HUNGARIAN JOURNAL OF
INDUSTRY AND CHEMISTRY
Vol. 50(2) pp. 27-33 (2022)
hjic.mk.uni-pannon.hu
DOI: 10.33927/hjic-2022-15

INVESTIGATION OF THE PYROLYSIS OF ANIMAL MANURE IN A LABORATORY-SCALE TUBULAR REACTOR: THE EFFECT OF THE PROCESS TEMPERATURE AND RESIDENCE TIME

Maria Elena Lozano Fernandez[1], Szabina Tomasek[1]*, Csaba Fáyköd[2] and Andrea Somogyi[3]

1 Research Centre for Biochemical, Environmental and Chemical Engineering, Department of MOL Hydrocarbon and Coal Processing, University of Pannonia, Egyetem u. 10, Veszprém, 8200, HUNGARY
2 Felső-Bacska Storage Windpark Ltd., Arany János út 200, Fadd, 7133, HUNGARY
3 Solver Unio Ltd., Ábel Jenő u. 8, Budapest, 1113, HUNGARY

This paper focuses on the pyrolysis of animal manure in a laboratory-scale tubular reactor between 300 and 900°C at nitrogen flow rates of 1 and 5 dm^3/h. During the experiments, it was found that both the temperature and nitrogen flow rate had significant effects on the product yields and compositions. The highest gas yield and syngas content were observed at 900°C at a nitrogen flow rate of 1 dm^3/h. In this case, since the gaseous product was characterized by a H_2/CO ratio of 0:5, its quality must be improved prior to being used for synthesis. The composition of the solid residue was also affected by the pyrolysis parameters. Based on the hydrogen/carbon and oxygen/carbon ratios, it was concluded that both the water-gas shift and Boudouard reactions were the most critical.

Keywords: cattle manure, pyrolysis, tubular reactor, product yield, composition

1. Introduction

The rapid growth of the world's population is leading to a significant rise in the demand and consumption of food, including meat and animal-derived products. As a consequence, farms and this sector generate huge amounts of waste such as livestock manure, sewage sludge and poultry litter [1]-[2]. The inadequate management of manure and sewage sludge causes serious health and environmental issues, e.g. water and air pollution as well as the emission of greenhouse gases and heavy metals in addition to the spread of pathogens. The composition of this residue includes a wide variety of chemical and biological compounds which are associated with the specific species of animals and age ranges amongst other factors. The residue consists of a complex mixture of compounds, mainly microbiota, lignocellulose, proteins as well as a significant amount of inorganic matter such as S, N, P, K, Ca, Mg and Cl. Additionally, heavy metals such as Cu, Pb, Cd, Zn and Mn can be found in the residue due to the use of antibiotics and hormones supplied to the animals [3]-[5]. Some of the practices concerning the disposal of sewage sludge and manure include landfilling, agricultural utilization, composting, anaerobic digestion and thermochemical conversion [6]. One of the most traditional and practical alternatives is the usage of these residues in agricultural land due to the high content of N and P which are essential elements required in plant fertilization. However, nowadays, this practice has diminished due to the enormous amount of waste generated, exceeding the nutritional requirements of the soil. Environmental regulations establish limits on the values allowed for the usage of sewage sludge in agriculture. The excessive use of manure on land causes problems such as contamination of the subsoil and surface, odors as well as the emission of greenhouse gases and ammonia [5,7-10].

Therefore, new alternatives for the proper management of this type of waste have been explored as well as studied more comprehensively in an attempt to solve the environmental and social impacts [8]. For example, thermal conversion techniques such as pyrolysis and gasification could be alternatives for transforming the residue into valuable products such as oil, char and gaseous products. Additional advantages of these techniques are that the huge volume generated is reduced, microorganisms are degraded and pathogenic organisms destroyed [1,9-10]. It is important to take into consideration that the percentage of humidity in the residues in the material is high and should be reduced while using the thermal techniques. The material could

---

Received: 26 Sept 2022; Revised: 10 Oct 2022; Accepted: 11 Oct 2022
*Correspondence: tomasek.szabina@mk.uni-pannon.hu

be dried through natural, mechanical and thermal drying techniques [11]. Depending on the thermal degradation technique applied, the composition of the feedstock; process conditions, e.g. temperature and heating rate; as well as product distribution and its composition will vary [11]. For example, during pyrolysis, degradation in the absence of oxygen occurs at high temperatures. Through pyrolysis, the feedstock decomposes to form char, oil and light non-condensable gases [11]. In the case of the raw material containing a large amount of hemicellulose and cellulose, a product consisting of a higher percentage of gases could be expected, while lignin contributes towards the formation of char. Regarding the temperature, the formation of char is favored by low temperatures, while that of oil and volatile gaseous components is more likely at high temperatures [12]. The products can be further utilized depending on their characteristics. Char has interesting physical properties, for example, a high surface area, microporosity as well as high adsorption and ion exchange capacities. Char potentially could be used as an adsorbent, a catalyst, in power plants or as a fertilizer. Char obtained from manure is rich in elements such as K, P, Ca and Mg [10], [12]. In the oil fraction, hydrocarbons are produced but the pyrolysis oil from manure and sewage sludge is not regarded as of high quality since the oil produced contains oxygen, which gives rise to the production of compounds such as alcohols, ketones, aldehydes and esters that decrease the quality of the product [1]. The gas produced contains a mixture of CO, CO_2, CH_4, H_2 and some light hydrocarbons (C_2H_2, C_2H_4, C_2H_6 and C_3H_8) [13]. The gas may be valuable because the energy it contains could be used in gas turbines and power plants or its compounds applied as a feedstock to be processed into a more added-value chemical product [13]-[14]. Despite the wide range of possible uses of the products, relatively few studies have investigated the pyrolysis of cattle manure. Consequently, limited information about the product yields and compositions is available.

In light of the above, this study focuses on the pyrolysis of cattle manure within the temperature range of 300-900°C using nitrogen flow rates of 1 and 5 dm^3/h as well as on the impact of the process parameters.

2. Materials and methods

2.1. Raw material

Cattle manure was used as a feedstock for the pyrolysis experiments. Before the experiments, the raw material was dried at 110°C to constant mass.

To determine the physical and chemical properties, the proximate and ultimate analyses of cattle manure (*Table 1*) were carried out. As data show, the raw material is characterized by 40.6% ash, 53.5% volatile compounds and 0.3% water content.

The C, H, N, S and O contents were determined by a Carlo Erba-type elemental analyzer and in order to identify the inorganic compounds, e.g. Ca, P, S, Si, Na, Mg, Fe and Al, Energy Dispersive X-Ray Analysis was performed (Shimadzu EDX).

Table 1. Proximate and ultimate analyses of cattle manure

	Parameter	Value (%)
Proximate analysis	Fixed carbon	5.59
	Ash content	40.68
	Volatile organic compounds	53.43
	Water content	0.30
Ultimate analysis	C	24.80
	H	3.00
	N	2.90
	S	1.30
	O	45.30
	Others (Ca, P, S, Si, Na, Mg, Fe, Al)	22.70

2.2. Pyrolysis experiments

Pyrolysis was performed in a laboratory-scale horizontal tubular reactor (*Fig.1*). The cattle manure was placed in the center of a glass wool tube. The experiments were performed at 300, 500, 700 and 900°C. A N_2 atmosphere was used and the flow rates established were 1 and 5 dm^3/h. The heating rate used for this experiment was 100°C/min. The reaction system was equipped with a scrubber and silica gel-filled tube, where the gaseous products were purified to remove possible impurities and dried. At the end of the reaction, the product yields were estimated by measuring and calculating their difference in mass.

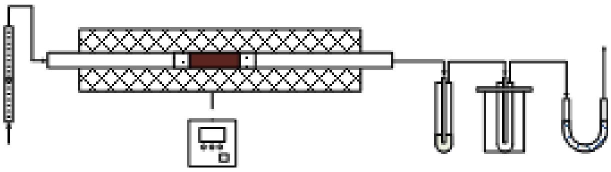


Figure 1. Experimental setup

2.3. Product analysis

The composition of the gaseous products was determined by a DANI-type gas chromatograph using a flame ionization and thermal conductivity detectors. The equipment contained two capillary columns (Rtx-1 PONA (100 m x 0.25 mm x 0.5 µm) and Carboxen TM-1006 PLOT (30 m x 0.53 mm)). Regarding the isothermal conditions of the PONA capillary column, the injector and detector temperatures were both 230°C. In terms of the Carboxen TM-1006 PLOT capillary column, the applied heating program was as follows: 35°C for 18 mins before being heated to 120°C at a heating rate of 15°C/min and maintained at 120°C for 2 mins. The retention times of the components were determined using gas mixtures and individual components.

3. Results and Discussion

3.1. Product yields

The product yields of the pyrolysis experiments are summarized in *Fig.2*. During the experiments, only gas and char were formed. As expected, the gas yields and amount of solid residue produced increased and decreased, respectively, as a function of the reaction temperature. During the pyrolysis process, a series of complex reactions took place.

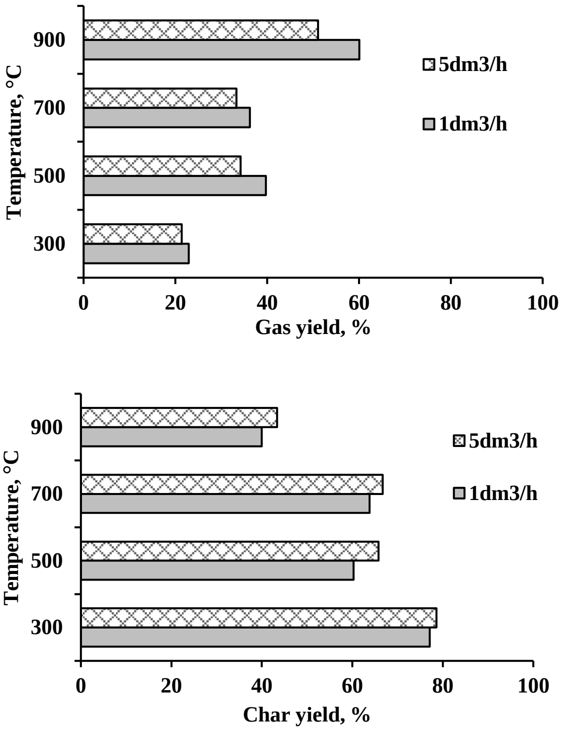


Figure 2. Product yields of pyrolysis

Up to 200°C, to all intents and purposes, only the water was removed from the cattle manure (*Fig.3*). In the torrefaction stage, since cellulose, hemicellulose and lignin were only slightly degraded, the final product was a solid carbonaceous material. This stage was followed by the pyrolysis process, where a significant reduction in mass resulted. In addition, a sharp peak appeared at approximately 300°C in the derivative thermogravimetric diagram (DTG), indicating that the reduction in mass occurred at a high speed. It is well known that cellulose degradation occurs between300 and 350°C, while protein decomposes between 450 and 660°C. In addition, deamination also took place.

During the pyrolysis stage, approximately 30% of the initial mass was lost. Above 600°C, another significant proportion of mass, ~25%, was lost. This reduction in mass was related to the degradation of chains of lignin, carbon and minerals. It was also observed that the rate at which the mass reduced was low and relatively stable. This effect could be attributed to the minerals and possible carbonated forms. Additionally, it is worth mentioning that within this temperature range, CO_2 was also formed. CO_2 acts as an oxygen donor, promoting the Boudouard reaction and, therefore, the formation of CO. Another peak is also visible at 800°C in the DTG curve, which can be attributed to the devolatilization of the char and decomposition of the mineral matter. At the end of the test, that is, at a temperature of 900°C, the percentage of mass consisting of ash and fixed carbon remaining in the crucible was the same as that reported during the proximate analysis.

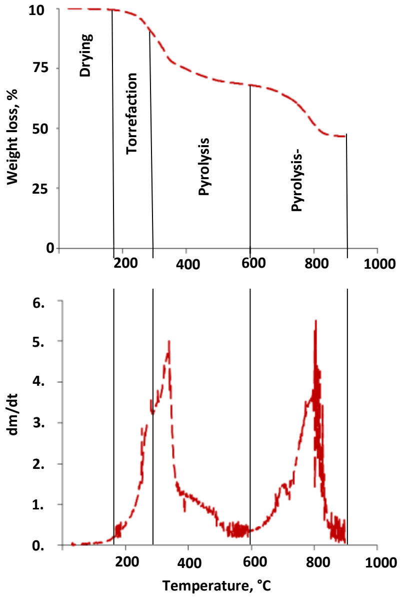


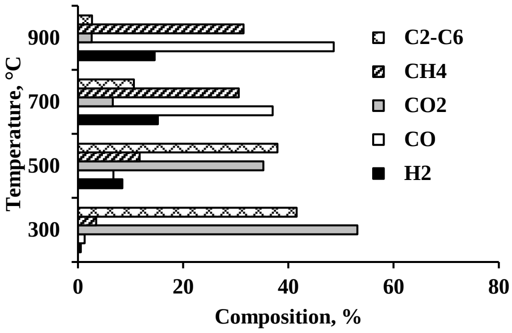
Figure 3. Thermogravimetric results with regard to the raw material

It is important to note that the N_2 flow rate also had an effect on the product yields. The lower flow rates facilitated the formation of the gaseous products. Given the longer residence time, the volatile vapors resuting from the pyrolysis exited the reactor more slowly, so they had sufficient time to degrade more comprehensively.

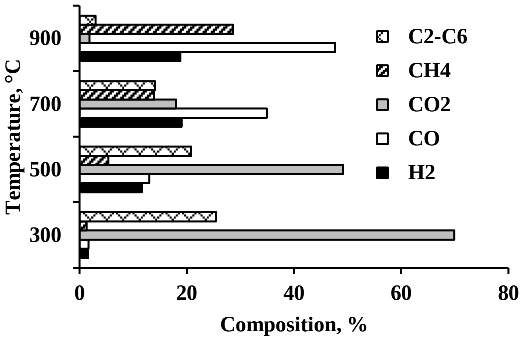
3.2. Composition of the gaseous products

Although the gaseous products consisted of H_2, CO, CO_2 and CH_4, C_2-C_6 hydrocarbons were also formed (*Fig.4*). H_2 was formed by dehydrogenation, however, it could have formed as a result of the reforming reactions. CO may be related to the reactions that facilitated the cleavage of bonds in the ether groups and decarbonylation from proteins [15]-[16].

As *Fig.4* shows, the formation of CO considerably increased above 700°C and the highest level was obtained at 900°C. This large increase was attributed to the Boudouard reaction, which has already been referred to in the thermogravimetric analysis. The Boudouard reaction can also be catalyzed by carbonates present in the manure [17]. The increase in CO can also be justified by a reaction between CO_2 and other compounds generated during pyrolysis, the reduction of CO_2 to CO



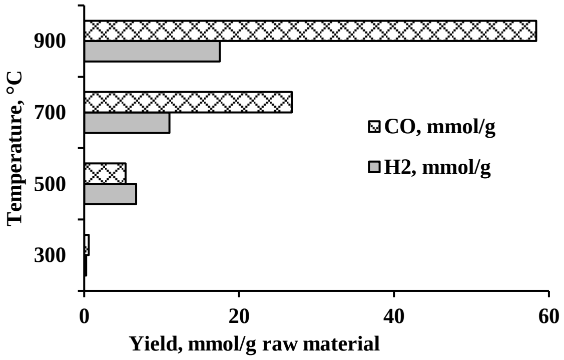
(N_2 flow rate: 1 dm^3/h)



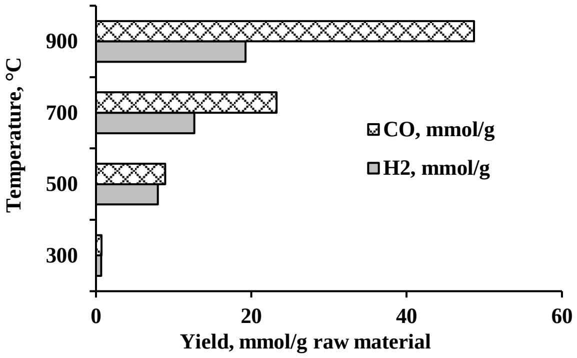
(N_2 flow rate: 5 dm^3/h)

Figure 4. Composition of the gas products

and simultaneously the oxidation of the carbon of the pyrolysis product through a homogeneous reaction [18].



(N_2 flow rate: 1 dm^3/h)



(N_2 flow rate: 5 dm^3/h)

Figure 5. Syngas yields

The quality of the gaseous product can be defined in terms of its chemical composition and calorific value. *Fig.5* represents the content of syngas, namely H_2 and CO, in the product.

From the results, it is remarkable that the production of syngas only took place above 500°C and the yield increased in proportion to the temperature. The highest syngas yields (~80%) were observed at 900°C. It is important to emphasize that the N_2 flow rate also had an effect on the syngas yield. The yield of syngas was higher at lower N_2 flow rates, in the same manner as the overall gas yield.

The H_2/CO ratio of syngas (*Fig.6*) is extremely important. The typical initial ratios for the transformation of methanol into chemicals are >2:1 for light olefins; <2:1 for diesel; 1.5:1 for aldehydes, higher alcohols and dimethyl ether; 1:1 for oxygen-containing alcohols and acetic acid; and 1:2 for polycarbonate [19]-[20]. As data in *Fig.6* show, although the ratio of H_2/CO at 500°C was approximately 1, at 700 and 900°C it was below 0.6.

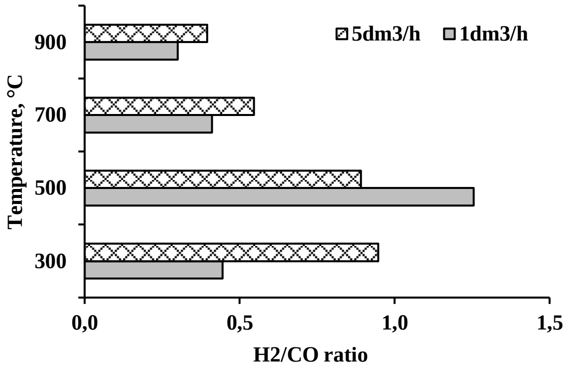


Figure 6. H_2/CO ratios of syngas

The heating values of the gases were also estimated. As is depicted in *Fig.7*, at lower temperatures (300 or 500°C) and an N_2 flow rate of 1 dm^3/h, the calorific value of the gas mixture was higher (~30 MJ/m^3), meanwhile, at higher N_2 flow rates, the heating value of the gaseous product was about 15 MJ/m^3 at the same temperatures.

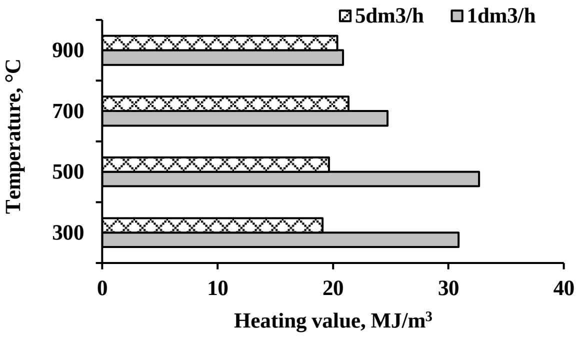


Figure 7. Heating values of the gaseous products

This can be explained by the fact that a higher percentage of light hydrocarbons is present, the individual components of which provide a higher calorific value than the other compounds present in the mixture [21].

Another interesting correlation is the difference in the proportions of different elements contained in the gas as well as the resultant study and proposition of possible reaction mechanisms at different temperatures. The trends observed when the ratio of components were estimated are summarized in *Table 2*. From the process, the water-gas shift reaction and Boudouard reaction are some of the critical reactions that took place [14].

3.3. Char

According to the International Biochar Initiative (IBI), the char obtained from the pyrolysis experiments can be regarded as biochar [22], in which the C content is greater than 10% except for during the tests carried out at 900°C.

Table 2. The proportions of different elements

Component ratio	N_2 flow rate: 1 dm^3/h	N_2 flow rate: 5 dm^3/h	Relationship	Proposed reaction
H_2/CO	Optimum (highest peak at 500°C)	Optimum (highest peak at 500°C)	Higher ratio at a flow rate of 5 dm^3/h (except for at 500°C)	$C_nH_m + H_2 \rightarrow \frac{n+m}{2H_2} + nCO$ $CO + H_2O \rightarrow CO_2 + H_2$
CO/CO_2	Increasing	Increasing	Higher ratio at a flow rate of 5 dm^3/h	$C + CO_2 \rightarrow 2CO$
H_2/CH_4	Optimum (highest peak at 500°C)	Optimum (highest peak at 500°C)	Higher ratio at a flow rate of 5 dm^3/h	$C + H_2 \rightarrow CH_4$
CO/CH_4	Optimum (highest peak at 700°C)	Increasing	Higher ratio at a flow rate of 5 dm^3/h	$CO + 3H_2 \rightarrow CH_4 + H_2O$
CO_2/CH_4	Decreasing	Decreasing	Higher ratio at a flow rate of 5 dm^3/h	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ $2CO + 2H_2 \rightarrow CH_4 + CO_2$

To determine the possible applications of char, it is recommended to evaluate the relationship between the proportions of some elements. For example, the C/N ratio could be a positive parameter to determine the microbial activity should this residue be used in soils. Another aspect possibly worth evaluating and analyzing is the H/C and O/C ratios of the manure as well as the char obtained in each test (*Table 3*). The ratios are valuable for understanding the reaction mechanisms during pyrolysis under specific conditions [15]. The atomic ratios show that the process of carbonization changed the chemical compositions by removing functional groups. Due to the cleavage of the functional groups, the nitrogen contents significantly decreased, moreover, as a result of the formation of CO, CO_2 and CH_4, the carbon contents also reduced.

Table 3. Elemental analysis of the char products

	Cattle manure	at N_2 flow rate of 1 dm^3/h				at N_2 flow rate of 5 dm^3/h			
		300°C	500°C	700°C	900°C	300°C	500°C	700°C	900°C
Elements content (%)									
C	24.8	23.40	20.20	20.90	6.30	23.50	20.50	18.90	7.20
H	3.00	1.80	0.70	0.30	0.80	1.60	0.60	0.30	0.80
N	2.90	2.50	1.50	1.00	0.40	2.30	1.60	0.80	0.80
S	1.20	1.50	1.40	1.40	2.50	1.40	1.60	1.40	2.90
O	45.30	48.20	53.50	53.70	67.30	48.50	53.10	55.80	65.60
Al	0.60	0.99	0.98	1.55	1.39	0.72	1.06	1.48	1.57
Ca	14.12	12.61	12.91	12.83	15.74	12.36	12.40	11.92	14.74
Cl	0.71	0.82	0.70	0.84	0.21	0.63	0.67	0.78	0.40
Fe	0.60	0.55	0.18	0.39	0.54	0.72	0.53	0.53	0.52
K	1.76	3.39	2.90	3.22	1.18	2.75	2.93	2.58	1.31
Mg	1.19	1.11	1.19	1.55	0.96	1.11	1.13	1.23	0.91
Mn	0.03	0.03	0.04	<0.001	<0.001	0.05	0.03	0.04	<0.001
P	2.16	1.40	1.99	2.32	0.96	1.93	2.09	2.05	1.17
Si	1.48	1.81	1.82	0.00	1.71	2.42	1.86	2.09	2.09
Atomic ratios									
C/N	8.6	9.4	13.5	20.9	15.8	10.2	12.8	23.6	9.0
H/C	0.10	0.08	0.03	0.01	0.13	0.07	0.03	0.02	0.11
O/C	1.8	2.1	2.6	2.6	10.7	2.1	2.6	2.9	9.1

4. Conclusions

In this study, cattle manure was pyrolysed in a horizontal tubular reactor between 300 and 900°C at N_2 flow rates of 1 and 5 dm^3/h. During the experiments, 20-60% gaseous and 40-80% solid carbonaceous residues were formed. The gas yields increased in proportion to the reaction temperature and residence time, while the amount of char decreased. The decomposition process resulted in the formation of H_2, CO, CO_2, CH_4 and C_2-C_6 hydrocarbons. Syngas was only produced above 500°C. The ratio of H_2/CO at 500°C was 1, while at 700 and 900°C, the proportion of CO was greater than that of H_2. At lower temperatures (300 or 500°C) and at an N_2 flow rate of 1dm^3/h, the calorific value of the gas mixture was higher (~30 MJ/m^3) than at the higher N_2 flow rate and same temperatures (~15 MJ/m^3). The process of carbonization changed the chemical composition of the raw material by removing functional groups, which also indicates the occurrence of the water-gas shift and Boudouard reactions.

Acknowledgement

This project (2019-2.1.13-TÉT_IN-2020-00071) was financed by the Ministry for Innovation and Technology from the National Research, Development and Innovation Fund within the 2019-2.1.13-TÉT_IN program.

REFERENCES

[1] Naqvi, S.R.; Tariq, R.; Shahbaz, M.; Naqvi, M.; Aslam, M.; Khan, Z.; Mackey, H.; Mckay, G.; Al-Ansari, T.: Recent developments on sewage sludge pyrolysis and its kinetics: Resources recovery, thermogravimetric platforms, and innovative prospects, *Comput. Chem. Eng.*, 2021, **150**, 107325, DOI: 10.1016/j.compchemeng.2021.107325

[2] Burton, C.H.; Turner, C.: Manure management: Treatment strategies for sustainable agriculture, 2nd edition (Silsoe Research Institute, Bedford, UK), 2003, ISBN: 0953128261

[3] Su, G.; Ong, H.C.; Mohd Zulkifli, N.W.; Ibrahim, S.; Chen, W.H.; Chong, C.T.; Ok, Y.S.: Valorization of animal manure via pyrolysis for bioenergy: A review, *J. Clean. Prod.*, 2022, **343**, 130965, DOI: 10.1016/j.jclepro.2022.130965

[4] Havukainen, J.; Nguyen, M.T.; Hermann, L.; Horttanainen, M.; Mikkilä, M.; Deviatkin, I.; Linnanen, L.: Potential of phosphorus recovery from sewage sludge and manure ash by thermochemical treatment, *Waste Manage.* , 2016, **49**, 221–229, DOI: 10.1016/j.wasman.2016.01.020

[5] Bernal, M.P.; Alburquerque, J.A.; Moral, R.: Composting of animal manures and chemical criteria for compost maturity assessment. A review, *Bioresour. Technol.*, 2009, **100**(22), 5444–5453, DOI: 10.1016/j.biortech.2008.11.027

[6] Hušek, M.; Moško, J.; Pohořelý, M.: Sewage sludge treatment methods and P-recovery possibilities: Current state-of-the-art, *J. Environ. Manage.*, 2022, **315**, 115090, DOI: 10.1016/j.jenvman.2022.115090

[7] Djandja, O.S.; Yin, L.-X.; Wang, Z.-C.; Duan, P.-G.: From wastewater treatment to resources recovery through hydrothermal treatments of municipal sewage sludge: A critical review, *Process Saf. Environ. Prot.,* 2021, **151**, 101–127, DOI: 10.1016/j.psep.2021.05.006

[8] Ruiz-Gómez, N.; Quispe, V.; Ábrego, J.; Atienza-Martínez, M.; Murillo, M.B.; Gea, G.: Co-pyrolysis of sewage sludge and manure, *Waste Manage.*, 2017, **59**, 211–221, DOI: 10.1016/j.wasman.2016.11.013

[9] Zhu, Y.; Zhai, Y.; Li, S.; Liu, X.; Wang, B.; Liu, X.; Fan, Y.; Shi, H.; Li, C.; Zhu, Y.: Thermal treatment of sewage sludge: A comparative review of the conversion principle, recovery methods and bioavailability-predicting of phosphorus, *Chemosphere*, 2022, **291**, 133053, DOI 10.1016/j.chemosphere.2021.133053

[10] Rangabhashiyam, S.; Lins, P.V.D.S.; Oliveira, L.M.T.D.M.; Sepulveda, P.; Ighalo, J.O.; Rajapaksha, A.U.; Meili, L.: Sewage sludge-derived biochar for the adsorptive removal of wastewater pollutants: A critical review, *Environ. Pollut.,* 2022, **293**, 118581, DOI: 10.1016/j.envpol.2021.118581

[11] Gao, N.; Kamran, K.; Quan, C.; Williams, P.T.: Thermochemical conversion of sewage sludge: A critical review, *Prog. Energy Combust. Sci.,* 2020, **79**, 100843, DOI: 10.1016/j.pecs.2020.100843

[12] Ippolito, J.A.; Cui, L.; Kammann, C.; Wrage-Mönnig, N.; Estavillo, J.M.; Fuertes-Mendizabal, T; Cayuela, M.L.; Sigua, G.; Novak, J.; Spokas, K.; Borchard, N.: Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review, *Biochar*, 2020, **2**(4), 421–438, DOI: 10.1007/s42773-020-00067-x

[13] Hoang, S.A.; Bolan, N.; Madhubashani, A.M.P.; Vithanage, M.; Perera, V.; Wijesekara, H.; Wang, H.; Srivastava, P.; Kirkham, M.B.; Mickan, B.S.; Rinklebe, J.; Siddique, K.H.M.: Treatment processes to eliminate potential environmental hazards and restore agronomic value of sewage sludge: A review, *Environ. Pollut.,* 2022, **293**, 118564, DOI: 10.1016/j.envpol.2021.118564

[14] Burra, K.G.; Hussein, M.S.; Amano, R.S.; Gupta, A.K.: Syngas evolutionary behavior during chicken manure pyrolysis and air gasification, *Appl. Energy,* 2016, **181**, 408–415, DOI: 10.1016/j.apenergy.2016.08.095

[15] Zhou, S.; Liang, H.; Han, L.; Huang, G.; Yang, Z.: The influence of manure feedstock, slow pyrolysis, and hydrothermal temperature on manure thermochemical and combustion properties, *Waste Manage.,* 2019, **88**, 85–95, DOI: 10.1016/j.wasman.2019.03.025

[16] Li, Q.; Lin, H.; Fan, H.; Zhang, S.; Yuan, X.; Wang, Y.; Xiang, J.; Hu, S.; Bkangmo Kontchouo, F.M.; Hu, X.: Co-pyrolysis of swine manure and pinewood sawdust: Evidence of cross-interaction of the volatiles and profound impacts on product characteristics, *Renew. Energ.*, 2021, **179**, 1370–1384, DOI: 10.1016/j.renene.2021.07.104

[17] Choi, D.; Oh, J.-I.; Baek, K.; Lee, J.; Kwon, E.E.: Compositional modification of products from Co-Pyrolysis of chicken manure and biomass by shifting carbon distribution from pyrolytic oil to syngas using CO_2, *Energy*, 2018, **153**, 530–538, DOI: 10.1016/j.energy.2018.04.084

[18] Cho, S.-H.; Jung, S.; Tsang, Y.F.; Lin, K.-Y.A.; Jeon, Y.J.; Kwon, E.E.: Strategic way for valorization of manure into chemicals and fuels, *J. Clean. Prod.*, 2021, **322**, 129109, DOI: 10.1016/j.jclepro.2021.129109

[19] Hua, Y.; Wang, J.; Min, T.; Gao, Z.: Electrochemical CO_2 conversion towards syngas: Recent catalysts and improving strategies for ratio-tunable syngas, *J. Power Sour*ces, 2022, **535**, 231453, DOI: 10.1016/j.jpowsour.2022.231453

[20] Zhao, S.; Li, H.; Wang, B.; Yang, X.; Peng, Y.; Du, H.; Zhang, Y.; Han, D.; Li, Z.: Recent advances on syngas conversion targeting light olefins, *Fuel*, 2022, **321,** 124124, DOI: 10.1016/j.fuel.2022.124124

[21] Sánchez, M.E.; Martínez, O.; Gómez, X.; Morán, A.: Pyrolysis of mixtures of sewage sludge and manure: A comparison of the results obtained in the laboratory (semi-pilot) and in a pilot plant, *Waste Manage.*, 2007, **27**(10), 1328–1334 DOI: 10.1016/j.wasman.2006.07.015

[22] Kim, S.-S.; Agblevor, F.A.; Lim, J.: Fast pyrolysis of chicken litter and turkey litter in a fluidized bed reactor, *J. Ind. Eng. Chem.*, 2009, **15**(2), 247–252 DOI: 10.1016/j.jiec.2008.10.004