sciendo

Civil and Environmental Engineering
Vol. 19, Issue 2, 640-648, DOI: 10.2478/cee-2023-0058

PYROLYSIS OF DOMESTIC SEWAGE SLUDGE: EFFECT OF PROCESS PARAMETERS ON BIOCHAR CALORIFIC VALUE

Husam AL-HAMAIEDEH [1,2,*], Salah H. ALJBOUR[3], Tayel EL-HASAN[4], Tuqa AL-MRAYAT[1], Ziad AL-GHAZAWI[5]

[1] Civil and Environmental Engineering Department, Mutah University, 61710 Al-Karak, Jordan.
[2] Civil Engineering Department, Faculty of Engineering Technology, Zarqa University, 2000 Zarqa 13110, Jordan.
[3] Chemical Engineering Department, Mutah University, 61710 Al-Karak, Jordan.
[4] Chemistry Department, Mutah University, 61710 Al-Karak, Jordan.
[5] Civil Engineering Department, Faculty of Engineering, Jordan University of Science and Technology, Irbid, Jordan.
[*] corresponding author: husamh@mutah.edu.jo

Abstract

This research aims to look into a sustainable technique for the treatment, reuse and disposal of domestic sewage sludge (DSS). The purpose of the study was to examine the operating factors that influence the calorific value of the produced biochar from the pyrolysis of DSS. Based on the analysis of the full factorial design, the impacts of the pyrolysis conditions, specifically: temperature, heating rate, and isothermal time on the calorific value of biochar were evaluated. When the pyrolysis temperature was raised from 300 to 500 ºC, the calorific value of biochar was decreased by 34%. A 14% decrease in the calorific content of the biochar was also noticed when the heating rate was increased from 5 to 35 ºC/min. When the isothermal time was increased from 45 to 120 minutes, the calorific value of the biochar remained essentially unchanged. No interaction effects among process variables were found using the factorial design methodology. A first-order regression model was developed to predict the calorific value of biochar using the magnitude of the effects of the process factors and their interactions. The model predictions agreed very well with the obtained experimental results.

Keywords:

Biochar;
Domestic sewage sludge;
Pyrolysis;
Calorific value;
Waste management.

1 Introduction

Annually**,** Jordan generates around 0.66 million tons of domestic sewage sludge (DSS) from the existing 33 wastewater treatment plants (WWTP) [1]. The accumulation of this huge amount of DSS without treatment forms serious environmental challenges. Currently DSS in Jordan is partially treated by anaerobic digestion only in two treatment plants which are Al-Samra and Al-Shallala WWTPS. In the remaining WWTPs, (DSS) is dried and temporary stored in the same plant to be disposed later to landfills [1]. With growing population and urbanization, DSS has been steadily rising throughout the world. Traditional DSS disposal technologies, such as land application and landfilling, have effectively been outlawed in many countries and regions since they are no longer appropriate for managing DSS in the future. Therefore, technologies that are both economically and environmentally viable are required for the proper handling of DSS [2].

On the other hand, more than 95% of the consumed energy in Jordan is being imported from outside the country [3-6]. The DSS is a heterogeneous biomass characterized by high organic matter content, these biosolids could be a source of clean bioenergy and biofertilizers if they converted thermochemically namely via pyrolysis [7-9]. Pyrolysis process involves thermochemical decomposition of organic compounds in the absence of oxygen, at a temperature range from 300 to 800 °C [4, 10, 11]. The main products of the pyrolysis process are recoverable volatile compounds mainly bio-oil, non-condensable gases and biochar (BC), these products are considered green energy sources [12-14].

© Author(s) 2023. This work is distributed under the Creative Commons BY 4.0 license (https://creativecommons.org/licenses/by/4.0/).

The solid product BC is environmentally friendly and considered a source of both energy and sustainable bio-fertilizer. Thermochemical conversion of DSS to BC also reduces the environmental pollution caused by the consumption of both conventional fuels and the chemical fertilizers. The conversion of DSS into bio fuel (bio-oil and BC) and syngas using pyrolysis have been investigated by many researchers [1, 14-16]. The investigations involved exploration of the optimum pyrolysis operational parameters that affect the yield and characteristics of pyrolysis end products. The main pyrolysis parameters were temperature, heating rate, isothermal time beside the moisture content and chemical composition of the feedstock [11]. Findings from literature studies showed that pyrolysis is effective in removing pathogens, significantly reducing the volume of DSS, and recovering materials and energy. According to Hu et al., the produced BC from DSS has a higher energy content than DSS, therefore, it may be burned in pulverized coal-fed systems since the emissions are similar to those of coal burning and the same emission mitigation strategies can be applied [2].

Recently, it has been thought that using DSS as a feedstock in the pyrolysis process is a potential method for recovering resources and energy. However, the properties of the final pyrolysis products vary greatly. Furthermore, the primary parameters influencing the environmental sustainability and commercial viability of DSS pyrolysis are process scale, technology used, sludge collection, and transportation costs. The feedstock cost should not exceed 83 US$/t dry mass for slow pyrolysis and 64 US$/t dry mass for fast pyrolysis to ensure profit generation. [17].

This study aims to investigate the conversion of DSS to BC via pyrolysis as innovative process to achieve safe disposal of DSS and possible reuse of the produced BC as energy source. The novelty in this study was the application of the full factorial design methodology. Full factorial designs provide a comprehensive understanding of how different factors influence the outcome and allow for the detection of interactions between factors. This approach is systematic and can be used to optimize processes or products. The design of experiment methodology employed in this study enables identifying the most influential parameters on the calorific values of the produced BC, through revealing the effect of the main pyrolysis parameters (Temperature, heating rate and isothermal time). Moreover, the possible interaction effects among the pyrolysis parameters can be explored by using this methodology.

2 Materials and methods

2.1 Materials

Samples of air dried DSS were collected from the drying beds at Mutah-Mazar wastewater treatment plant (MM-WWTP) in Jordan. DSS samples were collected via cylindrical containers. The samples then dried at 105 °C for 24 h, and ground to a size of maximum diameter of 5 mm.

2.2 Experimental apparatus

The production of biochar was carried out in a 50 mm ID tubular stainless steel reactor. A split-tube furnace (CARBOLITE, Type VST 12/300, England) used for reactor heating. Heating rate and reactor temperature were managed by a PID controller. The noncondensable gases (NCGs) and bio-oil (BO) were collected downstream the reactor. Two glass bottles were joined in a sequential manner and submerged in an ice bath as part of the BO catching system to ensure total condensation of BO. Gas sampling bags were used to collect the NCGs.

2.3 Experimental procedure

The experiments were carried out in a reduced-air environment. Suction was used to remove the air from the system. 100 g of DSS were added to the reactor and heated at various heating rates from room temperature to the desired final pyrolysis temperature. The isothermal time refers to the operational time after reaching the isothermal conditions. Once the reactor reached its final isothermal condition, the reactor was operated for 45, 60 or 120 min.

The calorific values of the produced BC were determined using gross heat of combustion test according to ASTM D 240-19 method, using a bomb calorimeter (6300 Calorimeter A1200 DDEE, Parr, IL, USA).

2.4 Full factorial design methodology

To examine the impacts of three process parameters, namely temperature (Temp), heating rate (HR), and isothermal time (Time), a 2^3 type full factorial design approach was used. The levels of the process parameters used in this study are shown in Table 1.

Table 1: Levels of process parameters employed in this study.

	Low level (-1)	**High level (+1)**
Temp [^{o}C]	300	500
HR [^{o}C/min]	5	35
Time [min]	45	120

The experiments are conducted for each combination of factor levels. The total number of experimental runs is equal to the product of the levels of all the factors. In a full factorial design, every possible combination of factor levels is tested. This means that all possible interactions between the factors are studied.

For each run, process response concerning calorific value (CV) of the produced BC were determined. To improve the reliability of the results, it is common to conduct multiple replicates of each experimental run. For each iteration of the experimental run, a set of three replicates was performed, and the reported data represents the arithmetic mean of these replicates. Table 2 displays the experimental runs and process response for the full factorial design approach used in this investigation. The means of effects and interactions were calculated using the statistical program Minitab 17. The software was also used to create the interaction, contour, and main effect plots.

Table 2: Levels of process parameters employed in this study.

	Temp	**HR**	**Time**	**CV [MJ/kg]**	**VM [%]**	**Ash [%]**	**FC [%]**
Experimental run for a 2^3 type full factorial design	-1	-1	-1	17.73	51.07	42.82	6.11
	+1	-1	-1	11.65	30.07	55.16	14.78
	-1	+1	-1	15.2	49.48	43.34	7.18
	+1	+1	-1	10.4	24.85	60.23	14.93
	-1	-1	+1	17.99	42.61	44.34	13.05
	+1	-1	+1	11.36	21.85	58.26	19.89
	-1	+1	+1	15.2	32.44	52.01	15.55
	+1	+1	+1	11.36	21.15	62.03	19.82
Experimental runs for model validation	0	-1	-1	17.15			
	0	1	-1	16.66			
	0	-1	1	15.11			
	0	1	1	12.9			
	-1	-1	-1.8	17.93			
	-1	1	-1.8	17.34			
	-1	-1	-0.6	17.04			
VM = volatile matter FC = fixed carbon							

3 Results and discussion

3.1 Full factorial design analysis

Full factorial design is a structured and rigorous approach to experimental design that allows exploring the effects of multiple factors and their interactions systematically. It is particularly useful for gaining a comprehensive understanding of complex systems or processes [19, 20]. The results of experiments based on the full factorial design methodology are analyzed by constructing the main effects and interaction plots shown in Figs. 1 and 2 respectively.

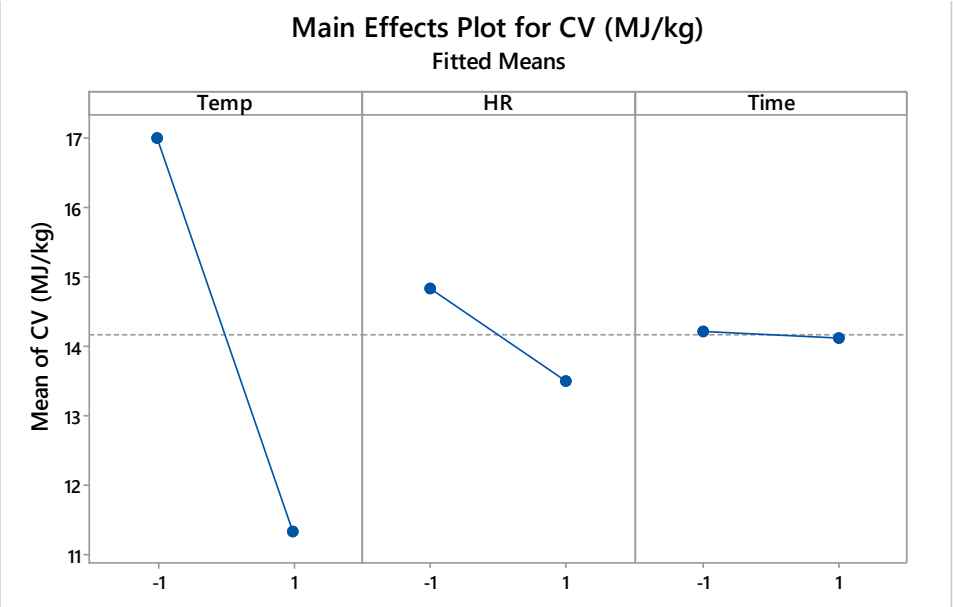


Fig. 1: Main effect plots for the process variables.

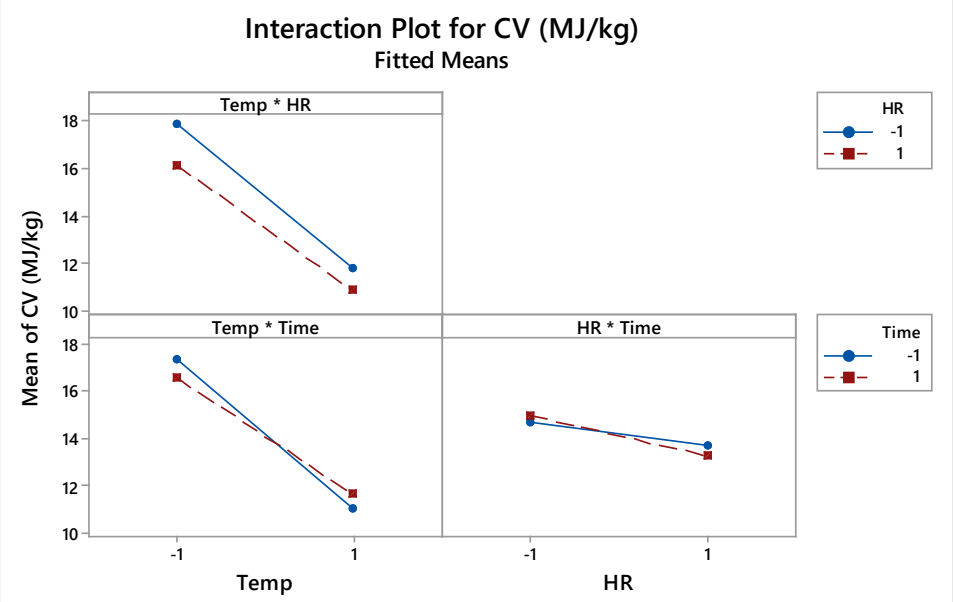


Fig. 2: Interaction plots for process variables.

Fig. 1 indicates that pyrolysis temperature has an adverse effect on the calorific value of the produced biochar. The production of biochar at low pyrolysis temperature (300 ^{o}C) yielded biochar samples with average calorific value of 17.0 MJ/kg. In contrast, biochar samples with an average calorific value of 11.3 MJ/kg were produced at high pyrolysis temperatures (500 ^{o}C). Increasing the pyrolysis temperature decreased the biochar CV. The decrease in biochar yield as temperature rises can be ascribed to either increased primary breakdown of the feedstock or secondary decomposition of the biochar residues [11].

The high temperature pyrolysis of DSS produced biochar with a lesser amount of volatile matters. The experimental results shown in Table 2 indicate that the average VM content for biochar samples produced at 300 ^{o}C was 43.9 %, while the average volatile matter (VM) content for biochar samples produced at 500 ^{o}C was 24.5%. A high pyrolysis temperature facilitates the synthesis of biochar with a high ash and carbon content but a low VM content. This is most likely owing to extensive organic matter breakdown [18]. Combustible gases such as hydrocarbons, hydrogen, oxygen, carbon monoxide, sulfur, and noncombustible gases make up the VM content. The hydrocarbons could be short- and long-chain hydrocarbons, and aromatic hydrocarbons. Biochar with a greater VM content can be advantageous for ignition and combustion processes because it is easier to ignite, has better flame stability, and improves carbon burnout [21].

The heating rate has also negatively impacted the CV of the produced biochar as shown in Fig. 1. Increasing the heating rate from 5 to 35 ^{o}C/min decreased the average biochar from 14.8 to 13.5 MJ/kg. At high heating rate, volatiles release is increased resulting in biochar with less VM content. The proximate analysis shown in Table 2 indicates that the average VM content for biochar samples produced at heating rate of 5 ^{o}C/min was 36.4 %, while the average VM content for biochar samples produced at a heating rate of 35 ^{o}C/min was 32.0 %. These results are in agreement with information from literature that increasing heating rate will promote a reduction in the VM content of biochar [22]. The production of biochar with less VM content at higher heating rates produced biochar with less heating value accordingly.

The pyrolysis time at isothermal conditions has barely affected the calorific value of biochar. Extending the time from 45 to 120 min, produced biochar samples with almost a constant calorific value for a given isothermal condition. It seems that most of the volatiles are released during the course of DSS heating and prior to reaching the isothermal conditions.

The results from the interaction plots (Fig. 2) indicate very week interaction effect exists among process variables. The effect of a given process variable (temperature, heating rate or time) on the CV of biochar is independent on the operating conditions of the other process variables.

Temperature and heating rate were identified as the two most critical factors influencing biochar CV in the previous analysis. For these two factors, the DOE contour plot is formed (Fig. 3). A contour plot is composed of curves, each of which has constant value for a fitted response (CV). The curves' response values are equally spaced. The contour plot is commonly used to choose settings that would optimize the response variable. It may also be used to find parameters that cause the response variable to reach a predetermined target value.

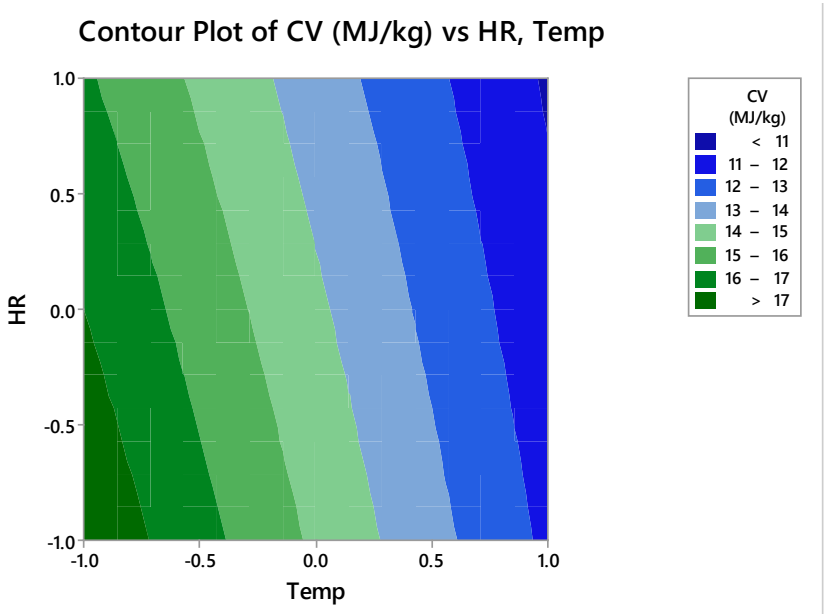


Fig. 3: Contour plot of biochar calorific values versus pyrolysis temperature and heating rate.

The contour plot indicates that biochar with higher CV are preferable to be produced at settings of low pyrolysis temperatures and heating rates.

A first order regression model is developed to predict biochar calorific value. A first-order regression model can serve as an exploratory tool to identify potential factors that influence biochar calorific value. It helps in the initial assessment of which variables are statistically significant and deserve further investigation. Developing this model can help in visualizing the data and understanding how the predictor variables are distributed and correlated with calorific value. This initial understanding can guide subsequent data collection efforts and research directions.

The model includes all coefficients representing the individual effects of each process variables and the two and three interaction effects among process variables. The regression model is based on the results of the full factorial design analysis. The regression model in un-coded units is given in equation 1:

$$\mathrm{CV}\left[\frac{\mathrm{MJ}}{\mathrm{kg}}\right] = 14.17 - 2.829\,\mathrm{Temp} - 0.6612\,\mathrm{HR} - 0.04375\,\mathrm{Time} + 0.1962\,\mathrm{Temp}*\mathrm{HR} + 0.3638\,\mathrm{Temp}*\mathrm{Time} - 0.1887\,\mathrm{HR}*\mathrm{Time} + 0.3487\,\mathrm{Temp}*\mathrm{HR}*\mathrm{Time} \quad (1)$$

Fig. 4 shows a comparison between the experimental values of the calorific value and the predicted ones.

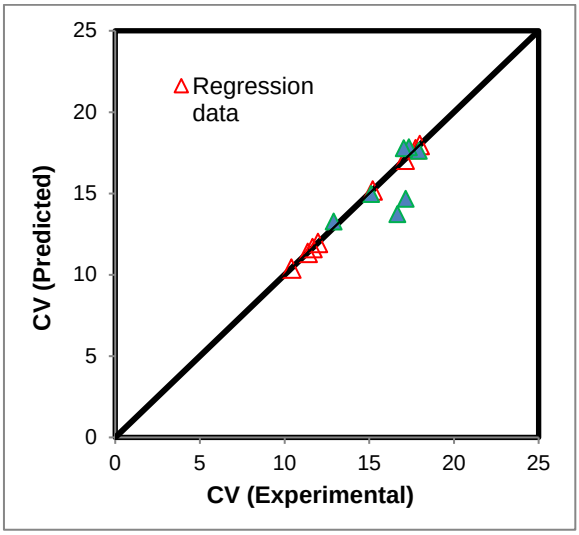


Fig. 4: First order model prediction of biochar calorific values.

The first-order model demonstrated a perfect fit to the experimental data, as evidenced by an R-squared coefficient of 0.999. It is important to validate if the numerical findings generated from the regression analysis which quantify the hypothesized relationships between variables are acceptable as data descriptions. A validation method was employed to verify the regression's goodness of fit and to see if the model's predictive ability deteriorated significantly when applied to data that were not used in model estimate. The second data set shown in Table 2 was used to validate the suitability of the first order regression model. The results shown in Fig. 4 indicate clearly that the first order regression model (Equation 1) fitted very well the experimental data of the calorific values. The obtained average absolute error between experimental and predicted values were 1.06.

3.2 Potential of DSS as energy source

The CV of the produced biochar in this study is compared to other types of fuels. Table 3 reports the calorific value of several type of fuels.

Table 3: Calorific values for various fuels.

Fuel	CV [MJ/kg]	Reference
Cow manure	12.3	[23]
Sheep and goats manure	16.9	[23]
Poultry manure	12.3	[23]
Olive cake (Jift)	19.8	[24]
Jordanian oil shale	36.84	[24]
Jordanian tar sand	22.01	[24]
RDF-1	23.75	[25]
RDF-2	19.55	[25]
Un-processed MSW	7.39	[25]
Raw dried DSS	12.69	This study
Biochar	10.4-17.99 14.2 (Average)	This study

It is essential to select a fuel that meets the needs in terms of energy output, cost-effectiveness, accessibility, and environmental concerns. Un-processed DSS possessed low CV. The pyrolysis of DSS produced various biochar products of high caloric value which enable their use as energy source. Even though biochar has a lesser calorific value than certain other solid fuels, using it as fuel can still have positive effects including lowering waste production and reducing the need for other fossil fuels.

It is worth noting that compared to other thermal processes like incineration, pyrolysis is often considered more environmentally friendly due to its lower air pollutant emissions and its ability to produce valuable byproducts like biochar and biofuels. However, as with any industrial process, environmental impacts must be carefully managed to minimize negative effects on air quality [26].

4 Conclusion

This study revealed that the treatment of DSS by pyrolysis can be applied as acceptable and sustainable management practice to solve the problem of DSS accumulation in Jordan. Moreover, the pyrolysis products are of high caloric value which enable their use as energy source. In this study the operational conditions of pyrolysis, namely: temperature, heating rate, and isothermal time, were tested based on full factorial analysis. The results show that the increase in pyrolysis temperature from 300 ^{o}C to 500 ^{o}C decreased the average CV of the produced BC from DSS by about 34%, due to the decrease of the VM content of the produced BC with temperature increase.

By raising the heating rate from 5 to 35 ^{o}C/min, the average CV of the produced BC decreased by about 14 %, due to decrease in the VM content in the produced BC which associated with the increase in the heating rate.

The average CV of the produced BC remained almost constant when the isothermal time increased from 45 to 120 minute especially when high pyrolysis temperatures were used. This probably occur as most of the volatiles are released during the course of DSS heating and prior to reaching the isothermal conditions. The results indicate that to produce BC with higher CV, low pyrolysis temperatures and less rates of heating are preferable.

Acknowledgement

The Center of Excellence for Innovation Projects at Jordan University for Science and Technology (UNICEF/WASH Innovation Hub) is acknowledged for the financial assistance in constructing the experimental apparatus.

The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), is acknowledged for the financial support for chemical analysis.

The Deanship for Scientific Research Support Fund at Mutah University/Jordan is acknowledged for the partial funding for this study.

References

[1] AL-MRAYAT, T. - AL-HAMAIEDEH, H. - EL-HASAN, T. - ALJBOUR, S.H. - AL-GHAZAWI, Z. - MOHAWESH, O.: Pyrolysis of domestic sewage sludge: influence of operational conditions on the product yields using factorial design. Heliyon, Vol., 2022.

[2] HU, M. - YE, Z. - ZHANG, H. - CHEN, B. - PAN, Z. - WANG, J.: Thermochemical conversion of sewage sludge for energy and resource recovery: technical challenges and prospects. Environmental Pollutants and Bioavailability, Vol. 33, 1, 2021, p. 145-163.

[3] ALJBOUR, S.H. - EL-HASAN, T. - AL-HAMAIEDEH, H. - HAYEK, B. - ABU-SAMHADANEH, K.: Anaerobic co-digestion of domestic sewage sludge and food waste for biogas production: A decentralized integrated management of sludge in Jordan. Journal of Chemical Technology and Metallurgy, Vol. 56, 5, 2021, p. 1030-1038.

[4] AL-AYED, O. - EL-HASAN, T. - AMRO, A. - MATOUQ, M. - KOOLI, F.: Treated oil shale ash and its capacity to remove Cd and Pb from aqueous solutions. Oil Shale, Vol. 39, 4, 2022, p. 308-324.

[5] AL-HAMAIEDH, H. - MAAITAH, O. - MAHADIN, S.: Using oil shale ash in concrete binder. Electronic Journal of Geotechnical Engineering, Vol. 15, 2010, p. 601-608.

[6] EL-HASAN, T. - SZCZERBA, W. - BUZANICH, G.n. - RADTKE, M. - RIESEMEIER, H. - KERSTEN, M.: Cr (VI)/Cr (III) and As (V)/As (III) ratio assessments in Jordanian spent oil shale produced by aerobic combustion and anaerobic pyrolysis. Environmental Science and Technology, Vol. 45, 22, 2011, p. 9799-9805.

[7] PULKA, J. - WIŚNIEWSKI, D. - GOŁASZEWSKI, J. - BIAŁOWIEC, A.: Is the biochar produced from sewage sludge a good quality solid fuel? Archives of Environmental Protection, Vol. 42, 4, 2016, p. 125-134.

[8] TRABELSI, A.B.H. - ZAAFOURI, K. - FRIAA, A. - ABIDI, S. - NAOUI, S. - JAMAAOUI, F.: Municipal sewage sludge energetic conversion as a tool for environmental sustainability: production of innovative biofuels and biochar. Environmental Science and Pollution Research, Vol. 28, 8, 2021, p. 9777-9791.

[9] ALJERADAT, R.A. - ALJBOUR, S.H. - JARRAH, N.A.: Natural minerals as potential catalysts for the pyrolysis of date kernels: effect of catalysts on products yield and bio-oil quality. Energy Sources, Part A: Recovery, Utilization, Environmental Effects, Vol., 2021, p. 1-9.

[10] ALJBOUR, S.H.: Catalytic pyrolysis of olive cake and domestic waste for biofuel production. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, Vol. 40, 23, 2018, p. 2785-2791.

[11] ALJERADAT, R.A. - ALJBOUR, S.H. - JARRAH, N.A.: Pyrolysis of date kernels using natural Jordanian Tripoli as a catalyst under different operational conditions. Case Studies in Chemical and Environmental Engineering, Vol. 6, 2022, p. 100212.

[12] FONTS, I. - GEA, G. - AZUARA, M. - ÁBREGO, J. - ARAUZO, J.: Sewage sludge pyrolysis for liquid production: a review. Renewable Sustainable Energy Reviews, Vol. 16, 5, 2012, p. 2781-2805.

[13] HASSEN-TRABELSI, A.B. - KRAIEM, T. - NAOUI, S. - BELAYOUNI, H.: Pyrolysis of waste animal fats in a fixed-bed reactor: Production and characterization of bio-oil and bio-char. Waste Management, Vol. 34, 1, 2014, p. 210-218.

[14] GAO, N. - KAMRAN, K. - QUAN, C. - WILLIAMS, P.T.: Thermochemical conversion of sewage sludge: A critical review. Progress in Energy Combustion Science, Vol. 79, 2020, p. 100843.

[15] ALVAREZ, J. - LOPEZ, G. - AMUTIO, M. - ARTETXE, M. - BARBARIAS, I. - ARREGI, A. - BILBAO, J. - OLAZAR, M.: Characterization of the bio-oil obtained by fast pyrolysis of sewage sludge in a conical spouted bed reactor. Fuel Processing Technology, Vol. 149, 2016, p. 169-175.

[16] KARACA, C. - SÖZEN, S. - ORHON, D. - OKUTAN, H.: High temperature pyrolysis of sewage sludge as a sustainable process for energy recovery. Waste Management, Vol. 78, 2018, p. 217-226.

[17] BROWN, T.R. - WRIGHT, M.M. - BROWN, R.C.: Estimating profitability of two biochar production scenarios: slow pyrolysis vs fast pyrolysis. Biofuels, Bioproducts and Biorefining, Vol. 5, 1, 2011, p. 54-68.

[18] ALJBOUR, S.H.: Intensification of Shale Oil Extraction from Oil Shale - An Alternative Solution for Sustainable Energy in Jordan, Journal of Engineering Science and Technology, Vol. 14 (4), 2020, p. 1764-1775.

[19] ALIEDEH, M.A. - ALJBOUR, S.H. - AL-HARAHSHEH, A.M. - AL-ZBOON, K. - AL-HARAHSHEH, S.: Implementing $2^{(4-1)}$ Fractional factorial Design for Filling the Gabs in OVAT Sorption Studies of Nitrates Ions onto Jordanian Zeolitic Tuff. Journal of Chemical Technology & Metallurgy, Vol. 56 (2), 2020, p. 331-341.
[20] TOMCZYK, A. - SOKOŁOWSKA, Z. - BOGUTA, P.: Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Reviews in Environmental Science and Bio/Technology, Vol. 19, 1, 2020, p. 191-215.
[21] MILLER, B., Fuel considerations and burner design for ultra-supercritical power plants, in Ultra-Supercritical Coal Power Plants. 2013, Elsevier. p. 57-80.
[22] TARELHO, L. - HAUSCHILD, T. - VILAS-BOAS, A. - SILVA, D. - MATOS, M.: Biochar from pyrolysis of biological sludge from wastewater treatment. Energy Reports, Vol. 6, 2020, p. 757-763.
[23] AL-HAMAMRE, Z. - AL-MATER, A. - SWEIS, F. - RAWAJFEH, K.: Assessment of the status and outlook of biomass energy in Jordan. Energy Conversion and Management, Vol. 77, 2014, p. 183-192.
[24] KABLAN, M.M. - ALKHAMIS, T.M.: An experimental study for a combined system of tar sand, oil shale, and olive cake as a potential energy source in Jordan. Biomass and Bioenergy, Vol. 17, 6, 1999, p. 507-515.
[25] AL-HAJAYA, M. - ALJBOUR, S.H. - AL-HAMAIEDEH - ABUZAID, M. - EL-HASAN, T.M. - HEMIDAT, S. - NASSOUR, A.: Investigation of Energy Recovery from Municipal Solid Waste: A Case Study of Al-Karak City/Jordan. Civil and Environmental Engineering, Vol. 17, 2, 2021, p. 610-620.
[26] ALHUNITY, R. - ALJBOUR, S.H. - EL-QADA, E.: Life Cycle Assessment of Asphalt Mix Containing Jordanian Oil Shale Ash. Ecological Engineering and Environmental Technology, Vol. 24, 2, 2023, p. 79-86.