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PROCESSING OF AGRICULTURAL AND FOOD BIOWASTE BY PYROLYSIS: COMPOSITION, PREPARATION, AND APPLICATION PROSPECTS

Abstract: *In the context of the increasing accumulation of agricultural and food bio-waste (grain husks, straw, corn stalks, etc.), the development of efficient and environmentally safe processing technologies is a highly relevant task. The study analyzes modern methods of biomass utilization, including composting, anaerobic digestion, biopolymer production, and the manufacture of construction materials. Pyrolysis has been selected as the primary processing technology, as it enables the production of a wide range of products – biochar, liquid and gaseous fuels – that can be potentially applied in agriculture, energy, and industry. The chemical composition of the initial bio-waste (cellulose, lignin, ash-forming elements) is characterized, and the methods of their preparation (drying, grinding, pretreatment) are discussed. The results of laboratory studies are presented, confirming the effectiveness of pyrolysis in producing valuable products. A comparative assessment with existing analogues has been carried out, along with an analysis of the environmental benefits (reduction of* CO_2 *and* CH_4 *emissions, decrease in landfilled waste volumes) and an economic evaluation of the prospects for industrial implementation. It is shown that bio-waste processing by pyrolysis has high practical significance for addressing resource conservation and environmental protection challenges. The study demonstrates the potential applications of the obtained products as organic fertilizers, energy sources, sorbents, and components of construction materials. Promising directions for further research are identified, including combined processing technologies and the expansion of the spectrum of target products.*

Key words: *biowaste, pyrolysis, biochar, renewable resources, recycling, eco-technologies, sustainable development*.

1. Introduction

Modern agriculture and the food industry generate vast amounts of biowaste each year, primarily in the form of plant residues such as straw, cereal husks, corn stalks, sunflower husks, and organic food waste. According to FAO estimates, the global volume of agricultural and food waste exceeds 1.3 billion tons annually – about one-third of all food produced [1]. If not properly utilized, this waste becomes a source of serious environmental problems. Uncontrolled decomposition releases greenhouse gases (CO_2, CH_4, N_2O), while uncontrolled disposal pollutes soil and water [2]. In many developing countries, open burning of agricultural residues remains a common practice, releasing fine particles and toxic compounds that degrade air quality and harm public health [3].Despite the considerable potential of biowaste as a feedstock for energy, organic fertilizers, sorbents, and advanced biomaterials, much of it is still managed inefficiently. Therefore, the development of integrated processing technologies is a key priority in the context of sustainable development, circular economy strategies, and reducing environmental impacts [4].

Agricultural biowaste generation is directly tied to the scale of crop production. For instance, cereal cultivation produces large amounts of by-products: on average, up to 1.3-1.5 tons of straw and husks per ton of grain. Globally, wheat straw accounts for more than 700 million tons annually, corn stalks nearly 1 billion tons, and rice husks over 150 million tons. Kazakhstan, like other agriculture-based economies, faces this challenge acutely. Millions of tons of straw, husks, and stalks are generated annually during crop cultivation and processing. Yet, most of this biomass is either burned or landfilled, representing not only an environmental burden but also a missed opportunity to generate energy, fertilizers, and value-added products [5].

The dominant disposal practices – burning and landfilling – intensify environmental risks. Burning straw, husks, and corn stalks is inexpensive but releases CO_2, CH_4, N_2O, and particulate matter ($PM_{2.5}$, PM_{10}), degrading both air quality and human health. Landfilling, in turn, causes anaerobic decomposition of biomass, releasing methane – a greenhouse gas 25 times more potent than CO_2 – while also creating risks of pathogen spread, soil contamination, and surface water pollution [6].

These drawbacks highlight the urgency of environmentally safe and resource-efficient solutions. Over recent decades, several biowaste processing technologies have been developed. Composting remains the most widely applied method, producing organic fertilizers and improving soil fertility, although it requires significant land and long processing times. Biogas and bioethanol production through fermentation offer dual benefits of waste utilization and renewable energy generation; in countries like Germany, China, and India, biogas plants have become integral to rural energy systems. Thermochemical conversion (pyrolysis, gasification, hydrothermal carbonization) shows promise in producing biofuels, biochar, and chemical intermediates, but high capital costs and energy demands hinder large-scale adoption [7].

Beyond energy, agricultural residues are increasingly explored as feedstock for new materials. Biopolymers such as PLA and PHA can be synthesized from starch-rich waste, offering biodegradable alternatives to petroleum-based plastics. Rice husks, corn stalks, and straw are used as fillers in lightweight construction composites [8], while pyrolysis products like ash and biochar serve as efficient sorbents for water and air purification. In animal husbandry, processed residues can even be converted into protein- and micronutrient-enriched feed additives [24 9]. These applications align with circular economy principles and open new market opportunities.

Nevertheless, widespread industrial implementation remains limited. Biowaste processing methods are often constrained by high energy inputs, expensive equipment, and the need for extensive pretreatment (e.g., grinding, hydrolysis, fermentation), which increase production costs [10]. Profitability is heavily scale-dependent, and at smaller volumes, operations are often unviable due to unstable markets and competition with conventional fuels and materials [11]. Logistics also poses a barrier: seasonal availability, bulky biomass, and high transportation costs complicate collection and storage. Moreover, insufficient government support – particularly in the form of subsidies, tax incentives, or concessional loans – slows technology adoption in many developing regions [12].

International experience illustrates both progress and persisting challenges. In the EU and North America, large-scale composting and biogas systems are widely adopted, combining effective waste management with renewable energy generation. In China and India, abundant feedstock availability and strong policy support have spurred bioethanol and biogas projects [13]. Yet, research still shows gaps: most studies emphasize single technologies rather than integrated systems capable of producing multiple value-added products from one feedstock. Additionally, challenges remain in integrating new biobased products, such as biodegradable plastics, into existing industrial and consumer markets due to higher costs and performance limitations. A striking imbalance also persists: while developed countries are advancing in biowaste valorization, developing regions – despite generating enormous waste volumes – lack the infrastructure and investment needed for efficient utilization [12].

In summary, global experience demonstrates a wide range of solutions, from traditional composting to advanced biofuel and biomaterial production. However, none of the existing approaches is yet universal. Addressing biowaste challenges requires the development of integrated, resource-efficient, and economically viable technologies adapted to regional conditions.

2. Materials and Methods

2.1. Characteristics of the Initial Biowaste

The raw materials used in this study included the most common types of agricultural biowaste – cereal straw, corn stalks and cobs, as well as rice and sunflower husks. Their chemical composition is mainly represented by cellulose, hemicelluloses, lignin, extractives, proteins, and mineral ash.

The cellulose content in materials such as wheat straw, corn stalks, and cereal husks typically ranges from 35-45%, hemicelluloses from 20-30%, and lignin from 10-20%. The ash content of agricultural residues varies between 5-15%, depending on the type of crop and growing conditions [14]. The protein fraction in plant residues is relatively low – ranging from 2 to 6%; however, in sunflower husks and certain other crops, it can be higher.

A key feature of agri-biowaste is its high structural heterogeneity and variability in composition, which complicates processing and necessitates preliminary feedstock preparation. For instance, straw is characterized by a high content of silica and ash, which reduces its suitability for biofuel production without specialized treatment methods. Rice husks contain up to 15-20% silicon dioxide, making them a promising raw material for producing sorbents and construction materials.

Thus, understanding the chemical composition and specific characteristics of biowaste is crucial for selecting and optimizing processing technologies.

2.2. Feedstock Preparation Methods

The composition and preparation of feedstock play a crucial role in determining both the yield and the physicochemical properties of pyrolysis products – biochar, bio-oil, and syngas. The efficiency of the process depends not only on the chemical composition of the biomass but also on the method of its pretreatment prior to thermal conversion.

In this study, biowaste underwent a series of standard pretreatment steps, including drying, grinding, and preliminary cleaning, to ensure stable feedstock quality and efficient conversion (Table 1). Drying reduces the moisture content to below 10-15%, minimizing energy losses during pyrolysis and increasing the yield of condensable vapors (bio-oil). Excess moisture promotes the formation of water vapor, which can dilute volatile products and decrease the oil yield.

Table 1 – Main Stages of Biowaste Preparation and Processing

Stage	Conditions/methods	Aim
Drying	Convection drying chamber, 60-70°C, to <10% moisture	Prevents microbiological degradation, facilitates grinding, and preserves cellulose and hemicelluloses.
Crushing	Crushing to 2-5 mm fractions (hammer and disc crushers)	Increases specific surface area and reactivity during hydrolysis, pyrolysis, and fermentation.
Pre-treatment	Alkaline (NaOH, $Ca(OH)_2$) – removal of lignin and hemicelluloses • Steam explosion – disintegration of cell walls • Biological (cellulose-degrading microorganisms, enzymes) – gentle destruction	Increases cellulose availability, reduces energy consumption, and increases porosity.
Pyrolysis (main technology)	400-600°C, anoxic/low-oxygen environment.	Produces three products: • Solid residue (biochar, sorption material) • Liquid products (pyrolysis oil) • Gases (CO, CO_2, H_2, CH_4)

Grinding increases surface area and homogenizes particle size, improving heat transfer and ensuring more uniform pyrolysis; smaller particles tend to produce higher bio-oil yields, whereas larger particles typically generate more biochar due to limited internal heating. Pretreatment such as washing, acid or alkaline treatment, and catalyst impregnation can modify the mineral and organic composition of the feedstock. For example, alkaline pretreatment removes inorganic impurities that catalyze secondary cracking, thereby improving oil quality, while the addition of metal salts or clays can promote gas formation or regulate the porosity of biochar.

The intrinsic composition of biomass feedstock plays a decisive role in determining the distribution of pyrolysis products. Materials with a high lignin content (e.g., woody biomass) typically produce greater yields of biochar with high aromatic carbon and fixed carbon contents, making it suitable for applications such as sorbents and soil conditioners. Biomass with high cellulose and hemicellulose content (e.g., agricultural residues) generally yields more bio-oil, although with higher oxygen content and acidity, requiring additional upgrading prior to its use as a fuel. Feedstocks containing high ash levels (e.g., food waste or manure) promote catalytic cracking and gasification reactions, thereby increasing syngas production while lowering the yield of liquid fuels.

Under optimized laboratory conditions (Fig. 1), using a tubular furnace with precise temperature control and a nitrogen atmosphere, drying and homogenization ensured reproducible thermal profiles and reliable product yield measurements. At heating rates of 5-20°C/min and temperatures ranging from 400 to 600°C, a balance between solid, liquid, and gaseous products was achieved depending on the feedstock characteristics. Pilot-scale trials using a continuous screw reactor (capacity 2-5 kg/h) confirmed that biomass with appropriate preparation and a stable composition ensures steady operation, improved energy efficiency, and enhanced product quality.

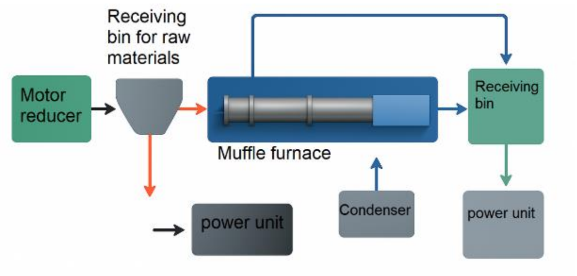

Figure 1 – Pyrolysis plant

In summary, the relationship between feedstock composition, pretreatment methods, and pyrolysis performance can be expressed as follows:

- Higher lignin content → increased biochar yield (a stable, carbon-rich solid).
- Higher cellulose/hemicellulose content → increased bio-oil production (an oxygen-rich liquid requiring upgrading)
- Higher ash or mineral content → increased syngas formation (an energy-rich gas).
- Proper drying → enhances bio-oil yield and energy efficiency.
- Fine grinding → improves heat transfer, uniform decomposition, and liquid product recovery.
- Chemical pretreatment → optimizes product composition and quality.

Therefore, careful feedstock preparation (as summarized in Table 1) directly determines not only the distribution of product yields but also the quality, stability, and potential applications of the resulting biochar, bio-oil, and syngas.

3. Results and Discussion

3.1 Efficiency of the Selected Technologies

The conducted studies confirmed the high efficiency of pyrolysis as a technology for biowaste processing. The results are presented in Figure 2. At a temperature of 450-550 °C, an optimal product distribution was observed: the yield of biochar was 28-35% of the dry feedstock mass, the liquid fraction (pyrolysis oil) accounted for 35-45%, and the gaseous products made up 20-30%. The obtained data are consistent with the results of previously published studies.

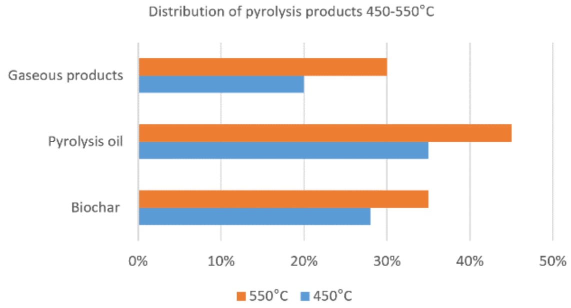

Figure 2 – Distribution of pyrolysis products at 450-550°C

The biochar characteristics were of particular importance. Analysis showed that it possessed a high specific surface area (up to 250 m²/g) and a well-developed porous structure, making it a promising material for use as an adsorbent, soil conditioner, and a component of composite materials. Elemental analysis revealed a decrease in atomic H/C and O/C ratios with increasing pyrolysis temperature, indicating enhanced aromaticity and stability of the carbon matrix.

The pyrolysis oil was characterized by a complex composition including phenolic compounds, oxygen-containing heterocycles, and organic acids. Despite its relatively high heating value, additional purification or catalytic upgrading is required before it can be used as a fuel.

The gaseous products consisted mainly of CO, H_2, and CH_4, which can be utilized as energy carriers to support the pyrolysis process itself. Thus, the technology demonstrated a closed-loop approach, where part of the products is used to meet the system's own energy requirements.

Overall, the results confirmed that pyrolysis of biowaste is an efficient technology for waste utilization and production of valuable products. However, to increase its economic feasibility, integration with purification and product upgrading methods is required.

The analysis of pyrolysis products showed that each of them possesses specific properties that open opportunities for practical application in various sectors.

3.2 Biochar (solid residue)

The T-Plot method was employed to evaluate the microporous structure of the sample using nitrogen adsorption data at liquid nitrogen temperature (77.3 K). A sample with a mass of 271 mg was analyzed, with nitrogen as the adsorbate, a saturated vapor pressure of 0.9900 bar, and an ambient temperature of 22.4°C. The total analysis time included 350 minutes of adsorption and 150 minutes of desorption.

In the obtained dependence of the adsorbed gas volume on the thickness of the hypothetical adsorption layer, a sharp increase in adsorption was observed at very low relative pressures ($P/P_0 < 0.01$). This indicates a significant development of microporosity, as micropores are filled first. With increasing pressure in the range P/P_0 = 0.01-0.1, the adsorption growth rate decreased, reflecting the formation of an adsorption layer and the possible involvement of small mesopores. At medium relative pressures ($P/P_0 > 0.1$), the curve became more gradual, indicating completion of micropore filling and transition to multimolecular adsorption on the external particle surface.

According to the T-Plot method, the linear portion of the dependence reflects adsorption on the external surface, while the excess adsorption compared to this trend corresponds to the contribution of micropores (Figure 3). Thus, the investigated sample can be characterized as a microporous material with a noticeable contribution from the external surface. The total volume of adsorbed nitrogen reached approximately 58.5 ml/g, which indicates a highly developed porous structure and significant specific surface area.

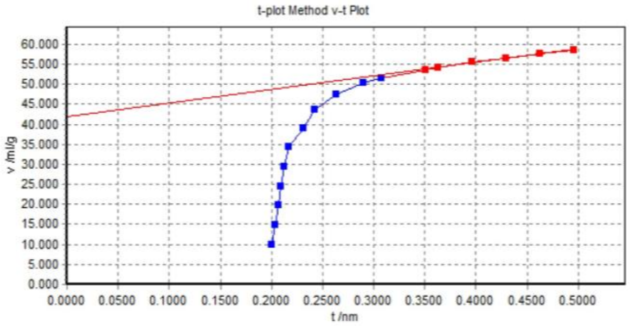

Figure 3 – T-Plot analysis of the sample

3.3 Pyrolysis oil (liquid fraction)

Chromatographic analysis revealed that the main components were phenolic and methoxyphenolic compounds (phenol, 2-methoxyphenol, 4-ethylphenol, cresol, catechol, vanillin, etc.) originating from lignin degradation. In addition, derivatives of furan, lactone, and carbohydrate series were identified (maltol, 1,4:3,6-dianhydro-α-D-glucopyranose), as well as a fatty acid (hexadecanoic acid) in the later retention region. Several unidentified compounds with a significant share (up to 10.7% for a single peak) were also detected (Figures 4-5).

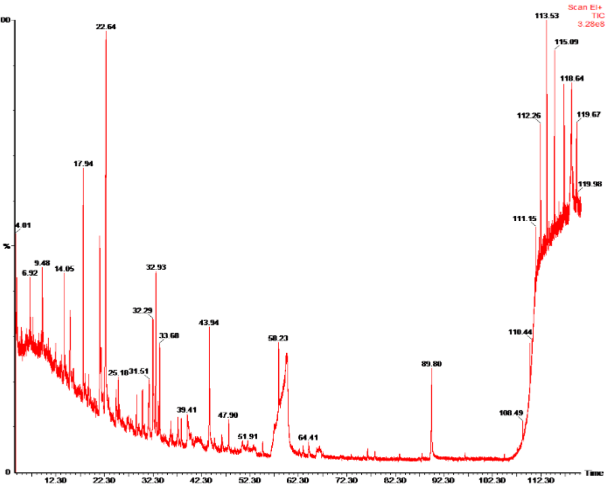

Figure 4 – Chromatogram of pyrolysis oil

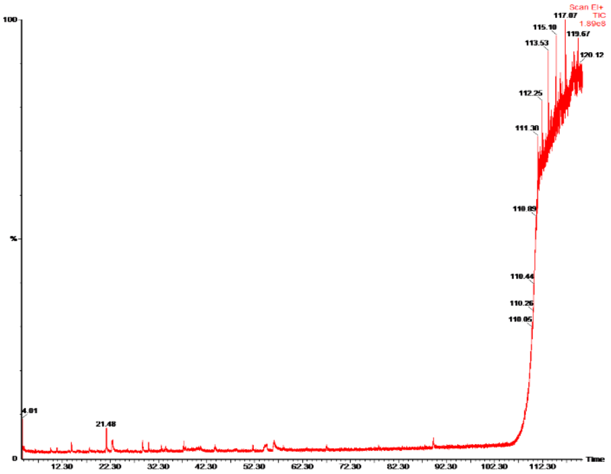

Figure 5 – Chromatogram of pyrolysis oil

Overall, the results confirmed the complex nature of the studied sample: it combined a microporous structure with a diverse chemical composition, including products of lignin, cellulose, hemicellulose, and other organic component decomposition. The obtained oil represented a complex mixture of phenolic, oxygenated, and hydrocarbon compounds. Its heating value was 16-19 MJ/kg, which is comparable to that of low-grade liquid fuels. However, its high acidity (pH 2-3) and instability limit direct application. After catalytic upgrading, pyrolysis oil can be used as boiler fuel or as a source of platform chemicals (furfural, phenols, organic acids) for the chemical industry.

3.4 Gaseous products

The gaseous products of pyrolysis included CO (20-30%), H_2 (10-20%), CH_4 (10-15%), and CO_2. Their calorific value was 5-10 MJ/m^3, which allows the gas to be used for partially or fully covering the energy requirements of the pyrolysis process itself.

3.5 Application in construction materials

The study confirmed that pyrolysis products possess multifunctional value, suitable for applications in agriculture, energy, and industry. Biochar and ash can be incorporated into cement, concrete, and bricks manufacturing, improving material performance and resource efficiency. Experimental and pilot-scale data demonstrated that the incorporation of 5-10 wt% biochar increases compressive strength by 8-15%, reduces density by 5-10%, and enhances thermal insulation by 10-18% [15]

Quantitative environmental indicators highlight the potential for greenhouse gas mitigation. Each ton of biomass processed into biochar enables 0.8-1.2 t CO_2-eq of long-term carbon sequestration, while fuel replacement with pyrolysis oil and gas provides an additional 0.4-0.6 t CO_2-eq/t reduction. The overall reduction potential therefore reaches up to 1.8 t CO_2-eq per ton. Moreover, pyrolysis gas and part of bio-oil can supply 60-90% of the internal heat demand, improving the net positive energy balance [4-6].

Product quality metrics aligned with global values: biochar yields reached 28-35%, specific surface area up to 250 m²/g, exceeding typical 150-200 m²/g [7,8]. The calorific value of pyrolysis oil (16-19 MJ/kg) and gas (5-10 MJ/m³) confirms strong potential for on-site energy use or integration into fuel production [9].

A detailed techno-economic assessment demonstrated strong market feasibility. With a baseline processing cost of USD 80-100/t, revenue consists of three key streams: sale of biochar, sale of pyrolysis oil, and energy savings from pyrolysis gas utilization. A conservative scenario (0.15 t biochar × USD 150/t; 0.25 t bio-oil × USD 300/t; USD 5 energy savings) yields ≈ USD 102.5/t revenue, corresponding to 12-22% profitability. A typical scenario (0.30 t biochar × USD 200/t; 0.35 t bio-oil × USD 400/t; +USD 15) increases revenue to ≈ USD 215/t with 50-60% profit. An optimistic scenario (0.35 t biochar × USD 350/t; 0.40 t oil × USD 500/t; +USD 25) yields ≈ USD 347.5/t and >70% profit. These results confirm strong financial resilience even under conservative market conditions [10, 11].

Overall, the integration of biochar into construction materials supports circular economy goals and provides measurable environmental and economic benefits.

4. Conclusion

This study demonstrates the high relevance of developing and implementing technologies for the utilization of agricultural and agro-industrial biowaste. Using pyrolysis as a case study, it was shown that residues traditionally disposed of by burning or landfilling can be efficiently converted into valuable products, thereby reducing greenhouse gas emissions and mitigating environmental risks. Agricultural biowaste management remains challenged by large generation volumes, low utilization rates, and the ecological hazards of conventional disposal methods; however, pyrolysis offers an efficient pathway for comprehensive valorization. The process yields biochar, pyrolysis oil, and gas, all of which were confirmed to be suitable for applications in agriculture, energy, and industry. Environmental and economic assessments further indicate significant benefits, including lower CO_2 and CH_4 emissions, reduced waste accumulation, and profitability potential of 15-25%, making pyrolysis particularly attractive for small and medium-sized enterprises.

The findings highlight the practical potential of establishing local biowaste processing lines in agricultural regions, enabling soil fertility improvement through biochar application, the production of renewable fuels, and the creation of new industrial materials such as composites, bioplastics, and sorbents. These outcomes contribute not only to ecological sustainability but also to rural economic development through «green» job creation.

Future research should concentrate on integrating pyrolysis with complementary methods such as anaerobic digestion and hydrothermal carbonization to expand the spectrum of valuable products. Efforts are also needed to modify and functionalize biochar to enhance its sorption capacity, electrical conductivity, and durability, enabling its application in water treatment and energy storage systems. Further optimization of pyrolysis conditions could increase both yield and product quality, while agronomic studies are required to confirm the long-term benefits of biochar for different soils and crops. Finally, large-scale implementation will demand life-cycle and carbon footprint assessments, alongside integration into existing production chains.

The techno-economic and environmental feasibility assessment shows that the technology not only reduces CO_2 emissions, but also effectively mitigates methane formation: the avoidance of landfilling prevents up to 0.3-0.5 t CH_4-eq/t waste. More than 70-85% of the biowaste mass is converted into useful products, minimizing residue disposal. The cost – benefit ratio remains favorable even at small-scale production (1-5 t/day), with a payback period estimated at 2-4 years depending on plant configuration and product prices. Thus, pyrolysis simultaneously addresses climate mitigation, waste minimization, and profitability.

In conclusion, biowaste pyrolysis emerges as a practical and promising tool for sustainable development, combining environmental advantages with economic feasibility and supporting the broader transition toward a circular economy.

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ПЕРЕРАБОТКА СЕЛЬСКОХОЗЯЙСТВЕННЫХ И ПИЩЕВЫХ БИОЛОГИЧЕСКИХ ОТХОДОВ МЕТОДОМ ПИРОЛИЗА: СОСТАВ, ПОДГОТОВКА И ПЕРСПЕКТИВЫ ПРИМЕНЕНИЯ

В условиях растущего накопления сельскохозяйственных и пищевых биоотходов (зерновой шелухи, соломы, кукурузных стеблей и т.д.) разработка эффективных и экологически безопасных технологий переработки является весьма актуальной задачей. В исследовании анализируются современные методы утилизации биомассы, включая компостирование, анаэробное сбраживание, производство биополимеров и производство строительных материалов. В качестве технологии первичной переработки был выбран пиролиз, поскольку он позволяет получать широкий спектр продуктов – биоуголь, жидкое и газообразное топливо, – которые потенциально могут быть использованы в сельском хозяйстве, энергетике и промышленности. Охарактеризован химический состав исходных биоотходов (целлюлоза, лигнин, золообразующие элементы) и рассмотрены способы их получения (сушка, измельчение, предварительная обработка). Представлены результаты лабораторных исследований, подтверждающие эффективность пиролиза при получении ценных продуктов. Была проведена сравнительная оценка с существующими аналогами, а также анализ экологических выгод (сокращение выбросов CO_2 *и* CH_4, *уменьшение объемов размещаемых на свалках отходов) и экономическая оценка перспектив промышленного внедрения. Показано, что переработка биоотходов методом пиролиза имеет большое практическое значение для решения задач ресурсосбережения и охраны окружающей среды. Исследование демонстрирует потенциальное применение полученных продуктов в качестве органических удобрений, источников энергии, сорбентов и компонентов строительных материалов. Определены перспективные направления дальнейших исследований, включая комбинированные технологии переработки и расширение спектра целевых продуктов.*

Ключевые слова: *биоотходы, пиролиз, биоуголь, возобновляемые ресурсы, вторичная переработка, экотехнологии, устойчивое развитие.*

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ПИРОЛИЗ ӘДІСІМЕН АУЫЛШАРУАШЫЛЫҚ ЖӘНЕ ТАҒАМДЫҚ БИОЛОГИЯЛЫҚ ҚОСПАЛАРДЫ ӨҢДЕУ: ҚҰРАМЫ, ДАЙЫНДАЛУЫ ЖӘНЕ ҚОЛДАНУ ПЕРСПЕКТИВАЛАРЫ

Ауыл шаруашылығы және азық-түлік биоқалдықтарының (астық қауызы, сабан, жүгері сабағы және т.б.) жинақталуының артуы жағдайында.), өңдеудің тиімді және экологиялық қауіпсіз технологияларын жасау өте өзекті міндет болып табылады. Зерттеу биомассаны кәдеге жаратудың заманауи әдістерін, соның ішінде компосттауды, анаэробты ас қорытуды, биополимерлерді өндіруді және құрылыс материалдарын өндіруді талдайды. Пиролиз негізгі өңдеу технологиясы ретінде таңдалды, өйткені ол ауыл шаруашылығында, энергетикада және өнеркәсіпте қолданылуы мүмкін көптеген өнімдерді – биокөміртекті, сұйық және газ тәрізді отынды өндіруге мүмкіндік береді. Бастапқы биоқалдықтардың (целлюлоза, лигнин, күл түзетін элементтер) химиялық құрамы сипатталады, оларды дайындау әдістері (кептіру, ұнтақтау, алдын ала өңдеу) талқыланады. Пиролиздің құнды өнімдерді шығарудағы тиімділігін растайтын зертханалық зерттеулердің нәтижелері келтірілген. Қолданыстағы аналогтармен салыстырмалы бағалау жүргізілді, сонымен қатар экологиялық тиімділікті талдау (CO_2 *және* CH_2 *шығарындыларын азайту, полигон қалдықтарының көлемін азайту) және өнеркәсіптік іске асыру перспективаларын экономикалық бағалау жүргізілді.. Биологиялық қалдықтарды пиролиз әдісімен өңдеудің ресурстарды үнемдеу және қоршаған ортаны қорғау мәселелерін шешуде жоғары практикалық маңызы бар екендігі көрсетілген. Зерттеу нәтижесінде алынған өнімдердің органикалық тыңайтқыштар, энергия көздері, сорбенттер және құрылыс материалдарының компоненттері ретінде әлеуетті қолданылуы көрсетілген. Әрі қарайғы зерттеулердің перспективалық бағыттары анықталды, оның ішінде біріктірілген өңдеу технологиялары және мақсатты өнімдердің спектрін кеңейту.*

Түйін сөздер: *биоқалдыру, пиролиз, биокөмір, жаңартылатын ресурстар, қайта өңдеу, экотехнологиялар, тұрақты даму.*

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ИЗУЧЕНИЕ ТЕРМОДЕСТРУКЦИИ РОТАЦИОННЫХ КОМПОЗИТОВ В ПРОЦЕССЕ РЕЦИКЛИНГА ПУТЕМ ИССЛЕДОВАНИЯ ГИДРОФОБНОСТИ ИХ ПОВЕРХНОСТЕЙ

Аннотация: *В данной статье представлено исследование, посвященное изучению проблемы повторной утилизации полиэтилена (его вторичной переработки – рециклингу) методом ротационного формования. В научной литературе рециклинг ротационных марок полиэтилена (РПЭ) очень слабо изучен, а представленные данные часто противоречивы. Однако для*