Advances in Science and Technology Research Journal

*Advances in Science and Technology Research Journal*, 2025, 19(5), 232–247
https://doi.org/10.12913/22998624/201347
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Received: 2025.02.12
Accepted: 2025.03.15
Published: 2025.04.01

# Harnessing waste-to-energy potential from plastic waste co-incineration

Agnieszka Kijo-Kleczkowska[1], Adam Gnatowski[1], Jaroslaw Krzywanski[2], Dariusz Kwiatkowski[1*], Iliya Iliev[3], Ivan Beloev[4], Muhammad Wakil Shahzad[5], Rasikh Tariq[6]

[1] Faculty of Mechanical Engineering, Czestochowa University of Technology, Czestochowa, Poland
[2] Faculty of Science and Technology, Jan Dlugosz University in Czestochowa Czestochowa, Poland
[3] Department of Heat, Hydraulics and Environmental Engineering, "Angel Kanchev" University of Ruse, 7017 Ruse, Bulgaria
[4] Department of Transport, "Angel Kanchev" University of Ruse, 7017 Ruse, Bulgaria
[5] Mechanical & Construction Engineering Department, Northumbria University, Newcastle Upon Tyne NE18ST, UK
[6] Institute for the Future of Education, Tecnologico de Monterrey, Ave. Eugenio Garza Sada 2501, Monterrey, N.L., 64849, Mexico
* Corresponding author's e-mail: dariusz.kwiatkowski@pcz.pl

## ABSTRACT

The development of civilization has resulted in increasing waste, including plastic. Strict legal regulations enforce the limitation of waste storage. The best neutralization method is thermal utilization, with the possibility of heat recovery. The primary objective of this paper is to conduct a novel analysis of the results of thermal tests in the air for selected polyamide, biomass, coal sludge, hard coal, and fly ashes wastes and their mixtures using thermogravimetry, differential scanning calorimetry, and mass spectrometry. The focus is particularly on the exothermic effect and $CO_2$ emission from the combustion of these waste mixtures. This unique approach to waste management research promises to shed new light on the thermal behavior of waste materials and their environmental impact. Adding fly ashes significantly reduces exothermic effects, while including biomass, coal, and coal sludge wastes in the plastic notably amplifies exothermic effects. Adding coal sludge, biomass, and fly ash to the plastic waste substantially decreases $CO_2$ emissions. However, supplementing hard coal with this plastic waste leads to a marked increase in $CO_2$ emissions, albeit still lower than coal alone. These findings underscore the crucial role of waste composition in the exothermic effects and $CO_2$ emissions during combustion. The innovation of the article results from the combination of experimental thermal research with the use of artificial intelligence to model thermal effects and $CO_2$ emissions. The paper introduces the fuzzy logic methods-based model, which enables the estimation of total exothermic impact and $CO_2$ emissions. Due to the absence of such tools, the developed Single Input and Multiple Outputs model brings a new framework for managing thermal processes in waste-to-energy systems. The model delivers new optimization functionalities for sustainable development and increased energy efficiency within the net-zero emissions strategy by providing insights into the energy potential and environmental implications essential for combating climate change, which is vital in the energy discipline.

**Keywords:** energy efficiency, sustainability, net-zero emission, plastic wastes, biomass, artificial intelligence.

## INTRODUCTION

This study outlines the findings of thermal research on different materials using thermogravimetry (TG), differential scanning calorimetry (DSC), and mass spectrometry (MS), considering $CO_2$ emission. In materials science, thermal analysis methods are pivotal for the characterization of materials and for assessing their composition and thermal resilience. These methodologies discern critical temperatures at which variations in mass loss rate and heat liberation manifest, delineating distinct phases of decomposition. Furthermore, such techniques, augmented by MS tests, are instrumental in detecting emissions of pollutants during the thermal breakdown of materials. This analytical framework deepens the comprehension of materials' thermal attributes and fosters enhancement, innovation in materials development, and manufacturing quality assurance across various domains, including environmental engineering, mining, energy, mechanical and materials engineering, chemical engineering, and pharmacology.

Employing polymer waste in thermal processes such as combustion, pyrolysis, and gasification serves three principal objectives: energy recovery through the thermal valorization of waste, ecological benefit via the mitigation of environmentally detrimental gas emissions, and economic advantage by substituting primary fuels like coal with waste materials. This multifaceted approach underscores waste utilization's energetic, ecological, and economic dimensions and aligns with the strategic imperatives of sustainable energy management and environmental stewardship.

Carbon dioxide emission during different thermal processes is considered in many works, including [1–3]. For example, the authors of the paper [4] stated that during polyoxymethylene combustion in a fluidized bed, 99.6% conversion of carbon to $CO_2$ can be achieved at temperatures as low as 800 °C. Employing $CO_2$ as a fluidizing agent during the pyrolysis of plastics represents a promising avenue for research, especially in light of the ongoing climate challenges. As mentioned earlier, restrictive legal regulations require appropriate waste management [5, 6], including reducing waste storage (also plastic waste). It can be replaced with thermal recycling [7–10]. The calorific value of polymer waste also enables energy recovery from them [11, 12]. The authors of the paper [13] stated that the combustion of plastics in a fluidized bed differs from coal and wood combustion. The polymer particles melt and decompose, leaving no char. The polymers can be combusted alone in a bubbling fluidized bed combustor. However, it is preferable to co-combustion with a high-ash fuel (e.g., another waste) to stabilize the process. Mixing polymers with another fuel minimizes premature melting.

In the study presented in the reference [14], the authors observed an enhancement in hydrogen production by 48%, which they attributed to the increase in the steam-to-polyethylene waste ratio, which leveraged the water-gas shift and reforming reactions.

The research documented in the paper [15] explores various strategies for valorizing plastic waste. It identifies catalytic pyrolysis as an environmentally friendly method for generating high-value outputs, including liquid fuels, hydrogen, plastic monomers, and carbon nanotubes. The study highlights that optimizing this process can be attained through strategic selections of plastic feedstocks, catalysts, operational temperatures, pressures, residence times, and fluidizing gases, positioning catalytic pyrolysis as a versatile and green technology for plastic waste conversion.

In the paper [16], the authors presented the thermogravimetric analysis results for biomass, bituminous coal, and lignite mixtures. They emphasized two stages of fuel combustion, which are connected with devolatilization and char combustion.

In the paper [17], the authors stated that the first peak on the TGA thermogram of PA6 at a temperature of 220 °C is due to the crystalline melting of this plastic. The next peak, at about 470 °C, is connected with the thermal degradation of PA-6. They also presented MS profiles of major evolved gases and stated that this temperature corresponds to the maximum DSC, mainly associated with $NH_3$, $CO_2$, hydrocarbon fragments, and CO emission.

Authors of papers [18, 19] stated that $CO_2$ is released in two stages during the thermal decomposition of coal, which can be observed as characteristic peaks. Mass spectrometry results [20] showed that $CO_2$, NO, or $NO_2$ are released after the temperature exceeds 300 °C.

The analysis of thermal tests for coal and biomass showed a lower combustion temperature and a higher biomass mass loss rate than coal [21].

The primary objective of the study detailed in the paper [22] was to showcase the findings from TG, derivative thermogravimetry (DTG), and differential thermal analysis (DTA) concerning the combustion of two distinct biomass types—sewage sludge and coal—and their co-combustion when mixed. The outcomes of co-combusting coal with either sewage sludge or biomass demonstrated that adding biomass and sewage sludge can effectively and beneficially augment coal combustion.

In a paper [23], the authors reported that for fly ashes, dehydration of $Ca(OH)_2$ occurs within the temperature range of 655 °C to 749.4 °C, while the decomposition of $CaCO_3$, $CaSO_4$, salts, and aluminum takes place between 732.1 °C and 900 °C.

When incorporated into composites with polymeric materials, fly ash, and quartz sands enhance their thermal and mechanical properties. This includes improved resistance to deformation, increased resistance to ignition and burning, and a reduction in the heat release rate at elevated temperatures [24].

In the paper [25], the authors presented the thermal behavior of ash using the TGA method, which allows the investigation of its decomposition processes to analyze the transformation of ash at elevated temperatures.

The incorporation of waste materials as fillers in plastic composites holds significant importance. The primary objectives behind this practice in processing polymeric substances include enhancing thermomechanical properties – such as increased stiffness, enhanced resistance to compression, stretching, bending, improved hardness, and decreased material flammability. Additionally, this approach serves an ecological purpose by minimizing waste accumulation and providing an economic benefit by reducing production costs.

In this context of tests of composite polymer materials, it should be noted that they have the potential to replace metals, as they are lighter, corrosion-resistant, and more flexible. Hybrid composites reinforced with fibers characterized by specific mechanical properties can be listed here [26], as they are enhanced with fibers' mechanical properties such as stretching, impact resistance, and bending. Experimental results have shown that fiber arrangements influence the mechanical properties of natural hybrid composites [26, 27]. Due to the different properties of polymers, the application of reinforcing fibers significantly affects the physical and chemical properties of the obtained materials.

The paper [28] presented a modern technology for processing HDPE. The HDPE composite's mechanical properties and thermal resistance reinforced with fibers were investigated. The results of the experiments indicated that the appropriate addition of fiber content is advantageous for enhancing surface finish as well as mechanical and thermal performance. Most research on polymer composites has centered on the influence of fiber concentration and orientation on material properties. Nevertheless, the matrix material's impact on composites' thermal properties remains underexplored. The study's goal [29] was to determine the thermal properties of polymer composites reinforced with carbon fibers by altering the matrix material. The methods employed comprised thermogravimetric analysis (TGA), DSC, and thermomechanical analysis (TMA). The results showed that the matrix material significantly affects thermal conductivity and coefficient of thermal expansion. At the same time, the glass transition temperature variability and specific heat do not change significantly compared to the polymer.

In work [30], the influence of adding carbon fibers on the structure, mechanical properties, and crystallinity of three different PAEK polymers was investigated. Incorporating minor quantities of short carbon fibers into PAEK increases their stiffness and operating temperature but alters their processing methods, structural characteristics, and material properties.

The impact of plastic waste on the environment is crucial. In the energy industry, fly ash, a type of solid waste, is a research subject for many authors, thus addressing the recycling of these materials [31,32].

The authors of the paper [33] synthesized a composite material developed from two industrial wastes: recycled polyethylene terephthalate (PET) and fly ash as the filler. They assessed the influence of various additions of fly ash on the thermal properties and microstructure of the composite material. The composite materials were subjected to thermal and microscopic analyses. A study using differential scanning calorimetry confirmed that the obtained composite's thermal properties improved after adding fly ash.

The paper's authors [34] used biochar particles and short basalt carbon fibers to reinforce PC/ABS and PBT/ABS blends. The mixing process involved preparing samples of hybrid composites, in which part of the fibrous filler was replaced with biochar powder. The prepared materials were manufactured using the injection molding method. For some samples, a thermal-oxidative aging procedure was applied. The research results confirmed that biochar particles do not lead to heat-induced decomposition of the matrix blend. However, the mechanical properties of the hybrid composites were slightly lower. As a result of the thermal aging procedure, the deterioration of properties was more significant, especially in the case of PC/ABS-based samples. Thermal analysis and structural examinations did not reveal substantial alterations in the macromolecular structure of the prepared materials, thus confirming their potential for use in demanding applications.

In the work [35], biologically sourced cellulose nanofibers were utilized to enhance the characteristics of PA6. The distribution of nanofillers in polymer matrices was addressed. It was demonstrated that nanocomposites containing cellulose nanofibers exhibit favorable strength parameters when processed through initial milling and subsequent compression molding. Considering the polymer compatibility, it is crucial to identify the components of polymer blends in recycling. The article [36] discusses the possibilities of detecting polymers in plastic blends and extruded mixtures. The identification of multi-component blends is possible through pyrolysis-gas chromatography/mass spectrometry and differential scanning calorimetry. Blends of low-density polyethylene (LDPE), polystyrene (PS), polypropylene (PP), polyamide (PA), and polycarbonate (PC) in various combinations were investigated. After selecting each blend, qualitative analysis was performed, detecting characteristic pyrolysis products for each polymer. Furthermore, a quantitative analysis of these polymers was conducted.

The authors of the paper [37] utilized natural fibers for reinforcing polymers. Recycled high-density polyethylene and hemp fibers were employed for the study. The composites' thermal, structural, mechanical, and antioxidant properties were evaluated using numerous complementary research techniques. Stereoscopic microscope images demonstrated satisfactory dispersion of hemp fibers in the polymer matrix while scanning electron microscope microphotographs revealed enhanced adhesion between the filler and the polymer matrix. The addition of hemp fibers contributed to the improvement of the composite's modulus of elasticity. The results indicated that with an increase in the content of hemp fibers, the antioxidant properties of the composite also increased.

The article [38] presents research and discusses the variability of thermomechanical parameters derived from recycling polypropylene/high-density polyethylene blends without adding other components, which is not commonly found in the literature. Comprehending the fluctuating characteristics of polymer blends, especially those derived from recycled sources, is imperative. This understanding is key to effectively reintegrating these materials into manufacturing cycles, which plays a significant role in advancing toward a sustainable, closed-loop economic model. The study [39] compared three recycling methods, including steam pyrolysis, mechanical grinding, and the dissolution process used for obtaining carbon fibers from recycling, regarding their applicability during the synthesis of polymer matrix composites. Polyethylene composites were fabricated to compare the mechanical properties of those produced through three different recycling methods. Furthermore, high energy efficiency was demonstrated in the steam pyrolysis process. The aim of the study conducted by the authors [40] was to assess the mechanical and thermal properties of recycled plastics, specifically PC, PS, glass fiber-reinforced polyamide 6 (PA6-GF30), and polyethylene terephthalate (PET). To achieve this, samples underwent two cycles of mechanical recycling. They were evaluated through thermal and mechanical analyses, including differential scanning calorimetry, hardness testing, tensile strength measurement, and flow rate assessment. The research results indicated that the materials used underwent minimal changes. This work demonstrates that mechanical recycling can be an interesting option for recovering certain materials depending on the desired quality of the end products.

The paper's authors [41] focused on some of the latest techniques for recycling and reusing plastics and composite materials. Thermal recycling is the most efficient technique for processing carbon and glass fibers in polymer composite recycling. This method's efficacy lies in its ability to maintain or closely replicate the properties of the recycled materials to that of their original counterparts. Additionally, thermal recycling demonstrates a marked advantage in energy efficiency, particularly compared to chemical recycling methods. Beyond this, an alternative recycling approach for plastics includes the direct extraction of energy, accomplished either through incineration or the conversion into fuel, offering a pathway for energy recovery from plastic waste. In the paper [42], the authors presented the results of experiments related to processing LDPE waste bags into fuel through economical catalytic pyrolysis.

The authors of the paper [43] investigated high-density polyethylene (HDPE) under thermal and catalytic pyrolysis conditions in two experimental setups. The conditions were optimized for the pyrolytic conditions for HDPE decomposition to maximize gas yield and minimize the amount of secondary waste, examining the efficiency of the process.

In [44], the potential recycling of PS plastic waste was evaluated through a stationary recycling system in a pyrolytic reactor. The novelty lies in examining the reactor's design impact on parameters and reaction kinetics to enhance process efficiency, activation energy, and chemical composition. Research results indicate that maintaining appropriate reactor temperature conditions remains a key parameter that enables achieving high oil production efficiency from PS. Examining experimental outcomes and numerical simulations relating to the combustion of plastics and fuels unveils various potential methodologies for executing these processes.

This analysis not only elucidates current practices but also paves the way for future investigative trajectories in this field [45,46]. Applying an integrated approach based on experimental and theoretical investigations of the combustion and thermal decomposition processes of polymers and their composites, such as methyl polymethacrylate, polyethylene, and glass fiber-reinforced epoxy resin, features of the combustion mechanism are identified. The research included the kinetics of thermal decomposition and the thermo-chemical structure of flames of the investigated materials [47].

The above initial analysis of waste behavior constitutes an essential step in understanding the dynamics of waste management. To understand this more comprehensively, future studies should be focused on polymer waste, including novel methods for either repurposing or recycling polymer materials and biofuel production. This progress is fundamental for the increase in energy efficiency, sustainability of waste-to-energy conversion processes, and movement towards the net-zero emissions strategy [48,49]. The broader context of these energy strategies aligned with circular economy concepts favors more sustainable and resilient energy ecosystems, covering the importance of environmental considerations in energy engineering and waste management due to the intricate interplay between economic factors and ecological impacts [50,51]. Moreover, an essential factor is to consider the profitability of sustainable technologies aspect as from the investors' perspective, the trends in funding are also necessary, and the financial viability of sustainable technologies is a critical factor of their success in the long run [52,53]. In modern manufacturing, the industry's point of view and advanced technologies, including process optimization and automation in decision-making, are crucial [54–56]. The energy self-sufficiency should also be considered a significant component of national sovereignty. This aspect emphasizes the critical significance of a nation's capacity for energy self-sufficiency, enhancing its autonomy and security on a global scale [57,58].

Considering the above issue, predicting waste behavior, especially plastic waste behavior during thermal analysis, is urgent but challenging. Due to environmental concerns, this issue is particularly relevant to recorded $CO_2$ emissions [59,60].

Therefore, the innovative aspect of this article also consists of the developed model, which allows the prediction of characteristics of thermal process curves for polyamide, coal fuels, biomass waste, fly ashes, and their mixtures. The model predicts the DSC, i.e., the difference in the heat transfer between the sample under test and its environment, identifying the exothermic reactions and ion currents I, expressing $CO_2$ emissions during tests. The model was built using fuzzy logic methods, one of the leading artificial intelligence (AI) methods, next to other modeling techniques, including artificial neural networks genetic algorithms [61–63] and other machine learning techniques [64–66]. The fuzzy logic approach found various applications in science and industry [67–69]. An Adaptive Network-based Fuzzy Inference System (ANFIS) was developed to optimize methane generation from the steam gasification process [70]. Multiple fuzzy logic controllers for energy management in storage systems were designed by Zahedi [71]. The study focused on battery stack, supercapacitor, and hydrogen tank. According to the results, the fuzzy logic approach's rule base and membership function optimization processes seem crucial for the developed systems. Finally, Yang et al. [72] introduced a fuzzy logic-based optimization approach to reduce the electric peak torque. The vehicle's speed was used as one of the indicators in the optimization procedure of the logic threshold control strategy.

The organization of this paper is as follows: Section 2 provides the properties of the materials and the methodology of measurements and modeling. Section 3 provides detailed results and analysis and discusses the experimental and modeling results. Lastly, Section 4 summarizes the conclusions and future research.

## MATERIALS AND METHODS

This article presents a thermal analysis of selected materials: hard coal (C), coal sludge-waste generated from flotation coal enrichment (CS), biomass waste (AB), fly ash – sproduced during the co-combustion of hard coal and coal sludge 65%/35% (fly ash C), fly ash – sproduced during the co-combustion of agro biomass and forest biomass 20%/80% (fly ash B), and polymer waste.

Hard coal, coal sludge waste, biomass waste, and fly ashes come from one Polish power plant. Polyamide 6 (PA6) waste is recycled plastics. The materials were properly comminuted for the tests, ground using a laboratory mill, and sieved through a 200 µm mesh.

Table 1 shows proximate and ultimate analyses of polyamide waste, coal fuels, biomass waste, and fly ashes used in the research. The studies of the materials were carried out by the standards PN-G-04560:1998, PN-G-04516:1998, PN-G-04513:1981, PN-G-04584:2001, PN-G-04571:1998, PN-EN 15414-3:2011, PN-EN 15403:2011, PN-EN 15402:2011, PN-EN 15400:2011, and PN-EN 15407:2011. This analysis identifies the content of the essential fuel elements: carbon, hydrogen, oxygen, nitrogen, and sulfur, as well as the content of moisture, ash, and volatile parts. This analysis also allows for determining the content of the solid combustible part in the fuel (FC) and the fuel's calorific value. It can be seen that polyamide recyclate and biomass waste have the highest volatile parts content. In contrast, coal has a high calorific value and a high value of (FC), connected with the high carbon content. The high LHV value in the case of polyamide recyclate is influenced by the high content of volatile parts, which burn intensively in the presence of oxygen.As mentioned earlier, the thermal analysis of the mentioned materials was carried out using the thermogravimetric method (TG), DSC, and mass spectrometry (MS). Thermogravimetry is a method based on recording variations in the mass of the tested sample as the ambient temperature increases. The TG curve shows the mass changes of this sample. The DTG curves illustrate the rate of change of sample mass. DSC is a technique that enables the analysis of the difference in the exchange of heat between the tested sample and its environment, alongside the characterization of exothermic and endothermic reactions. The DSC curve is an image of this analysis. Mass spectrometry analyzes the chemical composition of gaseous reaction products visualized on an MS curve. This method involves ionizing the atoms or molecules of the tested substance within the spectrometer chamber, then separating the resulting ions based on their mass-to-charge ratio: m/z, i.e., the so-called mass spectrum (m - mass, z - charge of the ion). The measurement results are ion current values (I) corresponding to specific mass-to-charge (m/z) ratios. The values of the ion currents are proportional to the concentrations of the gases from which these ions originate [73–75]. The m/z=44 mass spectrum is mainly responsible for $CO_2$ release [76–78]. This paper focuses on analyzing $CO_2$ emissions during the combustion process of selected materials.

The analyzed samples were subject to thermal analysis using a Netzsch STA 409 PG Luxx equipment coupled online with the QMS Aëolos 403C quadrupole mass spectrometer [79,80]. In this method, the volatile sample materials are directly transferred into the electron impact ion source of the MS via a fused silica capillary.

Alumina crucibles held the sample and the reference ($Al_2O_3$ crucible). Approx. 5 mg of a sample of each material was placed in the sample crucible. The samples were heated from 40 °C to 1000 °C, with 10K/min., in air atmosphere. Using air in thermal analysis enabled the combustion of the considered materials. The flow rate of air was 25 ml/min.

**Table 1.** Proximate and ultimate analyses of materials on an air-dry basis

| Material | Proximate analysis | | | | | Ultimate analysis | | | | | LHV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | M [%] | VM [%] | A [%] | FC [%] | FR [%] | C [%] | H [%] | N [%] | O [%] | $S_{total}$ [%] | [MJ/kg] |
| Hard coal (C) | 10.08 | 28.91 | 11.07 | 49.94 | 1.73 | 59.89 | 3.62 | 1.17 | 12.46 | 1.71 | 23.49 |
| Coal sludge (CS) | 4.51 | 20.45 | 39.43 | 35.61 | 1.74 | 40.12 | 2.82 | 0.54 | 12.11 | 0.72 | 15.02 |
| Biomass waste (AB) | 6.95 | 68.67 | 6.51 | 17.87 | 0.26 | 44.62 | 5.56 | 0.47 | 35.89 | 0.04 | 16.43 |
| Fly ash C | 0.34 | 2.61 | 95.51 | 1.54 | 0.59 | 1.18 | 0.00 | 0.00 | 3.31 | 1.40 | - |
| Fly ash B | 0.08 | 4.32 | 95.01 | 0.59 | 0.14 | 1.00 | 0.00 | 0.00 | 2.42 | 1.75 | - |
| Polyamide waste (PA6) | 1.13 | 98.65 | 0.04 | 0.18 | 0.002 | 62.48 | 9.07 | 15.17 | 11.92 | 0.01 | 28.59 |

**Note:** FC = 100 – (M = VM + A); FR = FC/ VM.

TG resolution was 2 μg and DSC resolution < 1 μW, with a detection limit of < 100 ppb. External companies performed the ultimate and proximate analyses of materials and the tests TG/DTG/DSC/MS.

Since computer technology is crucial for optimizing industrial processes, mainly in a sustainability-driven Industry 4.0, this article aims to develop a fuzzy logic-based tool for predicting the total exothermic effect of processes, which is defined as DSC (area under the DSC curve), and the total emission of $CO_2$ during processes, defined as ΔI (area under the ion current curve).

Fuzzy logic methods are mainly usable for complex systems as they describe sophisticated mechanisms where the experience is easier to access than rigid knowledge and system understanding. Moreover, in the context of energy and emissions management, fuzzy logic offers unique opportunities to model uncertainties and imprecisions that are difficult to capture using traditional methods. Finally, fuzzy logic methods can be utilized for tasks where the data is not so high, but the knowledge of an expert is correct enough to use it to build a model. This is the specific case considered in the article. A typical fuzzy logic-based system consists of a fuzzification, the fuzzy rule base, an inference engine, and the defuzzification block. The fuzzification module enables assigning a crisp input parameter value to a corresponding fuzzy set membership function value between 0 and 1. The rule base allows us To identify the relationships between input and output fuzzy sets and derive fuzzy conclusions. Using these conclusions, the defuzzification block generates the model's crisp output. Fuzzy systems primarily employ two methods of deductive inference: the Mamdani and Sugeno approaches. The difference between them consists of the output (consequent), which are fuzzy sets in Mamdami, and functions of the inputs in Sugeno models, respectively. The developed model allows for predicting the energetic effects and $CO_2$ emissions during the tests, and to the best of the authors' knowledge, this is the first study addressing the use of fuzzy logic for the purpose under consideration.

## RESULTS AND DISCUSSION

### Thermal analyses of the wastes

Table 1 shows proximate and ultimate analyses of materials used in the research. As shown in Table 1, hard coal is characterized by a high carbon content (C = 59.89%) and the highest fraction of the solid combustible component (FC = 49.94%). Biomass waste exhibits a high volatile matter content (VM = 68.67%) and the highest oxygen content (O = 35.89%). Among the analyzed materials, polyamide waste has a lower heating value (LHV) of 28.59 MJ/kg and the highest proportion of volatile matter (VM = 98.65%). Fly ash is notable for its ash content exceeding 95% and a low volatile matter content (VM = 2.61%–4.32%).

Figures 1–2 and Figures S1–S8 (Supplementary material) and Tables S1–S6 (Supplementary material) illustrate the measurement results of TG/DTG/DSC/MS and their analysis. The figures come directly from the Proteus® software program. The test results showed (in relation to polyamide waste) that:

1. An increase in the content of coal and coal sludge in a mixture with polyamide waste leads to:
   - insignificant shifting of the melting point towards higher temperatures,
   - an increase of the maximum value DSC at higher temperatures,
   - lowering the maximum value of the rate of mass loss DTG during the volatiles combustion and increasing this value at the char burning stage,
   - extending the total burn time of the material;
2. An increase in the content of biomass waste in a mixture with polyamide waste leads to:
   - insignificant shifting of the melting point towards higher temperatures,
   - an increase of the maximum value DSC at higher temperatures,
   - an increase of the maximum value of the rate of mass loss DTG during the combustion of volatiles and a decrease of this value in the stage of char burning,
   - extending the total burn time of the material;
3. An increase in the fly ash content in the mixture with polyamide waste leads to:
   - insignificant shifting of the melting point towards higher temperatures,
   - an increase of the maximum value DSC at lower temperatures,
   - lowering the maximum value of the rate of mass loss DTG,
   - shortening the total burn time of the material.

A 30% addition of fly ashes to polyamide waste leads to the most significant reduction of

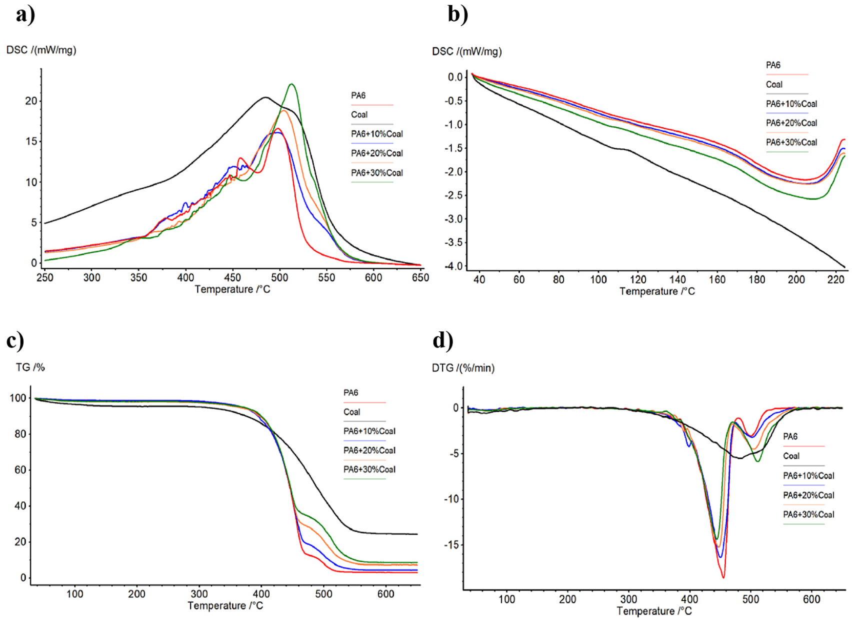



**Figure 1.** Thermal analysis of PA6 waste, coal, coal + PA6 waste (10%/90%), coal + PA6 waste (20%/80%), coal + PA6 waste (30%/70%): a) DSC (endothermic peak); b) DSC (exothermic peaks); c) TG; d) DTG

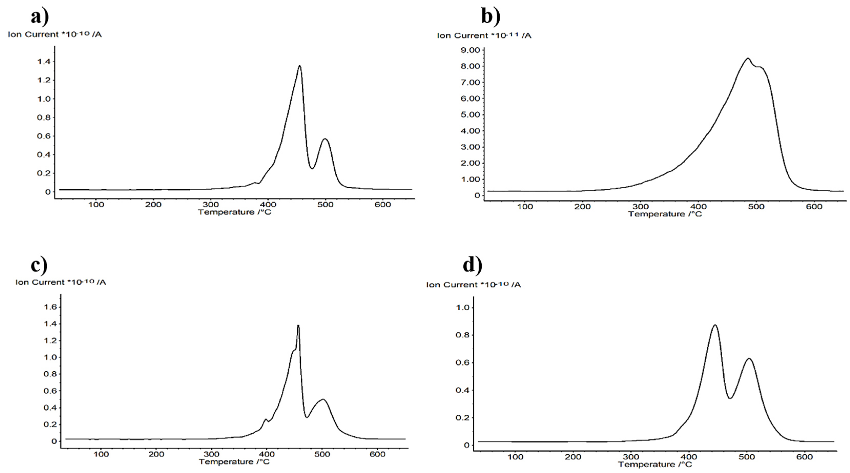



**Figure 2.** Thermograms MS (m/z=44) of coal + PA6 waste mixture: a) PA6 waste; b) coal; c) coal + PA6 waste (10%/90%); d) coal + PA6 waste (20%/80%); e) coal + PA6 waste (20%/80%); coal + PA6 waste (30%/70%)

$CO_2$ emission: total ion current – sarea under the ion current curve (ΔI) = $33.28 \cdot 10^{-9}$ A·s – for 30% fly ash C, and ΔI = $29.94 \cdot 10^{-9}$ A·s – sfor 30% fly ash B (in the case of polyamide waste: ΔI = $44.41 \cdot 10^{-9}$ A·s). And then: biomass waste (ΔI = $41.54 \cdot 10^{-9}$ A·s – for 30%) and coal sludge waste – CS (ΔI = $40.62 \cdot 10^{-9}$ A·s – for 30% CS). A 30% addition of hard coal to polyamide waste causes an increase in $CO_2$ emission (ΔI = $51.20 \cdot 10^{-9}$ A·s), but still, this emission is lower than for coal alone (ΔI = $61.13 \cdot 10^{-9}$ A·s).

The increase in the addition of coal, coal sludge, and biomass waste to polyamide waste leads to a rise in the value of ΔDSC (exothermic effect), while an increase in the addition of fly ashes to plastic waste results in a decrease in the value of ΔDSC (exothermic effect).

Fly ashes can be a suitable additive to the plastic used to create composites. The analyzed polyamide wastes have a high energy potential, and adding other materials, such as hard coal, coal sludge, and biomass waste, increases this value.

## Model of exothermic effect and total $CO_2$ emissions

An innovative model AI-based fuzzy logic model was introduced in the article. The fuzzy logic-based approach can describe imprecise, ambiguous, poorly defined mechanisms and processes [67, 81–83]. The Qtfuzzylite application (www.fuzzylite.com) was applied to develop the model [82]. The model comprises one input, i.e., the kind of waste material IDw (polyamide waste, hard coal, coal sludge, biomass waste, fly ash B, and fly ash C), and two outputs (i.e., the total exothermic effect of processes, ΔDSC and the total emission of $CO_2$ during processes, ΔI), making a SIMO (Single Input and Multiple Outputs) type model. The developed model SIMO is a step toward mimicking certain aspects of human inference, considering decision-making and uncertainty in the described processes. A fuzzy logic-based model was created to better deal with poorly defined problems, requiring step-by-step evaluation and mimicking the human thinking process, in which, based on a small amount of input data, the system can infer the correct behavior of a complex system. The scarcity of SIMO models in energy conversion and emissions management analysis makes this aspect potentially innovative. The Sugeno approach was applied when building the model, where triangular fuzzy and constant sets represented the input and outputs, respectively [84].

Polyamide(a-d), Biomass, FlashAshB, and FlashAshC fuzzy sets were employed to describe the output parameters, while very low (VL), low (L), average (A), high (H), very high (VH), and extremely high (EL) functions were employed. According to Figure 3, the procedure considering Polyamide a-d had to be undertaken to allow the model to evaluate various polyamide-parent waste mixtures [49]. The input was expressed by the terms describing the basic wastes. The fuzzy rule base applied for the model is given in Table 2.

**Table 2.** The knowledge base of the developed model

| ID | Fuzzy rule |
|---|---|
| 1. | if IDw is HardCoal then ΔDSC is VH* and ΔI is EH* |
| 2. | if IDw is CoalSludge then ΔDSC is A and ΔI is A |
| 3. | if IDw is Biomass then ΔDSC is H and ΔI is H |
| 4. | if IDw is FashAshC then ΔDSC is VL and ΔI is VL |
| 5. | if IDw is FashAshB then ΔDSC is VL and ΔI is L |
| 6. | if IDw is Polyamide6a then ΔDSC is L and ΔI is VH |
| 7. | if IDw is Polyamide6b then ΔDSC is L and ΔI is VH |
| 8. | if IDw is Polyamide6c then ΔDSC is L and ΔI is VH |
| 9. | if IDw is Polyamide6d then ΔDSC is L and ΔI is VH |

**Note:** * EH – extremaly high, VH—very high, H—high, L—low, VL—very low

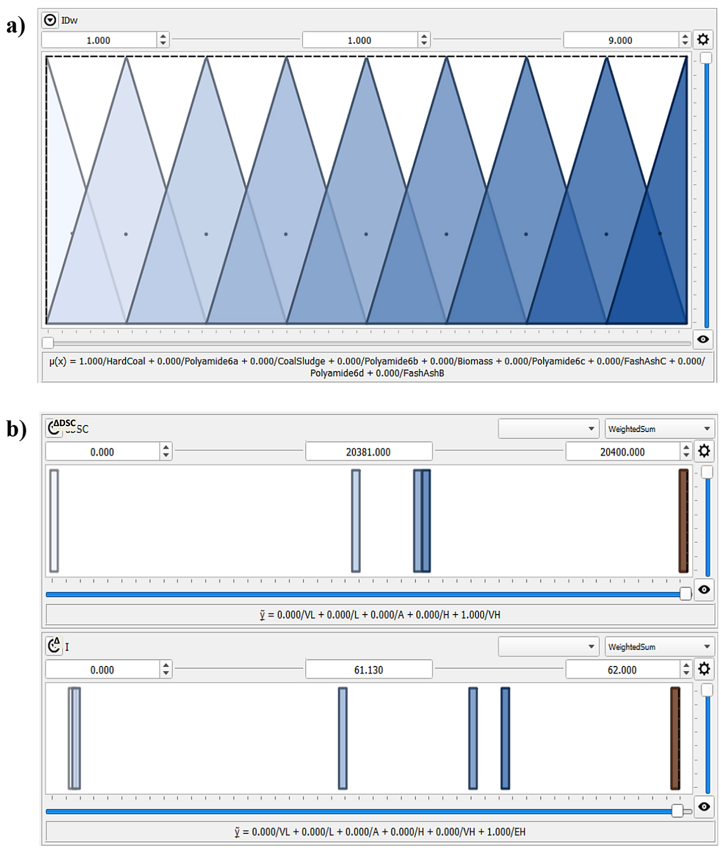



**Figure 3.** Input a) and outputs b) of the developed model

The comparison of the measures and calculated results are given in Figure 4. The developed model achieves good accuracy, as the R2 for ΔDSC and ΔI is 0.98 and 0.99, respectively. The maximum relative errors between measures and calculated results for ΔDSC and ΔI are 12% and 7%, respectively. According to the above metrics, the developed comprehensive model is very effective. Based only on one input, it allows accurate prediction of exothermic effects and $CO_2$ emissions during all the considered tests in a wide range (0–100 % wt.) of various wastes with the polyamide parent waste mixtures and outperforms the conventional programmed modeling methods [85–87].

For the first time, a comprehensive AI-based model allows the prediction of exothermic effects and $CO_2$ emissions for the entire input domain. Thus, the model provides the functionality of considering all possible blendings of basic wastes, among the paper's main innovations. The possibility of analyzing different types of waste and their impact on $CO_2$ emissions and exothermic effects is essential from the point of view of waste management and the optimization of energy processes. Figs. 5 and 6 depict examples of such calculations for coal sludge and biomass wastes, respectively.

Since coal sludge and biomass are characterized by higher exothermic effects and lower $CO_2$ emissions than polyamide, decreasing the polyamide wastes in the mixture leads to increased energetic effects and reduced $CO_2$ emissions. Predicting the two considered outputs can be conducted within the entire domain of the input variable, i.e., for any content of the waste fuel mixtures.

The developed fuzzy logic model with one input and two outputs (SIMO), which generates relative errors of less than 12%, is an effective tool for modeling some aspects of human inference in restricted domains. The model is good at dealing with uncertainty and can predict outcomes with relatively low relative error, which can be useful in many applications, from industrial process control to decision support systems.

Moreover, the developed model serves as an exemplary framework for conducting model-based research on the thermal analysis outcomes. This approach enhances the accuracy of thermal waste evaluation and offers a novel methodology for assessing environmental impacts and optimizing

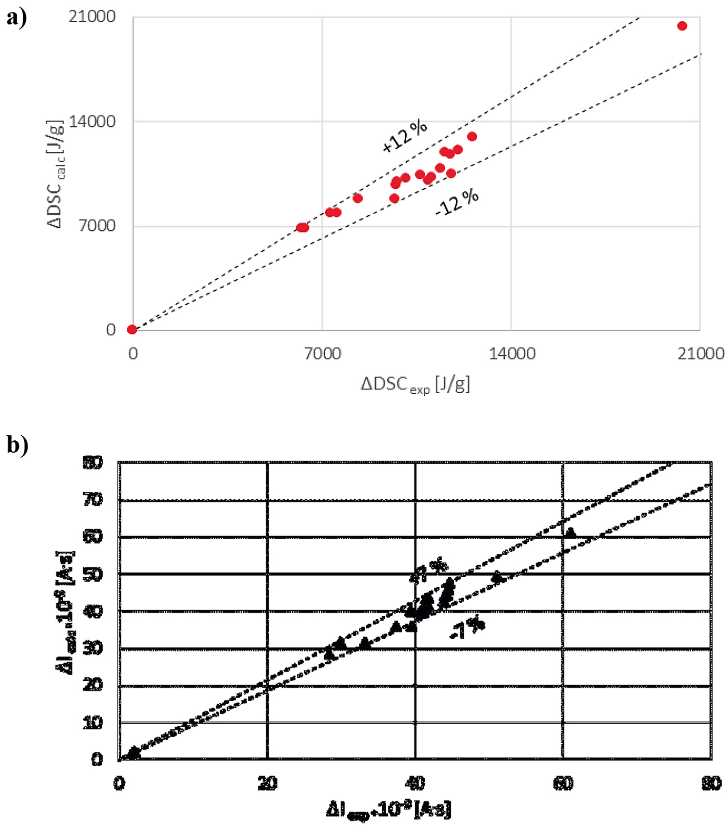
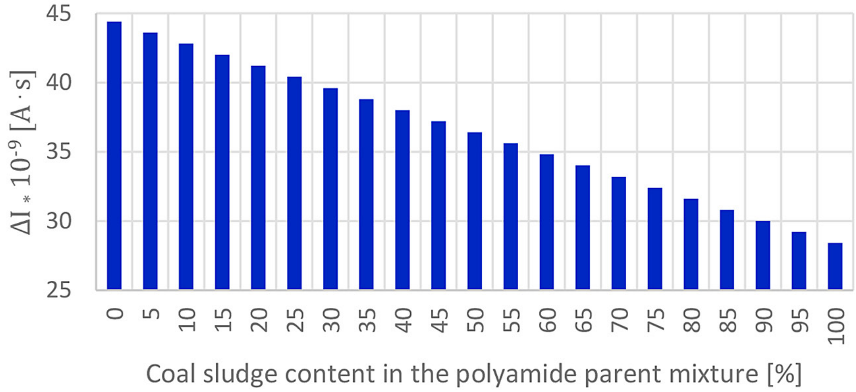



**Figure 4.** Comparison of the measures and calculated results for a) the total exothermic effect of processes, ΔDSC, and b) the total emission of $CO_2$ during processes ΔI

**a)**




**b)**

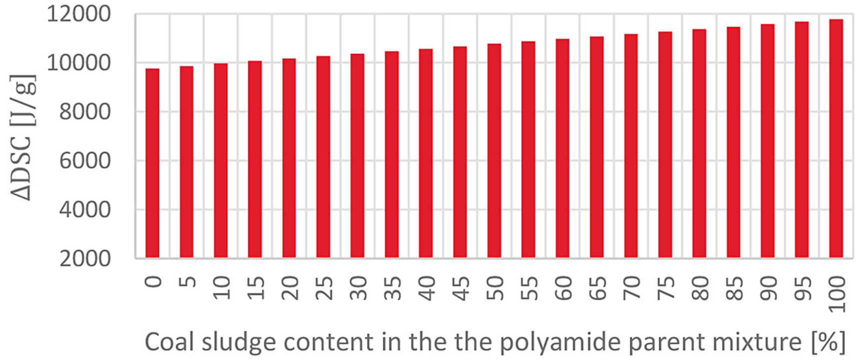
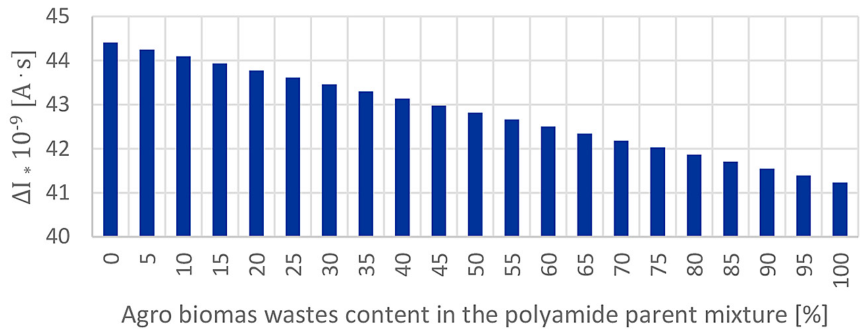



**Figure 5.** The impact of coal sludge content in the polyamide parent mixture on a) the total exothermic effect of processes, ΔDSC, and b) the total emission of $CO_2$ during processes ΔI

**a)**




**b)**

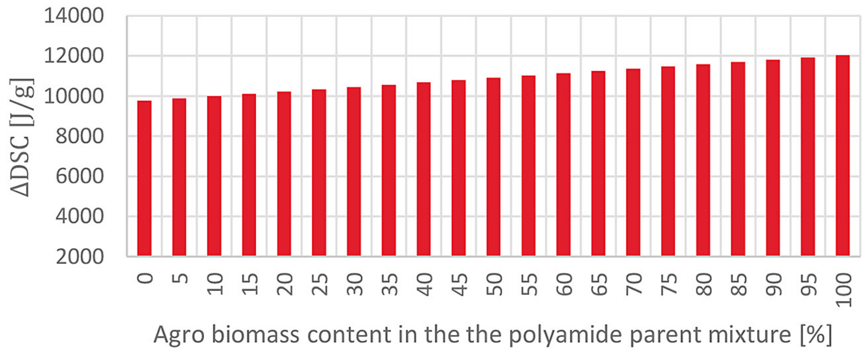



**Figure 6.** The influence of biomass content in the polyamide parent mixture on a) the total exothermic effect of processes, ΔDSC, and b) the total emission of $CO_2$ during processes ΔI

energy recovery processes. Through its application, the model demonstrates the potential of fuzzy logic in advancing the understanding and management of thermal processes in waste-to-energy systems.

## CONCLUSIONS

This manuscript explores timely and significant net-zero emissions, sustainability, and energy efficiency topics. Based on the results obtained, the following conclusions are presented.

1. The waste from the polyamide has a high energy potential.
2. Adding hard coal, coal sludge, and biomass waste to the considered plastic increases the exothermic value of ΔDSC.
3. Adding fly ashes to the analyzed plastic reduces the exothermic value of ΔDSC.
4. Incorporating coal sludge, biomass, and fly ash contributes to a reduction in $CO_2$ emissions; however, the 30% addition of fly ashes to polyamide waste leads to the most significant reduction of $CO_2$ emission in relation to plastic waste alone.
5. Adding hard coal to considered plastic waste increases $CO_2$ emissions, but this emission is lower than that from coal alone.
6. The fuzzy logic-based model developed enables the prediction of total exothermic effects and $CO_2$ emissions during the combustion of various waste mixtures, presenting a new perspective on the issue. The SIMO (single input and multiple outputs) model used to assess the total exothermic effect of processes and $CO_2$ emissions is particularly interesting because it allows for complex analysis with a relatively simple input.
7. The developed model serves as an exemplary framework for conducting model-based research on thermal analysis outcomes to improve the comprehension and control of thermal processes within waste-to-energy systems.
8. Based on the results obtained in the future, the authors intend to develop a more comprehensive model to predict other aspects of waste behavior during co-incineration, including gas emissions.

### Acknowledgment

The paper was carried out under BS/PB-1-100-301/2024/P (Czestochowa University of Technology, Faculty of Mechanical Engineering). The paper was also prepared under SBR/WNSPT/ZZMO/24/2023 (Jan Dlugosz University in Czestochowa). This study is financed by the European Union-NextGenerationEU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project № BG-RRP-2.013-0001-C01.

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