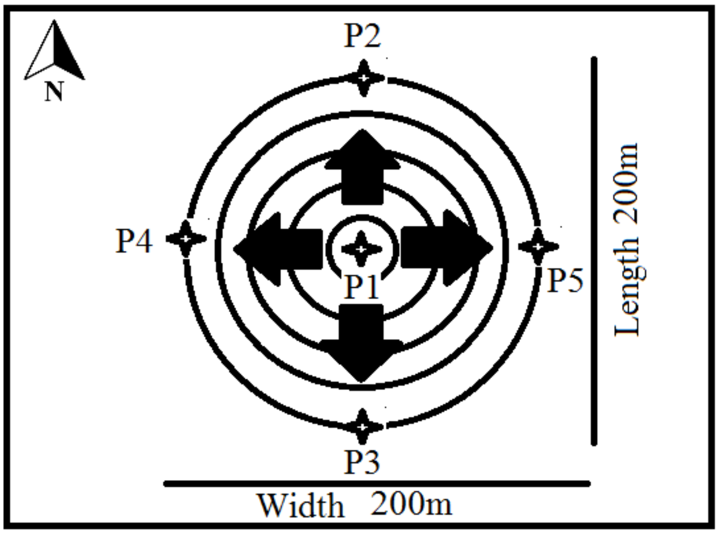
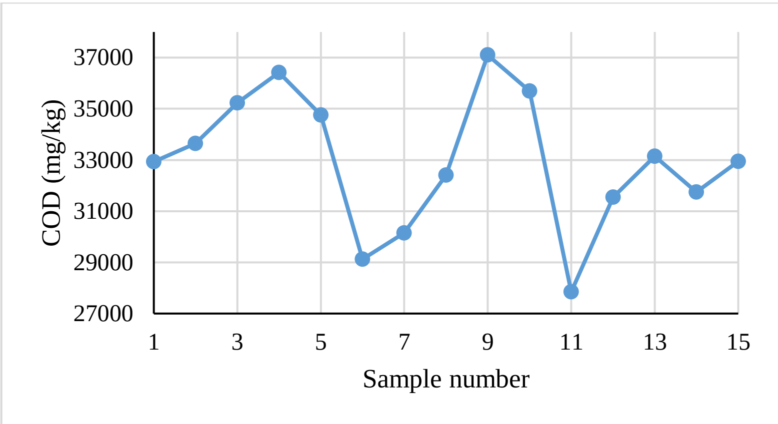


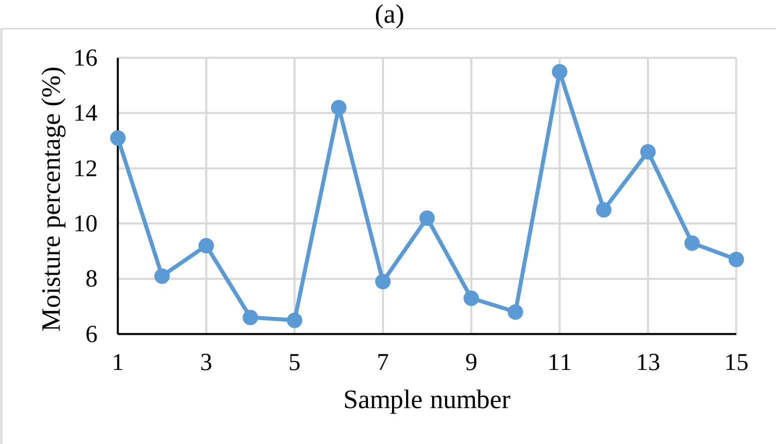
Fig. 4. The arrangement of sludge storage and sampling in the case study.

4. RESULTS AND DISCUSSIONS

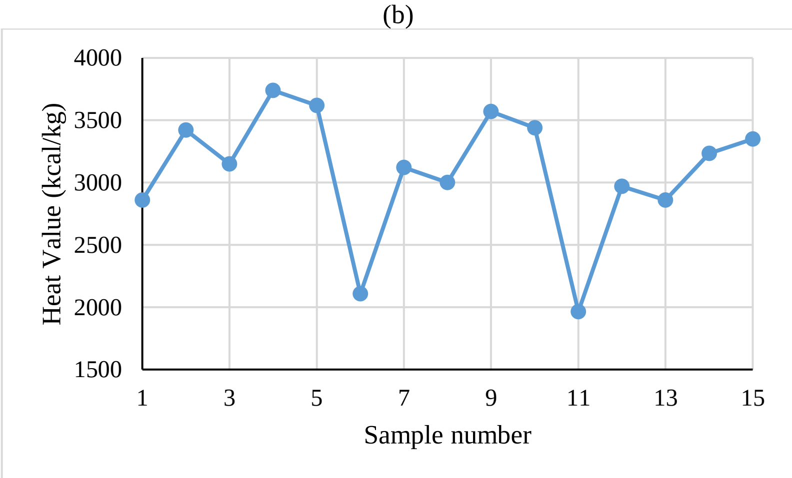
The results of different tests in 15 samplings are shown in Fig. 5. As can be seen in Fig. 5a, the COD value of different samples varies between 27,000 and 37,000 mg/kg. The changes in calorific value and precipitation percentage of sludge samples are also variable in the ranges of 2000 to less than 4000 kcal/kg (Fig. 5c) and 6 to 16 % (Fig. 5b), respectively. The variation of the COD and calorific values are relatively in harmony with each other and the changes in the moisture percentage curve are the opposite of these two cases. As a result, the calorific value with the COD has a direct relationship with the moisture percentage.



(a)



(b)



(c)

Fig. 5. The changes of (a) COD (mg/kg), (b) Moisture percentage (%), and (c) heat value (kcal/kg).

To predict the available energy based on the moisture percentage of the sludge and also the amount of COD, the implicit polynomial function of degree 2 in x and degree 3 in y was modelled in MATLAB 2018b software. The model has a regression correlation of 0.96 (Eq. 1) and the corresponding procedure is shown in Fig. 6. increase in humidity in sludge samples with lower COD, which also have lower thermal energy amounts; It is affected by the process of anaerobic digestion in the deeper layers. Due to anaerobic digestion in the deeper layers, hydrolysis occurs and the percentage of moisture in the samples increases and is affected by microbial activities, the amount of organic load decreases and the calorific value also decreases [19, 20].

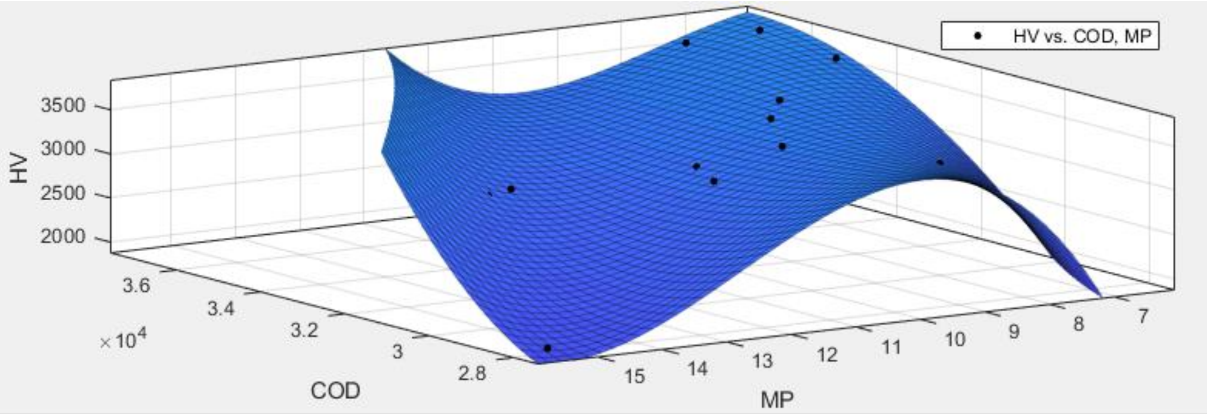


Fig. 6. The polynomial regression equation of heat value prediction based on COD and moisture percentage.

(1)

f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2 + p21*x^2*y + p12*x*y^2 + p03*y^3

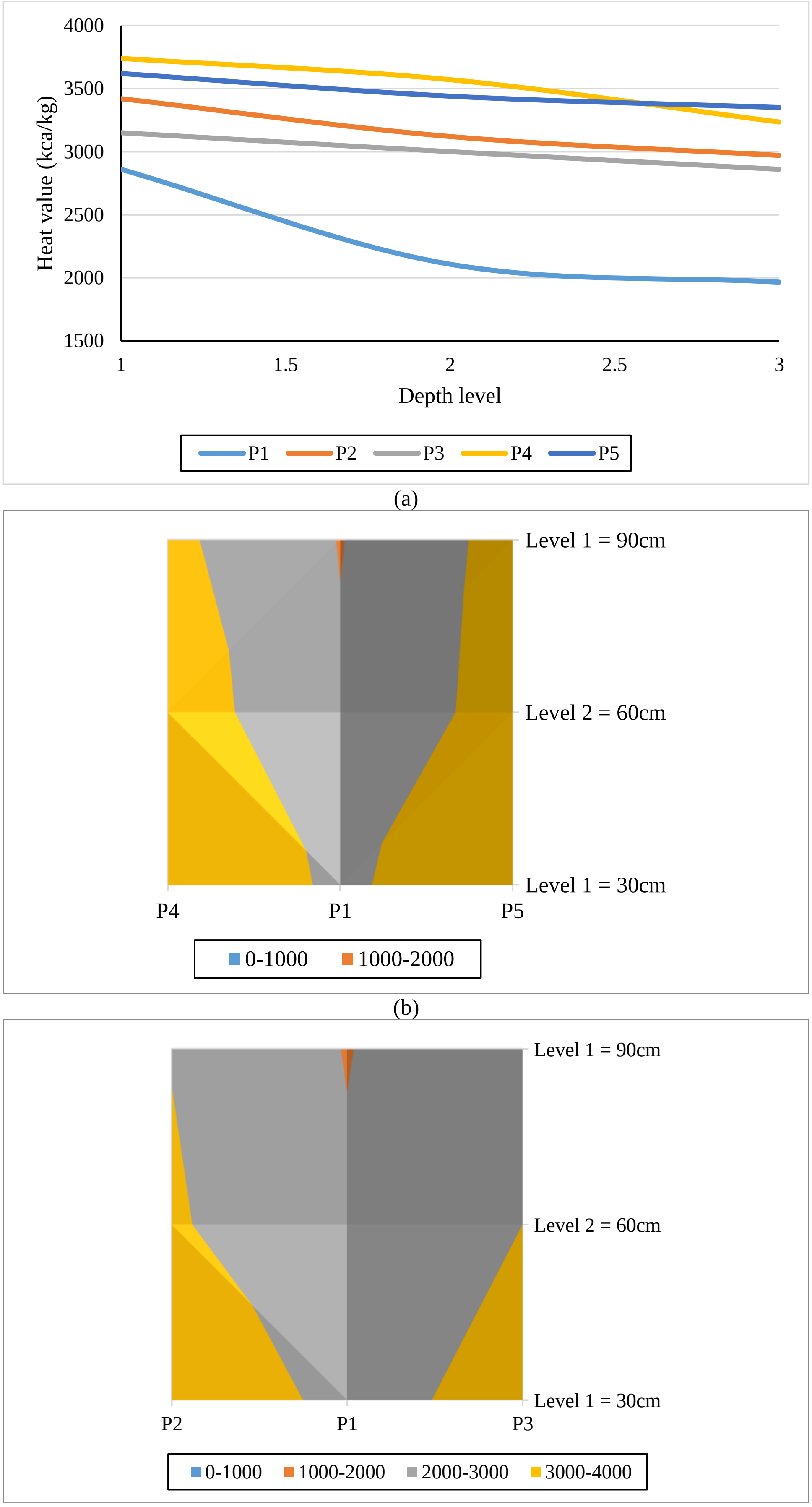
f(x,y) = Heat Value (HV), x = Moisture Percentage (MP), y= Chemical Oxygen Demand (COD)

Coefficients (with 95% confidence bounds):

p00 = -2.116e+05 (-7.028e+05, 2.796e+05)
p10 = 9.584 (-15.45, 34.62)
p01 = 3.535e+04 (-4.281e+04, 1.135e+05)
p20 = -0.0001066 (-0.0004241, 0.0002108)
p11 = -1.308 (-4.93, 2.314)
p02 = -1449 (-3526, 628.1)
p21 = 1.168e-05 (-2.943e-05, 5.28e-05)
p12 = 0.02805 (-0.02281, 0.0789)
p03 = 17.73 (0.8573, 34.61)

Goodness of fit:
SSE: 5.337e+04
R-square: 0.9853
Adjusted R-square: 0.9656
RMSE: 94.31

According to Fig. 7a, it can be concluded that due to the same reason, as the anaerobic digestion of organic compounds, in depth profiles, with increasing sampling depth, the calorific value decreases. While considering the transverse and longitudinal profiles (Figs. 7b and 7c), it can be found that the lowest heat value corresponds to point P1 or the oldest sludge storage place. The reason for this factor can also be considered the biochemical reactions of anaerobic bacteria. Because these samples have been around for 5 years and enough time has been provided to carry out reactions [20].



(c)

Fig. 7. The heat value fluctuation in (a) depth, (b) transverse, and (c) longitudinal profiles.

Considering the accumulation of 4,000 tons of sludge in a very large area in this refinery, and the average calorific value of 3,100, the total amount of energy produced will be significant (12,400 GCal). However, operators should be aware of air pollution management as well as ash residue from combustion and apply the necessary management perspectives [21-23]. This analysis shows a strong nexus of wastewater-energy-pollution in a refinery treatment plant as a major industry unit which is similar to other nexus approaches such as nexus of water-energy-pollution in wastewater treatment plants or the nexus of food-water-energy in the manufacturing industry [24-25].

5. CONCLUSIONS

Sludge management is one of the most important features in wastewater treatment plants. According to many references, between 40 and 60 % of the operating costs of each wastewater treatment plant are related to sludge management. Meanwhile, if the sludge in the treatment plant is recovered and it is produced into energy, a circular economy can be established and a structure can be executed for the integrated sustainable management of the solid waste of the sewage treatment system, especially in industrial units.

This study considered the attention to the wastewater-energy-pollution nexus approach such that a stable structure can be created to create energy from sludge. In oil and gas refineries, the resulting energy is considered significantly that the resulting energy can be used for the management of the refinery or treatment plant. At the same time, the average energy obtained in this study was equal to 3,100 kcal/kg and had a positive relationship with COD and an inverse one with humidity.

It is also recommended for future researches that by estimating the energy consumption of industrial wastewater treatment plants, the role and percentage of sludge energy supply can be proven. Finally, by designing the experiment, more effective factors such as nitrogen and phosphorus can be evaluated in the mentioned process.

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