JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(8), 422–429
https://doi.org/10.12911/22998993/204004
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.03.31
Accepted: 2025.05.26
Published: 2025.06.10

Fuel production using municipal sewage sludge

Krzysztof Rećko[1]

[1] Faculty of Infrastructure and Environment, Częstochowa University of Technology, Brzeźnicka 60a, 42-200 Częstochowa, Poland
E-mail: krzysztof.recko@pcz.pl

ABSTRACT

The depletion of conventional fossil fuel deposits and the increasing energy demand are forcing the search for new energy sources. The sewage sludge produced during the wastewater treatment process is a form of waste biomass. That can be used for energy recovery with the development of appropriate technology. This paper presents the possibility of using sewage sludge, sunflower husk and food packaging waste to produce alternative fuel. Suitably prepared fuel mixtures were granulated and the fuel properties were then determined: calorific value, moisture content and ash content. The resulting calorific value of the fuel increased as the amount of packaging waste increased and the amount of sewage sludge in the mixture decreased. The research carried out made it possible to obtain fuel based on sewage sludge, which did not require a drying process. The fuel obtained was characterised by the fuel parameters required for alternative fuels used in the cement and energy industries.

Keywords: sewage sludge, biomass, sunflower hulls, polypropylene packaging waste, alternative fuels.

INTRODUCTION

The global energy consumption has grown rapidly in recent years. The International Energy Agency predicts an increase in global energy demand of around 4% for the period 2025–2027. The developing economies are leading consumers of electricity, but electrification emerging in industry and residential buildings is also becoming highly energy intensive [IEA World Energy Outlook 2024; Power Library – Electricity analysis and forecast to 2027, 2025]. The increase in energy demand is due in part to advances in electrically driven technologies. Heat pumps, household air conditioning, electric vehicles or artificial intelligence with its energy-intensive facilities of huge server rooms are increasing the demand for electricity [Wiatros-Motyka, et al., 2024]. As a result, global energy demand will grow faster than the growth of the global economy [Global Energy Perspective, 2024].

Currently, most of the energy is generated by burning fossil fuels, the deposits of which are limited and will be depleted [Singh, et al., 2022; Paramati, et al., 2022]. The burning of fossil fuels increases greenhouse gas emissions, particularly carbon dioxide, causing global warming and thus leading to climate change and its degradation [Alengebawy, et al., 2022; Arzaghi and Squalli, 2023]. As a result, the European Union is launching an action plan for a sustainable European Union's economy, the so-called European Green Deal. It aims to move away from fossil fuels and replace them with other less carbon-intensive fuels [Kalak,2023]. A low-carbon economy is one of the goals that will enable the European Union to achieve climate neutrality by 2050 [Chudy-Laskowska, et al., 2022; Kujawiak, et al., 2024]. Therefore, it becomes necessary to search for alternative energy sources, which undoubtedly include waste and biomass.

The growth of the economy and consumerism are generating large amounts of waste, the energy potential of which will allow it to be used as a raw material for fuel production. We can include plastic waste among such wastes. The production of plastics (excluding synthetic fibres [United Nations Environment Programme, 2021]) has increased rapidly worldwide in recent years and exceeded 450 million tonnes in 2022 [OECD, 2022]. In the European Union, total plastics production accounted for 54 million tones [Branża tworzyw sztucznych, 2023]. The most recent data shows that polypropylene (PP) production has the highest demand for plastics, accounting for around 20% of global demand [Plastic Europe, 2022]. Polypropylene plastics, due to their properties such as good strength, stiffness, durability, lightness and ease of manufacture, are widely used in the food industry for packaging and bottles and in the automotive industry for the production of car parts. They are also used in the pharmaceutical and medical industries due to their properties [Sin, et al., 2023; Zheng, et al., 2023]. The use of plastics in industry is leading to an increase in their production worldwide. This results in an increasing amount of raw materials and finished plastic products, which over time become waste [Koumpakis, et al., 2024]. In 2021, the amount of plastic waste generated in the European Union was 16.13 million tonnes. Only 6.56 million tonnesof this waste was recycled [Recykling odpadów z tworzyw sztucznych w UE, 2024].The remaining plastic waste, which has a high calorific value of around 46 MJ/kg in the case of polypropylene, can also be managed. The waste with a high calorific value can therefore be an excellent raw material for alternative fuels used in the cement industry or in the energy sector [Javed, et al., 2023].

The sewage sludge is a source of biomass, the energy potential of which can also be used in the co-creation of alternative energy sources such as fuels from waste. The sewage sludge is produced during the treatment of municipal and industrial wastewater. They contain organic and inorganic pollutants as well as heavy metals and pathogens, and can therefore pose a threat to the environment and humans [Kujawiak, et al., 2024; Gusiatin, et al., 2024]. The amount of sludge generated depends on the amount of wastewater flowing into the wastewater treatment plant. With economic development and population growth, the volume of wastewater will increase. This will lead to the generation of larger quantities of sludge, requiring further management in an environmentally safe manner [Lima et al., 2024; Rijo, et al.,2024]. The ways of handling sewage sludge are regulated by waste management legislation. Among them we distinguish the agricultural use of sewage sludge, which requires its appropriate preparation in accordance with legal requirements. Unfortunately, the content of persistent and toxic organic compounds and heavy metals in sewage sludge can lead to its negative impact on the environment [Buta, et al., 2021; Kostrz-Sikora, 2024]. The legislation allows sludge to be disposed of in landfills, but after meeting the relevant legal criteria. Therefore, this method of sludge management has a limited role in waste management strategies [Olejnik, 2024]. The best way to deal with sewage sludge is to use it as a potential energy source. The application of thermal sludge treatment methods leads to sludge disposal with simultaneous energy recovery. The incineration of sewage sludge with other wastes and biomass is therefore an alternative to the method of its agricultural use or storage. It allows the sludge to be used as a raw material for alternative fuel production using its energy potential [Vávrová, 2023; Jakubus, 2024].

The biomass is a renewable energy source of plant and animal origin [Tchapda and Pisupati, 2014]. The main advantage of biomass is its ability to replace fossil fuels, primarily coal, in energy production processes [Praeger, et al., 2019]. During the biomass combustion process, the amount of carbon dioxide emitted into the atmosphere is balanced with the amount of carbon dioxide absorbed by plants during photosynthesis [Jaworski and Wajda, 2022]. The use of biomass for energy production can contribute to reducing atmospheric emissions and thus play a key role in the European Union's decarbonisation strategy [Perea-Moreno, et al., 2018]. Furthermore, the combustion of biomass reduces atmospheric emissions of SOx and NOx, as the content of these compounds in biomass is much lower than that of fossil fuels, mainly coal [Chen, et al., 2017]. The sources of biomass are natural materials and wastes, which include wood, energy crops or agricultural residues [Mignogna, et al., 2024]. Undoubtedly, the waste biomass can include sunflower hulls, which are produced in the food industry during the extraction of sunflower seeds for the production of oils and other products. The processing of sunflower seeds produces about 50% of the waste mass in the form of sunflower husks. It has a calorific value in the range of 17.3–18.5 MJ/kg, a moisture content of 5.5% to 9.8% and an ash content of 2.2% to 4.9%. These properties make it an excellent raw material for fuel production when combined with other waste materials [Lunguleasa, et al., 2024].

This paper presents the results of laboratory tests on the production of alternative fuel from sewage sludge, sunflower husk waste biomass and

PP packaging waste. The fuel parameters obtained indicate the possibility of using it as a substitute for fossil fuel in the cement or energy industry.

MATERIALS AND METHODS

Sewage sludge, sunflower hulls and PP plastic packaging waste were used for fuel production in the study. The representative sludge sample for the study was obtained from the wastewater treatment plant. The filter press sample was taken in accordance with the Polish standard PN-EN ISO 5667-13:2011 and was obtained from mixed single samples taken at the same time from different sludge locations. The sewage sludge to be tested is shown in Figure 1.

The waste sunflower seed husks for the study were obtained from a plant producing sunflower seeds for the food industry. The sunflower kernel shelling process was carried out on a special processing line that allowed the kernels to be separated from the husk. This was done by transferring sunflower kernels from a tank into the shelling chamber, where, under the action of centrifugal force, the kernels hit the hammers and walls of the chamber, leading to the separation of the kernels from the shell. The extracted sunflower husks are shown in Figure 2.

The PP plastic packaging waste used in the study was taken from the waste sorting plant after the waste segregation line. They represented various types of packaging used in the food industry: bottles, cups for yoghurt, cream, cheese and other products. The packaging waste is shown in Figure 3. In the following part of the study, a set of fuel blends was prepared, obtained by mixing the wastes in appropriate proportions (Table 1). Variable proportions of individual wastes were used to create the fuel mixtures in order to achieve the best possible fuel performance. Before the mixing and granulation process of the prepared blends, sunflower husk waste was subjected to a grinding process in a laboratory vibrating mill to form 0÷1 mm fines (Figure 4). The packaging waste, like the sunflower husk waste, was ground with a knife mill to a 0÷1 mm fines (Figure 5). The process of shredding and grinding the waste produces a homogeneous fuel mixture. Thus, the processed waste was subjected to mixing in a laboratory mixer in appropriate proportions according to Table 1. The prepared mixtures were then sent to a laboratory granulator, where they

Figure 1. Sewage sludge

Figure 2. Sunflower husks

Figure 3. Polypropylene packaging waste

Table 1. Fuel mixture sets in different proportions

Percentage % of wastes	TEST			
	I	II	III	IV
Sewage sludge	50 %	40 %	30 %	25 %
Sunflower husk wastes	25 %	20 %	30 %	25 %
Polypropylene packaging waste	25 %	40 %	40 %	50 %

were granulated to obtain cylindrical granules in the shape of rolls with lengths of 10 mm to 50 mm and diameters of 6 mm. The resulting solid fuel in pellet form is shown in Figure 6.

The analyses of the tested waste and fuel mixtures were carried out in accordance with the application of the Polish Research Standards and ISO Standards. Test procedures in accordance with the Polish Committee for Standardisation database were used in the analysis to determine the necessary fuel properties. The list of tests performed for fuel properties of waste and fuel blends is presented in Table 2.

RESULTS AND DISCUSSION

The results of the waste tests carried out are shown in Tables 3, 4, 5. Table 3 shows that the sludge tested had a moisture value of 80%, an ash content of 33.54% and a volatile matter content of 59.75%. The results in Table 4 relating to sunflower husk waste show that the waste had a moisture content of 6.96%, an ash content of 2.95% and a volatile matter content of 76.60%. In contrast, Table 5 shows that PP packaging waste had a moisture content of 0.16%, an ash content of 0.98% and a volatile matter content of 98.79%. It should be noted that the test results obtained for sewage sludge, indicate its highest moisture and ash content in relation to sunflower husk waste and PP packaging waste. Unfortunately, too high a content of moisture and ash present in sewage sludge can affect the most important parameter of the fuel produced, i.e. its calorific value, causing it to be lowered [Lis et al., 2020; Šurić et al., 2022]. Analysis of the results of PP packaging waste and sunflower husk waste presented in Tables 5 and 4 showed that the packaging waste had the highest amount of volatile parts. The higher volatile fraction obtained in the wastes tested testifies to the high amount of combustible substances having a positive effect on the combustion process. [Jaworski et al., 2022; Vassilev et al., 2010]. A

Figure 4. Ground sunflower husk wastes

Figure 5. Shredded packaging wastes

Figure 6. Solid fuel in granulated form

Table 2. Tests performed on fuel properties of waste and fuel blends

Parametr	Symbol	Unit	Standard procedure
Water content	W	%	PN-EN 15414-3:2011
Ash content	A	%	PN-EN 15403:2011
Volatile matter content	V	%	PN-EN 15402:2011
Carbon content	C	%	ISO 29541:2010
Hydrogen content	H	%	ISO 29541:2010
Sulfur content	S	%	ISO 19579:2006
Chlorine content	Cl	%	PN-ISO 587:2000
Calorific value	Qi	MJ/kg	ISO 1928:2009

sulphur content of 1.36% was found in the sewage sludge, while it represented values below 1% in the other wastes. The chlorine content of the studied wastes represented values ranging from 0.07% to 0.11%. Elevated sulphur and chlorine contents can cause corrosion of equipment and installations used in combustion processes [Slepetys et al., 2012; Wang et al., 2021]. Due to the high degree of hydration of the sludge, its calorific value was the lowest at only 0.89 MJ/kg. The highest calorific value was achieved by PP packaging waste at 46.04 MJ/kg. A summary of the results of the granular fuel parameters obtained in the study is presented in Table 5. Due to the high degree of hydration of the sludge, its calorific value was the lowest at only 0.89 MJ/kg. The highest calorific value was achieved by PP packaging waste at 46.04 MJ/kg.

Table 6 shows the results of pelletised fuel produced from sewage sludge, sunflower husk waste and PP packaging waste. Taking into account the test results obtained for the granulated fuel, it should be concluded that the moisture value ranged from 39.53% to 16.81% depending on the content of the individual wastes. The decrease in the moisture content of the fuel was influenced by the decreasing content of sewage sludge in the mixture. The granulated fuel was characterised by an ash content ranging from 3.42% to 6.12%, and this value is comparable to that of eco-pea fuel, for which the ash content is 6.4% [Stala-Szlugaj, 2017]. The volatile content of the fuel produced was high, ranging from 90.14% to 95.98%. A higher volatile content increases the

Table 3. Results of tests on sewage sludge properties

Sewage sludge		
Parameter	Unit	Value
Water content W	%	80.22
Ash content A	%	33.54
Volatile matter content V	%	59.75
Carbon content C	%	30.50
Hydrogen content H	%	3.60
Sulfur content S	%	1.36
Chlorine content Cl	%	0.08
Calorific value Qi	MJ/kg	0.89

Table 4. Results of tests on the properties of sunflower husk waste

Sunflower husk waste		
Parameter	Unit	Value
Water content W	%	6.96
Ash content A	%	2.95
Volatile matter content V	%	76.60
Carbon content C	%	50.10
Hydrogen content H	%	6.10
Sulfur content S	%	0.02
Chlorine content Cl	%	0.11
Calorific value Qi	MJ/kg	17.79

Table 5. Results of testing the properties of packaging waste

Polypropylene (PP) packaging waste		
Parameter	Unit	Value
Water content W	%	0.16
Ash content A	%	0.98
Volatile matter content V	%	98.79
Carbon content C	%	44.70
Hydrogen content H	%	7.12
Sulfur content S	%	0.19
Chlorine content Cl	%	0.07
Calorific value Qi	MJ/kg	46.04

Table 6. Parameters of granulated fuel produced in the tests

Parameter	Unit	Granulated fuel			
		Test I	Test II	Test III	Test IV
Water content W	%	39.53	29.02	22.09	16.81
Ash content A	%	6.12	5.10	4.52	3.42
Volatile matter content V	%	90.14	90.58	95.11	95.98
Carbon content C	%	34.27	42.08	46.84	54.24
Hydrogen content H	%	8.89	9.12	9.43	9.98
Sulfur content S	%	0.21	0.19	0.36	0.07
Chlorine content Cl	%	0.03	0.05	0.04	0.06
Calorific value Qi	MJ/kg	17.56	24.10	27.98	31.12

calorific value of the fuel. The results of the fuel tested showed that the calorific value ranged from 17.56 MJ/kg to 31.12 MJ/kg. The results showed that the fuel was characterised by a calorific value that, already at 17.56 MJ/kg, is comparable to that of lignite at 15–21 MJ/kg [Symanowicz, et al., 2023]. The high calorific value results of the tested fuel within the range of 24.10–31.12 MJ/kg are comparable to the calorific value of hard coal of 24–28 MJ/kg [Smołka-Danielowska et al., 2021; Liu et al. 2025]. The sulphur and chlorine amount of the pelletised fuel was present in trace amounts and therefore will not have a negative impact on the thermal fuel conversion equipment and plant. On the basis of the results obtained, it can be concluded that the granular fuel obtained has suitable parameters indicating that it can be used as an alternative fuel.

CONCLUSIONS

The research carried out has produced a fuel with suitable parameters for use in the cement and energy industries as a substitute for fossil fuels for the production of heat or electricity. Furthermore, it can be concluded that:

- produced granular fuel can be a good option for solid fossil fuel,
- combustion of granular fuel can contribute to the ecological disposal of harmful substances contained in sewage sludge,
- the presented method of producing granular fuel can reduce the energy consumption of its production compared to other used methods of producing sludge-based fuel,
- the produced granular fuel can contribute to reducing dependence on fossil fuels and reduce their extraction,
- the use of the resulting granular fuel in the cement industry and in the commercial power industry can enable the transition to a closed-loop economy.

Given these conclusions, further research should be considered to determine the optimisation of combustion parameters or co-firing of the produced fuel with other natural fuels.

Acknowledgements

The publication was funded by the university under project BS/PB-400-301/25.

REFERENCES

1. Alengebawy, A., Mohamed, B.A., Ghimire, N., Jin, K., Liu, T., Samer, M., Ai, P. (2022). Understanding the environmental impacts of biogas utilization for energy production through life cycle assessment: An action towards reducing emissions. *Environ. Res*., *213,* 113632; https://doi.org/10.1016/j.envres.2022.113632
2. Arzaghi, M., Squalli, J. (2023). The environmental impact of fossil fuel subsidy policies. *Energy Econom., 126*, 106980; https://doi.org/10.1016/j.eneco.2023.106980
3. Buta, M., Hubeny, J., Zieliński, W., Harnisz, M., Korzeniewska, E. (2021). Sewage sludge in agriculture–the effects of selected chemical pollutants and emerging genetic resistance determinants on the quality of soil and crops–a review. *Ecotoxicology and Environmental Safety*, *214,* 112070; https://doi.org/10.1016/j.ecoenv.2021.112070
4. Branża tworzyw sztucznych 2023. Raport Fundacji Plastics Europe Polska. (2023) Available online: https://plasticseurope.org/pl/wp-content/uploads/sites/7/2023/09/Raport-Roczny-PlasticsEurope_Polska-2023_.pdf (accessed on 29.02.2025)
5. Chen, J., Li, C., Ristovski, Z., Milic, A., Gu, Y., Islam, M.S., Wang, S., Hao, J., Zhang, H., He, C.,Guo, H., Fu, H., Miljevic, B., Morawska, L., Thai, P., Lam, Y.F., Pereira, G., Ding, A., Huang, X., Dumka, U.C. (2017). A review of biomass burning: Emissions and impacts on air quality, health and climate in China. *Science of the Total Environment.,579*, 1000-1034; https://doi.org/10.1016/j.scitotenv.2016.11.025
6. Chudy-Laskowska, K., Pisula, T. (2022). An analysis of the use of energy from conventional fossil fuels and green renewable energy in the context of the European union's planned energy transformation. *Energies, 15,* 7369; https://doi.org/10.3390/en15197369
7. Global Energy Perspective 2024 Report. https://www.mckinsey.com/industries/energy-and-materials/our-insights/global-energy-perspective (accessed: 23.02.2025)
8. Gusiatin, M.Z., Kulikowska, D., Bernat, K. (2024). Municipal Sewage Sludge as a Resource in the Circular Economy. *Energies*, *17*(11), 2474; https://doi.org/10.3390/en17112474
9. IEA. World Energy Outlook 2024 – Analysis International Energy Agency. (2024). https://www.iea.org/reports/electricity-2024/executive-summary (accessed: 21.02.2025)
10. Jakubus, M. (2024). Current trends in sustainable sewage sludge management - A case study for Poznań county, Poland. *Sustainability, 16*(12), 5056; https://doi.org/10.3390/su16125056
11. Javed, N., Muhammad, S., Iram, S., Ramay, M.W.,

Jaffri, S.B., Damak, M., Fekete, G., Varga, Z., Székács, A., Aleksza, L. (2023). Analysis of fuel alternative products obtained by the pyrolysis of diverse types of plastic materials isolated from a dumpsite origin in Pakistan. *Polymers*, 15, 24. https://doi.org/10.3390/polym15010024

12. Jaworski, T., Wajda, A. (2022). Wykorzystanie paliw z odpadów, biomasy oraz osadów ściekowych w ciepłownictwie. *Nowa Energia,4*(85), 42–51; bwmeta1.element.baztech-4520ee1b-85c7-4b33-aed3-074c69d7321b
13. Kalak, T. (2023). Potential use of industrial biomass waste as a sustainable energy source in the future. *Energies, 16(4),* 1783; https://doi.org/10.3390/en16041783.
14. Kostrz-Sikora, P. (2024). Zmienność zawartości pierwiastków śladowych w osadach ściekowych wybranych oczyszczalni ścieków w Polsce. *Przegląd Geologiczny*, *72*(7), 308–324; http://dx.doi.org/10.7306/2024.15
15. Koumpakis, D.A., Michailidou, A.V., Vlachokostas, C., Mertzanakis, C. (2024). Closing the loop between plastic waste management and energy cogeneration: An innovative design for a flexible pyrolysis small-scale unit. *Recycling, 9,* 92; https://doi.org/10.3390/recycling9050092
16. Kujawiak, S., Makowska, M., Janczak, D., Czekała, W., Krzesiński, W., Antonowicz, A., Kupryaniuk, K. (2024). An analysis of the physicochemical and energy parameters of briquettes manufactured from sewage sludge mixtures and selected organic additives. *Energies, 17*(18), 4573; https://doi.org/10.3390/en17184573
17. Lima, D., Li, L., Appleby, G. (2024). A review of renewable energy technologies in municipal wastewater treatment plants (WWTPs). *Energies*, *17(23),* 6084; https://doi.org/10.3390/en17236084
18. Lisý, M., Lisá, H., Jecha, D., Baláš, M., Križan, P. (2020). Characteristic properties of alternative biomass fuels. *Energies, 13*, 1448; https://doi.org/10.3390/en13061448
19. Liu, F., Li, S. (2025). Prediction of carbon emissions from coal-fired power plants during load cycling with varying coal characteristics. *Fuels*, *6*, 1; https://doi.org/10.3390/fuels6010001
20. Lunguleasa, A., Olarescu, A., Spirchez, C. (2024). Pellets obtained from the husks of sunflower seeds and beech sawdust for comparison. *Forests, 15*(6), 902; https://doi.org/10.3390/f15060902
21. Mignogna, D., Szabó, M., Ceci, P., Avino, P. (2024). Biomass energy and biofuels: perspective, potentials, and challenges in the energy transition. *Sustainability, 16*, 7036; https://doi.org/10.3390/su16167036
22. OECD. Global Plastics Production: Annual Production of Polymer Resin and Fibers. (2022). Available online: https://ourworldindata.org/plastic-pollution (accessed on 29 February 2025)
23. Olejnik, D. (2024). Evaluation of the heavy metals content in sewage sludge from selected rural and urban wastewater treatment plants in Poland in terms of its suitability for agricultural use. *Sustainability, 16*(12), 5198; https://doi.org/10.3390/su16125198
24. Paramati, S.R., Shahzad, U., Doğan, B. (2022). The role of environmental technology for energy demand and energy efficiency: Evidence from OECD countries. *Renew. Sustain. Energy Rev., 153*, 111735; https://doi.org/10.1016/j.rser.2021.111735
25. Perea-Moreno, M.A., Manzano-Agugliaro, F., Perea-Moreno, A.J. (2018). Sustainable energy based on sunflower seed husk boiler for residential buildings. *Sustainability, 10*, 3407; https://doi.org/10.3390/su10103407
26. Plastic Europe. Plastics -The Facts. (2022). Available online: https://plasticseurope.org/wp-content/uploads/2022/10/PE-PLASTICS-THE-FACTS_V7-Tue_19-10-1.pdf (accessed 3 March 2025)
27. Power library - Electricity Analysis and forecast to 2027. (2025). https://powerlibrary.theelectricityhub.com/2025/03/04/electricity-2025-analysis-and-forecast-to-2027/ [Accessed: 23.02.2025]
28. Praeger, F., Paczkowski, S., Sailer, G., Derkyi, N.S.A., Pelz, S. (2019). Biomass sources for a sustainable energy supply in Ghana - A case study for Sunyani. *Renew. Sustain. Energy Rev., 107*, 413–424; https://doi.org/10.1016/j.rser.2019.03.016
29. Recykling odpadów z tworzyw sztucznych w UE: fakty i liczby (in Polish). (2024). Available online: https://www.europarl.europa.eu/topics/pl/article/20181212STO21610/recykling-odpadow-z-tworzyw-sztucznych-w-ue-fakty-i-liczby (accessed 03.03.2025)
30. Rijo, B., Nobre, C., Brito, P., Ferreira, P. (2024). An overview of the thermochemical valorization of sewage sludge: principles and current challenges. *Energies*, *17*(10), 2417; https://doi.org/10.3390/en17102417
31. Sin, L.T., Tueen, B.S. (2023). Eco-profile of plastics. *Plastics and Sustainability.* Elsevier: Amsterdam, The Netherlands, 45–89. https://doi.org/10.1016/B978-0-12-824489-0.00010-6
32. Singh, A.R., Singh, S.K., Jain, S. (2022). A review on bioenergy and biofuel production. *Mater. Today Proc.,49,* 510–516; https://doi.org/10.1016/j.matpr.2021.03.212
33. Slepetys, J., Kadziuliene, Z., Sarunaite, L., Tilvikiene, V., Kryzeviciene, A. (2012). Biomass potential of plants grown for bioenergy production. In: Growing and Processing Technologies of Energy Crops. Proceedings of the International Scientific Conference Renewable Energy and Energy Efficiency, Jelgava, Latvia, University of Agriculture: Jelgava; 66–72.

34. Smołka-Danielowska, D., Jabłońska, M., Godziek, S. (2021). The Influence of hard coal combustion in individual household furnaces on the atmosphere quality in Pszczyna (Poland). *Minerals*,*11*,1155; https://doi.org/10.3390/min11111155
35. Stala-Szlugaj K. (2017). The development of the market of qualified coal fuels in Poland. *Gospodarka Surowcami Mineralnymi – MineralResources Management 33*(3), 95–108; https://doi.org/10.1515/gospo-2017-0031
36. Symanowicz, B, Toczko, R. (2023). Brown Coal waste in agriculture and environmental protection: a review. *Sustainability*, *15*(18), 13371; https://doi.org/10.3390/su151813371
37. Šurić, J., Brandić, I., Piotr, A., Bilandžija, N., Leto, J., Karažija, T., Kutnjak, H., Poljak, M., Voća, N. (2022). Wastewater sewage sludge management via production of the energy crop Virginia Mallow Virginia. *Agronomia, 12*, 1578; https://doi.org/10.3390/agronomy12071578
38. Tchapda, A. H., Pisupati, S. V. (2014). A review of thermal co-conversion of coal and biomass/waste. *Energies, 7*(3), 1098-1148; https://doi.org/10.3390/en7031098
39. United Nations Environment Programme. From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution. Nairobi. (2021). Available online: https://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution (accessed on 29 February 2025)
40. Vassilev, S.V., Baxter, D., Andersen, L.K., Vassileva, C.G. (2021). An overview of the chemical composition of biomass. *Fuel*, *89*, 913–933; https://doi.org/10.1016/j.fuel.2009.10.022
41. Vávrová, K., Králík, T., Janota, L., Šolcová, O., Čárský, M., Soukup, K., Vítek, M. (2023). Process economy of alternative fuel production from sewage sludge and waste celluloses biomass. *Energies, 16*(1), 518; https://doi.org/10.3390/en16010518
42. Wang, T., Rong, H., Chen, S., Zhou, Y., Li, J., Xiao, Y., Xue, Y. (2021). TG- MS Study on in Situ Sulfur Retention during the Co-Combustion of Reclaimed Asphalt Binder and Wood Sawdust. *J. Hazard. Mater.*, *403*, 123911; http://dx.doi.org/10.1016/j.jhazmat.2020.123911
43. Wiatros-Motyka, M., Fulghum, N., Jones, D. (2024). Report Global Electricity Review 2024 – Ember. https://ember-energy.org › app › uploads › 2024/05 (accessed: 23.02.2025)
44. Zheng, K., Wu, Y., Hu, Z., Wang, S., Jiao, X., Zhu, J., Sun, Y., Xie, Y. (2023). Progress and perspective for conversion of plastic wastes into valuable chemicals. *Chem. Soc. Rev., 52,* 8–29. DOI: 10.1039/D2CS00688J