JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(11), 317–327
https://doi.org/10.12911/22998993/226406
ISSN 2299–8993, License CC-BY 4.0

Received: 2026.06.30
Accepted: 2026.09.15
Published: 2026.10.01

Laboratory testing of selected properties of fuel blends based on waste and biomass

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ABSTRACT

This publication presents laboratory studies involving the production of fuel from peanut shells, sewage sludge, and waste from used footwear. Under laboratory conditions, energy parameters such as moisture content, ash content, and calorific value were determined for selected fuel components. Based on the analysis of the results, trials were conducted to blend the fuel components in appropriate proportions based on moisture content and calorific value. The fuel obtained in this way was then tested for its energy parameters. This publication presents the results of fuel testing, whose measured parameters enabled the determination of the fuel's suitability for energy purposes. The results indicate that the fuel has potential for further research into its quality as a waste-based alternative fuel for the cement and power generation industries.

Keywords: peanut shell waste, sewage sludge, worn-out shoes, rubber waste, fuels.

INTRODUCTION

As global energy demand rises, so do the extraction and consumption of fossil fuels [Shahbaz, et al., 2023], the use of which for energy production can result in the emission of large amounts of carbon dioxide into the atmosphere, thereby contributing to climate change and environmental pollution [Chen, et al., 2022]. The combustion of fossil fuels causes environmental pollution by emitting sulfur dioxide, nitrogen oxides, particulate matter, and other gases into the atmosphere, which can lead to health problems due to poor air quality [Garg, et al., 2023]. It is estimated that approximately 23% of global carbon dioxide emissions into the atmosphere are caused by the combustion of fossil fuels [El Naggar, et al., 2024]. Carbon dioxide emissions associated with energy production from fossil fuels are projected to increase by 2% to 34% by 2050. [Ma, et al., 2025].

Energy demand is linked to the rapid development of modern technologies and devices that primarily require electricity [Axenbeck, et al., 2024]. The use of electric cars in cities enables zero-emission travel but requires frequent charging. The use of heat pumps to heat buildings in winter increases energy demand, and the installation of air conditioning systems – used for heating or cooling depending on outdoor weather conditions – also contributes to increased energy consumption. The use of devices for collecting and storing data generates enormous energy demand, which may increase dramatically as information technology advances. According to the World Energy Outlook, global energy demand is estimated to increase by 19% by 2040 [World Energy Outlook 2025].

In view of the growing demand for energy and the depletion of fossil fuels, alternative energy sources must be sought [Xi, et al., 2023]. Undoubtedly, biomass and waste can be counted amongst such sources [Proskurina et al., 2016]. The volume of waste generated depends on population growth, urbanization, economic development, and changes in lifestyles worldwide [Soprych, et al., 2024]. The energy potential of waste makes it an excellent raw material for producing alternative fuels. The use of waste for fuel production is most often driven by the large volumes of waste generated and the challenges associated with its management [Zhang, et al., 2019]. Therefore, waste such as rubber and biomass offers an alternative that enables the production of fuels to replace a certain proportion of the conventional fossil fuels used for energy generation [Nabeel, et al., 2023].

Global rubber production from natural and synthetic rubber in 2022 totaled over 29 million metric tons [Cruz-Morales, et al., 2023]. Rubber is a durable, stretchy, and elastic material characterized by high abrasion resistance and water resistance [Arias, et al., 2019]. It possesses unique properties and manufacturing capabilities that make it widely used, for example, in the footwear industry for the production of insoles or shoe soles [Torres, et al., 2023]. Global footwear production reached 23,9 billion pairs in 2024 [Portuguese shoes. World Footwear Yearbook 2025]. Such high production is driven by growing demand for footwear resulting from changing fashion trends, as new styles are introduced to the market within a short period of time [Van Rensburg, et al., 2020]. Inexpensive, mass-produced footwear has a shorter lifespan due to the poor quality of the materials used in its production. Approximately 40 different materials are used in footwear production, including: leather – 25%, polyurethane – 17%, synthetic materials – 38%, rubber – 7%, and textiles – 6% [Alves, et al., 2025].

As a result, this generates large amounts of post-consumer waste in the form of worn-out shoes, which can pose serious challenges for their management [Van Rensburg, et al., 2021]. It is estimated that approximately 20 billion pairs of shoes are discarded worldwide each year, of which only 15% are recycled, while the remainder ends up in landfills [Dennis, 2022]. During the disassembly and separation of used footwear, we can recover waste rubber, an excellent material for the production of alternative fuels [Kowalik-Klimczak, et al., 2024].

Sewage sludge, which can be classified as waste biomass, may also serve as an alternative to fossil fuels in energy production [Siddiqui, et al., 2023]. Sewage sludge is generated at wastewater treatment plants as a byproduct of municipal wastewater treatment and is viewed as waste requiring management [Feng, et al., 2023]. In 2022, the global volume of municipal wastewater generated was approximately 380 billion m^3/year, and projections indicate increases of 24% and 51% by 2030 and 2050, respectively [European Investment Bank, Wastewater as a Resource, 2022]. China generates the largest annual volume of sewage sludge – approximately 60 million metric tons – followed by the European Union at approximately 50 million metric tons and the United States at approximately 40 million metric tons [Hu, et al., 2022]. The increase in sewage sludge volume is driven by rapid urbanization and global population growth [Kim and Phae, 2022]. Currently, the most commonly used methods of sewage sludge management include direct use in agriculture for fertilizing farmland, land reclamation, and thermal treatment [Vávrová, et al., 2023]. The use of sewage sludge in agriculture as an organic fertilizer [Hechmi, et al., 2022] stems mainly from its high organic matter content, which serves as a source of essential plant nutrients. Fertilizing soil with sewage sludge improves its structure and promotes crop growth. In addition to organic matter, sewage sludge may contain several potentially hazardous compounds, including heavy metals, microplastics, pharmaceuticals, pathogenic microorganisms, and other microbial and organic contaminants that pose threats to the environment and human health [Reyes-Contreras, et al., 2018].The presence of contaminants in sewage sludge limits its use in agriculture as a fertilizer for traditional food crops, but permits the use of sewage sludge as a fertilizer for crops not intended for human consumption or feed [Kowalik, et al., 2021; Kowalski, et al., 2022]. The application of sewage sludge to land is permitted provided that the conditions set forth in §2 of the Regulation of the Minister of the Environment of February 6, 2015, on the use of municipal sewage sludge (Journal of Laws 2023, item 23) [Regulation of the Minister of the Environment 2015]. Thermal treatment of sewage sludge is a method that, given current energy challenges, fits perfectly into the waste management strategy. It allows for the rapid decomposition of hazardous compounds, a significant reduction in sewage sludge volume ranging from 70% to 90%, and energy recovery [Kowalski et al., 2024]. A key factor in the thermal treatment of sewage sludge is its calorific value. The calorific value of mechanically dewatered sewage sludge is low, typically less than 4,5 MJ/kg, depending on the degree of dewatering [Schnell et al., 2020]. The high moisture content of sewage sludge significantly impedes energy efficiency in the thermal conversion process. A moisture content of 60% to 80% in dewatered sewage sludge acts as a barrier that prevents autothermal combustion

[Negr et al., 2025]. Therefore, it becomes necessary to co-incinerate sewage sludge with other wastes and agricultural biomass to produce a fuel with good performance characteristics [Yurten and Ozdemir, 2024]. Biomass energy is considered a clean, renewable energy source that can serve as an alternative to fossil fuels [Cai et al., 2023]. It is estimated that global biomass energy production accounts for approximately 9% of the world's energy demand and amounts to about 56 EJ [Reports Global Energy Review 2021]. Global projections predict that by 2035, biomass energy will meet one-quarter of global energy demand [Hameed et al., 2021]. Globally, biomass energy has become the fourth-largest energy source after coal, natural gas, and crude oil [Tong, 2019].

The use of biomass for energy reduces greenhouse gas emissions, including carbon dioxide, to net zero in the overall balance, because during growth plants absorb as much carbon dioxide as is released during combustion [Tursi, 2019]. Therefore, burning biomass is beneficial because it reduces the emission of harmful compounds into the atmosphere. Biomass waste includes agricultural, forestry, energy crop, and industrial waste [Guo et al., 2024]. Biomass waste includes peanut shells, which are generated as byproducts of the agri-food industry [Zhang et al., 2025]. Peanuts are used in the production of both food and industrial products [Zhao et al., 2023]. Global peanut production amounts to approximately 46,4 metric tons per year, and waste from peanut processing in the form of shells accounts for about 22% of the total peanut yield, or approximately 10 million metric tons of waste [Gerber and Roberts, 2024]. Relevant energy parameters such as moisture content, calorific value, volatile matter content, and ash content indicate the potential for using peanut shells to produce fuels in combination with other wastes [Perea-Moreno et al., 2018].

This publication presents the results of laboratory studies that determined the quality of fuel produced from peanut shells, sewage sludge, and rubber waste from used footwear, as well as its suitability for use in the energy industry.

MATERIALS AND METHODS

The study utilized materials such as peanut shells, sewage sludge, and rubber waste from worn-out shoes. The peanut shells came from a nut processing plant that produces food products such as roasted peanuts and peanut butter. Peanut shells are a byproduct generated during the peanut harvesting process, specifically during shelling. The shelling process initially involves sorting the peanuts by size using screens, followed by passing them through rollers sized appropriately for their dimensions. After passing between the rollers, we obtain peanuts and crushed shells, which are separated using oscillating vibrating screens and air separators. Peanut shell samples were collected from various waste collection points at the plant and combined into a single laboratory sample. The peanut shells are shown in Figure 1.

A sewage sludge sample for testing was collected from the municipal wastewater treatment plant after the filter presses. The composite sample for testing was obtained by combining and thoroughly mixing individual samples collected simultaneously from different locations within the sludge intended for testing. Figure 2 shows the sewage sludge used in the study.

The rubber waste originated from the disassembly and separation of worn-out footwear obtained from a municipal waste sorting facility. The disassembly of the worn-out footwear involved separating the individual materials using mechanical cutting. After disassembly, the rubber waste intended for testing, in the form of soles,

Figure 1. Peanuts shells

Figure 2. Sewage sludge used in the study

was set aside. The worn-out footwear and its rubber waste are shown in Figure 3.

Before preparing the actual test samples, the peanut shell waste was ground in a laboratory vibrating mill to a particle size of 0 to 1 mm, as shown in Figure 4.

Rubber waste in the form of soles from worn-out shoes was shredded in a knife mill to a particle size of 0 to 1 mm, as shown in Figure 5.

Further preparation of the samples for testing involved thoroughly mixing, in appropriate proportions, ground peanut shells, sewage sludge, and shredded rubber waste from used footwear. The proportions of each waste type were selected based on moisture content and calorific value to obtain mixtures with the best possible parameters, as shown in Table 1. The mixing process was performed in a laboratory mixer with an adjustable mixing speed. The waste treatment processes used ensured the homogeneity of the mixture, which significantly impacts the final fuel parameters. Fuel mixtures I, II, and III were unsuitable for the pelletization process due to their higher moisture content, which prevented pelletization, as shown in Figure 6. Fuel mixture IV, which exhibited the best parameters, was subjected to pelletization in a laboratory pelletizer, yielding cylindrical pellets with a diameter of 6 mm and a length of 15 to 45 mm, as shown in Figure 7. The tests and analyses of the waste and fuel mixtures were conducted in accordance with applicable standards, as shown in Table 2. The calorific values of the fuel blends produced were tested in three replicates, and the mean and standard deviation were calculated.

Figure 4. Ground peanut shell wastes

Figure 5. Shredded rubber waste from worn-out shoes

RESULTS AND DISCUSSION

As part of the study, analyses were conducted on samples of peanut shell waste, sewage sludge, and rubber waste from worn-out footwear, as shown in Tables 3, 4, and 5. An analysis of the results shows that peanut shell waste has the lowest ash content, at 3.61%. For sewage sludge and rubber waste, the ash content was 33.54% and 19.86%, respectively. An excessively high ash content is referred to as “ballast,” which significantly reduces the fuel’s calorific value [Jaworski and Wajda, 2022]. Another important parameter affecting fuel quality is moisture content. Tables 3, 4, and 5 show that sewage sludge had the highest moisture content, exceeding 80%. In the case of peanut waste, the moisture content was 6.09%, while the lowest was found in rubber waste at just 0.74%. A high moisture content directly

Figure 3. Worn-out footwear and rubber waste from worn-out footwear

Figure 6. Fuel mixture

Table 3. Results of the analysis of peanut shell waste

Parameter	Symbol	Unit	Value
Water content	W	[%]	6.09
Ash content	A	[%]	3.61
Volatile matter content	V	[%]	84.59
Carbon content	C	[%]	49.82
Hydrogen content	H	[%]	6.23
Sulfur content	S	[%]	0.07
Chlorine content	Cl	[%]	0.06
Calorific value	Qi	[MJ/kg]	18.39

Figure 7. Fuel mixture in granulated form

affects the fuel's calorific value, which decreases with increasing moisture content. Additionally, it leads to increased energy consumption during water evaporation in the combustion process [Lisý, et al., 2020]. The volatile matter content in the tested samples ranged from 59.75% for sewage sludge to 84.59% for peanut waste. The sum of volatile matter and solid matter constitutes the total combustible content in the samples [Mirowski, et al., 2018]. After determining the volatile matter content, the sulfur and chlorine contents in the tested samples were measured. The highest sulfur content was recorded in sewage sludge at 1.36% and in rubber waste at 1.31%. The chlorine content in the tested samples was negligible. Burning fuel containing excessive amounts of sulfur or chlorine compounds leads to corrosion of the fuel combustion system [Chen, et al., 2018]. After conducting the analyses, the calorific values of the individual samples were determined. Tables 3, 4, and 5 show that the highest calorific value was obtained for rubber waste from used footwear, which was 30.75 MJ/kg, while for peanut shell waste it was 18.39 MJ/kg. Sewage sludge had the lowest calorific value of 0.89 MJ/kg, which is due to its high moisture content. The results of tests on fuel blends derived from peanut shell waste, sewage sludge, and rubber waste from used footwear are presented in Table 6. The fuel blends presented in Table 6 had ash contents ranging from 14.96% to 17.60%, which correspond to the values obtained during lignite combustion [Kijo-Kleczkowska, et al., 2015]. The lower the ash content in the mixtures, the lower the likelihood of slag and impurities forming in boiler equipment [Attanatho, et al., 2024; Almeida Moreira, et al., 2024]. The

Table 1. Percentage of wastes in the fuel mixture

Fuel blends	Percentage of wastes		
	Peanut shell wastes [%]	Sewage Sludge [%]	Rubber waste from used footwear [%]
I	25	50	25
II	40	40	20
III	40	30	30
IV	50	25	25

Table 2. Types of testing and analysis of waste and fuel mixture

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

Table 4. Results of the analysis sewage sludge

Parameter	Symbol	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 5. Results of the analysis of rubber waste from used footwear

Parameter	Symbol	Unit	Value
Water content	W	[%]	0.74
Ash content	A	[%]	19.86
Volatile matter content	V	[%]	72.10
Carbon content	C	[%]	55.31
Hydrogen content	H	[%]	4.81
Sulfur content	S	[%]	1.31
Chlorine content	Cl	[%]	0.20
Calorific value	Qi	[MJ/kg]	30.75

moisture content in the mixtures ranged from 18.02% to 38.81% and is similar to that of fossil fuels, where for bituminous coal this value ranges from 3.2% to 19.10%, and for lignite from 10.90% to 54.60% [Wasilewski, et al., 2015]. The moisture content of the mixtures was reduced by increasing the proportion of peanut shells and decreasing the amount of sewage sludge. In the resulting fuel blends, the volatile matter content ranged from 73.42% to 77.41%, which significantly affects the calorific value. These values were significantly higher than those for bituminous coal from 21.20% to 40.20% or lignite from 45% to 55% [Jelonek, et al., 2018; Wasilewski, et al., 2015]. The addition of 50% peanut shell waste increased the volatile matter content of fuel mixture IV, thereby improving its final performance characteristics. The sulfur content in the fuel blends ranged from 0.30% to 0.58% and was comparable to the sulfur content in lignite from 0.60% to 1.10%. Chlorine accounted for a small proportion, ranging from 0.02% to 0.04%. The lower the sulfur and chlorine content in fuels, the lower the corrosive impact on thermal conversion equipment [Wang, et al., 2024]. Heavy metals in sewage sludge from industrialized areas, where industrial wastewater accounts for a significant portion of municipal wastewater, may pose a problem. Therefore, it is advisable to co-incinerate sewage sludge with other waste in order to bring its heavy metal content into compliance with the requirements of the cement industry and the commercial power generation sector. In the power generation industry, the resulting ash can pose challenges for management, which may involve landfilling, use in construction after high-temperature processing, or use as an additive in cement production [Rusănescu et al., 2022]. In contrast, in the cement industry, ash resulting from the co-incineration of fuels is incorporated into the final product-clinker. Consequently, there is no issue with its management. However, attention must be paid

Table 7. Calorific value of fuel mixtures (value ± SD)

Fuel mixture	Calorific value [MJ/kg] (wartość ± SD)
I	14.01 ± 0.21
II	17.16 ± 0.35
III	20.04 ± 0.14
IV	22.04 ± 0.18

Table 6. Results of fuel mixture testing

Parameter	Symbol	Unit	Fuel mixture			
			I	II	III	IV
Water content	W	[%]	38.81	31.04	22.34	18.02
Ash content	A	[%]	15.43	17.60	14.96	15.98
Volatile matter content	V	[%]	73.42	74.01	76.79	77.41
Carbon content	C	[%]	32.18	37.15	41.08	47.03
Hydrogen content	H	[%]	7.30	7.02	6.67	6.61
Sulfur content	S	[%]	0.58	0.49	0.44	0.30
Chlorine content	Cl	[%]	0.02	0.03	0.03	0.04

to the heavy metal content in the ash, as significantly exceeding the permissible limits can reduce the strength of the cement and prolong its setting time [Pang et al., 2023]. The calorific values of the resulting fuel blends, along with their means and standard deviations, are presented in Table 7. The calorific value of the fuel blends produced, as shown in Table 7, ranged from 14.01 MJ/kg to 22.04 MJ/kg. The highest calorific value, 22.04 MJ/kg, was obtained for fuel blend IV this increase was due to a 50% reduction in the proportion of sewage sludge and a 50% increase in the proportion of peanut shells. The calorific values obtained for the blends were comparable to those of lignite 15 MJ/kg and bituminous coal from 21 MJ/kg to 23 MJ/kg [Vávrová, et al., 2023; Liu, and Li, 2025]. Chen et al. obtained a similar calorific value of 21.67 MJ/kg when producing fuel from wood dust and sewage sludge [Chen, et al., 2018]. In their research, Smoliński et al. produced fuel by mixing sewage sludge and bituminous coal in appropriate proportions, achieving a similar calorific value of from 14 MJ/kg to 18 MJ/kg [Smoliński et al., 2019]. According to the PN-EN ISO 21640:2021 classification of solid secondary fuels, alternative fuels are divided into classes. The produced fuel blends III and IV achieved the calorific value required for Class 2 ($20 \leq NCV < 25$), fuel blend II for Class 3 ($15 \leq NCV < 20$), and fuel blend I for Class 4 [PN-EN ISO 21640:2021 Solid recovered fuels-Specifications and classes]. Fuel blend IV achieved the best parameters, exhibiting the highest calorific value and volatile matter content, as well as the lowest moisture and ash content, with 25% sewage sludge. Furthermore, fuel blend IV is suitable for pelletization, which is very important for fuel storage and transport. The best application for the produced fuel blends would be their use in the co-incineration process in a cement kiln. The combustion conditions in a cement kiln meet the requirements for thermal treatment of waste due to the high temperatures and alkaline conditions. The produced fuel blends fall within the specified classes of alternative fuels; therefore, they should not pose any problems with pollutant formation during combustion. The use of waste-derived fuels for co-incineration in the cement industry can lead to savings in the form of reduced coal consumption by incorporating a 10% share of waste-derived fuels, generating revenue from waste disposal fees, and lowering fees associated with CO_2 emissions into the atmosphere [Wojtacha-Rychter et al., 2022; Modenisha et al., 2025]. The availability of materials for large-scale fuel production is feasible due to the large volume of waste generated. In the case of sewage sludge, availability is very high and stable due to the large volumes produced by wastewater treatment plants. In contrast, the volume of peanut shell waste is increasing year by year due to the growing demand for peanuts. As for used footwear, the large volume stems from regulatory changes requiring the removal of used footwear from the mixed waste stream. Consequently, this has led to a sharp increase in the mass of this waste and challenges in its management. This situation creates an opportunity to use used footwear for fuel production. Based on the laboratory tests conducted, it can be concluded that the resulting fuel blends possess energy potential and can be used in the cement industry as a substitute for conventional fuels.

CONCLUSIONS

Laboratory test results indicate that it is possible to produce fuel from peanut shells, sewage sludge, and rubber waste from worn-out shoes. Furthermore, the fuel's properties make it suitable for use in the energy sector.

Based on the results obtained, it can be concluded that:

- the fuel blends produced have an energy potential that indicates the possibility of co-combustion with other fuels,
- it is possible to dispose of sewage sludge that does not meet the requirements for use in agriculture,
- when used in the energy industry for co-combustion with other fuels, the produced fuel can reduce dependence on fossil fuels,
- the fuel's parameters indicate the potential for energy production.

Further research is recommended on the combustion and co-combustion of this fuel with other fuels in order to determine how to optimize combustion process parameters in the cement or power generation industries.

Acknowledgements

The publication was funded by the university under project BS/PB-400-301/26.

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