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Analysis Of Thermal And Technical Parameters Of Alternative Fuels Obtained From Biomass Pyrolysis

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Abstract: This study is devoted to the analysis of the elemental composition of the main products formed during biomass pyrolysis, namely pyrolysis liquid, pyrolysis gas, and pyrolysis char. The research scientifically evaluates the influence of the physicochemical and structural properties of biomass feedstock, particularly the relative proportions of lignocellulosic components—cellulose, hemicellulose, and lignin—on the composition of pyrolysis products. The analytical results demonstrate that lignin-rich biomass feedstocks produce pyrolysis char with a significantly higher carbon content, which can be attributed to an intensified carbonization process. In contrast, biomass rich in cellulose and hemicellulose generates a greater amount of volatile compounds during pyrolysis, leading to increased yields of pyrolysis liquid and gas. The presence of oxygen-rich functional groups was found to increase the oxygen content in the pyrolysis liquid and gas, thereby influencing their calorific value. Furthermore, the low nitrogen content confirms the environmental advantage of biomass pyrolysis. The obtained results are of considerable scientific and practical importance for biomass feedstock selection, optimization of pyrolysis technologies, and preliminary assessment of raw materials for targeted product generation. The conducted analysis indicates that biomass pyrolysis represents a promising pathway for energy production, chemical synthesis, preparation of solid adsorbents, and the production of renewable fuels.

Keywords: Biomass pyrolysis, lignocellulosic components, physicochemical and structural properties, biomass resources.

INTRODUCTION:

Fuel–energy and environmental issues have become one of the most pressing global challenges of the modern era. The rapid growth of fuel and energy consumption has led to the extensive exploitation of conventional fossil energy resources—such as natural gas, coal, and crude oil—which, in turn, has resulted in significant environmental pollution, increased greenhouse gas emissions, and disruption of ecological balance [55; pp. 211–216]. Moreover, the gradual depletion of fossil fuel reserves, the intensification of the global energy crisis, and the growing international focus on climate change mitigation and environmental sustainability have substantially increased scientific and technological interest in bioenergy, particularly biomass energy, as a renewable, carbon-neutral, and environmentally friendly energy source. As a consequence, the contribution of biomass to the global energy mix has been steadily increasing [1-5].

Biomass is generally regarded as a complex biological raw material predominantly composed of cellulose (40–50%), hemicellulose (25–30%), and lignin (20–30%), which together form the structural framework of plant-based materials [6,7]. Cellulose is a high-molecular-weight linear polymer consisting of glucose monomers linked via β-1,4-glycosidic bonds and represents one of the most abundant natural polysaccharides on Earth. It serves as the primary structural component of plant cell walls, providing mechanical strength, rigidity, and resistance to deformation, while also playing a crucial role in determining cell shape and overall plant morphology [8].

Hemicellulose, in contrast, comprises a heterogeneous group of branched heteropolysaccharides formed from various monosaccharides—such as glucose, galactose, xylose, mannose, and others—as well as uronic acids. Unlike cellulose, hemicellulose exhibits a lower degree of polymerization and a highly branched molecular architecture. It interacts with cellulose microfibrils through hydrogen bonding, forming a complex supramolecular network that facilitates structural cohesion within the plant cell wall. This interfacial bonding between cellulose and lignin components plays a vital role in maintaining the integrity, flexibility, and mechanical stability of the cell wall matrix.

METHODS

Comprehensive characterization of biomass pyrolysis products is essential for understanding conversion mechanisms, evaluating product quality, and optimizing thermochemical processing conditions. In this study, a combination of elemental, thermal, chemical, and structural analytical techniques was employed to determine the composition and properties of biomass feedstock as well as the resulting pyrolysis liquid, pyrolysis gas, and biochar.

The elemental composition of the biomass feedstock and solid pyrolysis products was determined using CHNS/O elemental analysis, which provided the mass fractions of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O). These data were used to evaluate fuel quality, estimate higher and lower heating values, and assess the environmental performance of the pyrolysis products.

Lignin is a three-dimensional, highly cross-linked aromatic polymer biosynthesized through oxidative coupling reactions of three primary phenylpropanoid monolignol precursors: p-hydroxyphenyl (H), guaiacyl (G), and syringyl (S) units. Its macromolecular structure consists of a complex arrangement of ether (C–O–C) and carbon–carbon (C–C) linkages, which impart substantial rigidity, hydrophobicity, and chemical resistance to secondary cell walls [8-11].

Sustainable lignocellulosic biomass resources—such as agricultural residues, forestry by-products, dedicated energy crops, and municipal solid waste—are increasingly recognized as renewable and low-carbon feedstocks for the production of alternative fuels, energy carriers, value-added organic chemicals, and advanced functional materials. The utilization of these biomass resources not only contributes to reducing dependence on fossil fuels but also supports circular economy principles and promotes environmentally sustainable energy systems [8].

Biomass is considered a relatively inexpensive, renewable, and widely available feedstock. According to expert assessments, approximately 220 billion tons of biomass are generated annually worldwide, indicating the existence of a large and sustainable resource base for the global energy system [12]. Studies have shown that nearly 10–14% of the total energy produced globally is currently supplied by biomass-based energy sources [13].

The conversion of biomass into renewable alternative fuels involves a range of biochemical and thermochemical processes and technologies. Biochemical conversion methods are primarily based on anaerobic digestion, which typically requires extended processing times. In contrast, thermochemical processes can be completed within seconds or minutes, offering significantly higher conversion rates. The principal thermochemical routes for biomass conversion include direct combustion, gasification, pyrolysis, and hydrothermal liquefaction [14].

Among these methods, pyrolysis represents the classical thermochemical process for biomass conversion and is generally conducted within a temperature range of 300–800 °C. The distribution of pyrolysis products is strongly dependent on the applied temperature regime. At relatively low temperatures (300–400 °C), biochar formation predominates, accompanied by smaller quantities of tar—defined as a dark, viscous, high-molecular-weight organic liquid formed during the thermochemical decomposition of biomass—and pyrolysis gas [14-16]. Within the intermediate temperature range of 400–600 °C, the production of biofuel in the form of pyrolysis liquid (bio-oil) becomes dominant [17]. At higher temperatures exceeding 600–800 °C, the yield of gaseous products increases significantly due to enhanced secondary cracking reactions [18-19].

To accurately describe the degradation behavior of biomass under varying thermal conditions, kinetic modeling of the thermochemical conversion process is required. Under practical operating conditions, biomass pyrolysis is a highly complex process that occurs over very short time scales—ranging from seconds to minutes—and involves multiple parallel and consecutive reactions taking place simultaneously.

Elemental analysis of the biomass feedstock reveals the following composition [20]: carbon (C) – 49.33%, oxygen (O) – 44.57%, hydrogen (H) – 6.06%, and nitrogen (N) – 0.04%. Thermochemical processing of biomass via pyrolysis results in two principal product streams: volatile vapor–gas mixtures released during pyrolysis and solid biochar (pyrolysis char). The volatile vapor–gas mixture can be further separated into condensable fractions (pyrolysis liquid or bio-oil) and non-condensable fractions (pyrolysis gas) [20].

Experimental studies indicate that, relative to the initial biomass mass, the average product yields under fast pyrolysis conditions are approximately 60–75% pyrolysis liquid, 10–20% pyrolysis gas, and 10–25% biochar. In contrast, slow pyrolysis typically produces 20–40% pyrolysis liquid, 25–35% pyrolysis gas, and 25–40% biochar [21-22]. The elemental composition of each fraction is presented in Table 1, while the chemical compositions of the pyrolysis liquid and pyrolysis gas are provided in Tables 2 and 3, respectively [20-22].

Table 1.
Elemental composition of pyrolysis products [23].

No	Elements	Concentration amount,%		
		Pyrolysis liquid	Pyrolysis gas	Pyrolysis coal
1	Carbon (C)	41.6	39.2	82.7
2	Oxygen (O)	50.0	58.8	11.4
3	Hydrogen (H)	8.1	2.0	2.9
4	Nitrogen (N)	0.2	0.0	0.1

RESULTS AND DISCUSSIONS

The data presented in Table 1 indicate significant differences in the elemental composition of the pyrolysis products—namely pyrolysis liquid, pyrolysis gas, and pyrolysis char—formed during the biomass pyrolysis process. These differences are primarily governed by the physicochemical and structural characteristics of the biomass feedstock, particularly the relative proportions of its lignocellulosic components, including cellulose, hemicellulose, and lignin.

The markedly high carbon (C) concentration observed in pyrolysis char (82.7%) is a characteristic feature of lignin-rich biomass types, such as wood residues, hardwood biomass, and bark materials. Due to its aromatic macromolecular structure, lignin undergoes extensive carbonization during thermochemical decomposition, resulting in the formation of carbon-rich biochar with low volatility. In contrast, biomass with a high content of cellulose and hemicellulose—such as agricultural residues, plant stalks, and straw—tends to generate a larger proportion of volatile compounds during pyrolysis. This behavior enhances the yields of pyrolysis liquid and gas, consequently leading to a relative reduction in the carbon content of the solid char fraction.

The elevated oxygen (O) content in the pyrolysis liquid and, in particular, in the pyrolysis gas (50.0–58.8%) reflects the abundance of oxygen-containing functional groups in biomass, including hydroxyl, carboxyl, and ether linkages. Biomass types rich in cellulose and hemicellulose contain a higher concentration of these functional groups, which promotes the intensive release of oxygenated compounds—such as CO, CO_2, water vapor, organic acids, and aldehydes—during pyrolysis. As a result, the oxygen content of the pyrolysis gas derived from such biomass is relatively high, leading to a lower calorific value compared to the pyrolysis gas obtained from lignin-rich biomass.

The relatively high hydrogen (H) concentration in the pyrolysis liquid (8.1%) can be attributed to the accumulation of hydrocarbons, phenolic compounds, and oxygenated organic species in the liquid fraction. When the biomass contains a higher proportion of extractives and hemicellulose, the hydrogen content of the pyrolysis liquid increases, thereby enhancing its fuel reactivity and suitability for subsequent chemical upgrading. Conversely, the low hydrogen content observed in the pyrolysis gas (2.0%) indicates the predominance of light gaseous components such as CO, CO_2, and CH_4 in its composition.

The very low nitrogen (N) content across all pyrolysis product fractions (0.0–0.2%) confirms a key environmental advantage of biomass pyrolysis. In particular, nitrogen-poor biomass types—such as wood, stalks, and lignocellulosic residues—contain minimal nitrogenous compounds, which significantly reduces the potential formation of nitrogen oxides (NO_x) during thermal conversion. However, when nitrogen-rich biomass feedstocks—such as fertilized agricultural residues or municipal biowaste—are subjected to pyrolysis, a slight increase in nitrogen-containing gaseous products may occur, necessitating optimization of process parameters.

Overall, the analysis of Table 1 demonstrates that the elemental composition of pyrolysis products varies substantially depending on the type of biomass feedstock. Lignin-rich biomass is more suitable for the production of high-carbon biochar, whereas biomass rich in cellulose and hemicellulose is more effective for maximizing the yields of pyrolysis liquid and gas. Therefore, comprehensive pre-characterization of the elemental and structural composition of biomass feedstocks is of critical scientific and practical importance when designing pyrolysis technologies and selecting target product pathways.

Table 2.

Elemental composition of pyrolysis fluid [23].

Component name	Concentration amount,%
Phenols	21,89
Ketones	8,46
Saccharides	5,92
Furans	4,41
Acids	3,62
Alcohols	2,65
Aldehydes	2,56
Unidentified fractions	16,82
Water	33,67

Table 3.

Elemental composition of pyrolysis gas [23].

The name of the component	Formula	Concentration amount,%
Carbon(II) oxide	CO	46,13
Carbon (IV) oxide	CO_2	44,66
Methane	CH_4	4,90
Ethylene	C_2H_4	1,17
Propene (or propylene)	C_3H_6	1,01
Ethan	C_2H_6	0,79
Propane	C_3H_8	0,63
Butene or butylene	C_4H_8	0,65
Hydrogen	H_2	0,05

CONCLUSION

The conducted scientific analyses demonstrate that biomass pyrolysis represents a versatile and high-potential thermochemical conversion pathway capable of generating multiple value-added products. The obtained results confirm that the elemental and structural composition of biomass feedstocks, particularly the relative proportions of lignocellulosic components, plays a decisive role in determining both the yield distribution and the qualitative characteristics of pyrolysis products. Consequently, a scientifically grounded understanding of feedstock properties is essential for effective process control and optimization.

By systematically optimizing key process parameters—such as temperature, heating rate, residence time, and feedstock properties—the proportion and quality of pyrolysis products, including bio-oil, biochar, and pyrolysis gas, can be purposefully regulated. Such optimization enables enhancement of the energy density of bio-oil, improvement of the structural and adsorption properties of biochar, and upgrading of the calorific value of pyrolysis gas. As a result, the overall energetic efficiency and functional performance of the pyrolysis system can be significantly improved.

In addition to its technical advantages, biomass pyrolysis offers substantial environmental benefits due to its reliance on renewable feedstocks and its potential to reduce greenhouse gas emissions and waste accumulation. The conversion of biomass into energy carriers, chemical precursors, and solid adsorbents supports circular economy principles by transforming low-value or waste materials into high-value products. This multifunctionality positions biomass pyrolysis as a promising technology for sustainable energy generation, chemical synthesis, production of solid adsorbents, and renewable fuel development.

Overall, the findings of this study provide a solid scientific foundation for the development of energy-efficient, environmentally friendly, and economically viable pyrolysis technologies. Future research focused on kinetic modeling, advanced reactor design, and integration of pyrolysis systems into hybrid energy frameworks is expected to further enhance the industrial applicability and scalability of biomass pyrolysis.

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