Jurnal Presipitasi
Media Komunikasi dan Pengembangan Teknik Lingkungan
e-ISSN: 2550-0023

Vol 22, No 2, 2025, 360-379
Article available at [homepage presipitasi]

Original Research Article

Innovative Pyrolysis Reactor for Liquid Smoke, Activated Carbon, and Limestone Production

Muhammad Naswir[1*], Intan Lestari[1], Jalius[2], Desfaur Natalia[1], Yudha Gusti Wibowo[3]

[1]Department of Chemistry Fakulty of Sciens and Technology, Universitas Jambi, Jambi, Indonesia
[2]Department of Environmental Engineering, Faculty of Science and Technology, Universitas Jambi, Jambi, Indonesia
[3]Department of Mining Engineering, Institut Teknologi Sumatera, Lampung, Indonesia
* Corresponding Author, email: m.naswir@yahoo.com

Abstract

This study presents the development and application of an innovative 3-in-1 nanotechnology pyrolysis reactor designed to simultaneously produce liquid smoke, activated carbon, and limestone from locally sourced raw materials in Jambi Province, Indonesia. The multifunctional reactor combines three production processes, which are traditionally performed separately, into a single, efficient unit, addressing both economic and environmental challenges. Coal serves as the primary heat source and material for activated carbon, whereas shell waste is calcined to produce limestone. The reactor operates at temperatures exceeding 550°C to ensure optimal conversion, with a glass wool insulator replacing clay to enhance thermal efficiency. The liquid smoke undergoes further distillation to achieve purification, while residual activated carbon is chemically activated with H_3PO_4 to enhance its adsorption capacity. The experimental results demonstrate that this reactor can produce high-quality products with minimal resource wastage. This 3-in-1 pyrolysis reactor represents a sustainable, cost-effective solution for resource-limited settings, with broad potential for application in waste-to-product conversion, environmental remediation, and rural development.

Keywords: 3-in-1 pyrolysis reactor; activated carbon; liquid smoke; limestone; innovative pyrolysis

1. Introduction

The abundant natural resources in Jambi Province, Indonesia, including coal (Wibowo et al., 2022a), limestone (Dona et al., 2017), and shell waste (Wibowo et al., 2022b), present significant opportunities for developing sustainable local industries. However, many of these resources remain underutilized, largely because of technological limitations that hinder efficient and environmentally sound processing. Among these resources, coal and shell waste hold particular promise for producing valuable materials such as activated carbon (Budihardjo et al., 2021), liquid smoke (Simon et al., 2005), and limestone (Labastida et al., 2017), each with wide-ranging applications in environmental remediation, industrial processes, and agricultural enhancement.

Traditional methods for producing activated carbon, liquid smoke, and calcined limestone involve separate processes that are often resource-intensive and require sophisticated equipment, making them less feasible in rural or resource-limited settings. In response, this study introduces an innovative

3-in-1 nanotechnology pyrolysis reactor that integrates the production of these three materials into a single, compact system. This reactor was initially developed to meet the demand for sustainable raw materials, including those used in patented peat water purification methods; however, it has since evolved into a versatile, multifunctional technology.

This 3-in-1 pyrolysis reactor operates by utilizing coal as both a heat source and raw material, whereas the shell waste is calcined to produce limestone. Optimal pyrolysis temperatures, such as 500–600°C, are critical for achieving efficient material transformation and maximizing outputs, as demonstrated in previous studies on biochar activation processes (Chen et al., 2016). A glass wool insulator minimizes heat loss, while residual carbon from combustion is activated using phosphoric acid (H_3PO_4), which enhances its adsorption properties to reach surface areas exceeding 1000 m^2/g (Ahmad et al., 2007). The liquid smoke produced undergoes additional distillation to improve its purity for high-value applications. Integrating these processes maximizes resource efficiency and minimizes waste, providing a cost-effective solution particularly suitable for regions with limited access to advanced technologies (Veses et al., 2016).

This study evaluates the reactor's efficiency, output quality, and potential applications in resource conversion. For example, similar systems demonstrated yields of 36.15 wt% liquid products and 52.09 wt% gas products during catalytic pyrolysis, highlighting their potential for scaling and environmental sustainability (Charusiri and Vitidsant, 2017). The technology's contribution to waste reduction and rural development presents a scalable, environmentally friendly model for transforming locally available materials into high-value products.

2. Methods

2.1 Materials

The reactor system and additional equipment included a custom-designed 3-in-1 nanotechnology pyrolysis reactor, specifically created for this study to produce liquid smoke, activated carbon, and limestone in one integrated process. To improve thermal retention, the reactor was lined with glass wool insulation, a superior heat-retaining material compared to the clay initially used. This insulation minimizes heat loss, allowing the reactor to reach necessary high temperatures. The system also included a 2.5-inch blower, which was adjusted to 0.5 in. at the inlet to increase the air pressure and enhance combustion. Other tools used were an electric drill, aluminum nails, and a thermometer capable of measuring up to 550°C to monitor the reactor temperature. Additionally, a condenser was connected to the reactor to cool the pyrolysis gases, and a water pump provided a continuous water supply for condensation. Two 200-liter drums were used for storing the raw liquid smoke, and 5-liter jerrycans were designated for storing purified liquid smoke after distillation

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2.3. Reactor Setup and Insulation Improvement

To optimize the performance of the reactor, significant insulation improvements were undertaken. Initially, clay was used to line the reactor walls; however, due to its insufficient thermal retention, it was replaced with glass wool insulation. Glass wool was applied along the inner walls of the reactor and secured with an aluminum layer to prevent heat loss, enabling the reactor to maintain temperatures above 500°C, critical for efficient pyrolysis. This setup allowed for optimal heat transfer within the reactor, enhancing the production efficiency of activated carbon, liquid smoke, and limestone. The dimensions of the reactor (**Figure 1**) are a height of 1.75 m and a diameter of 5.0 m

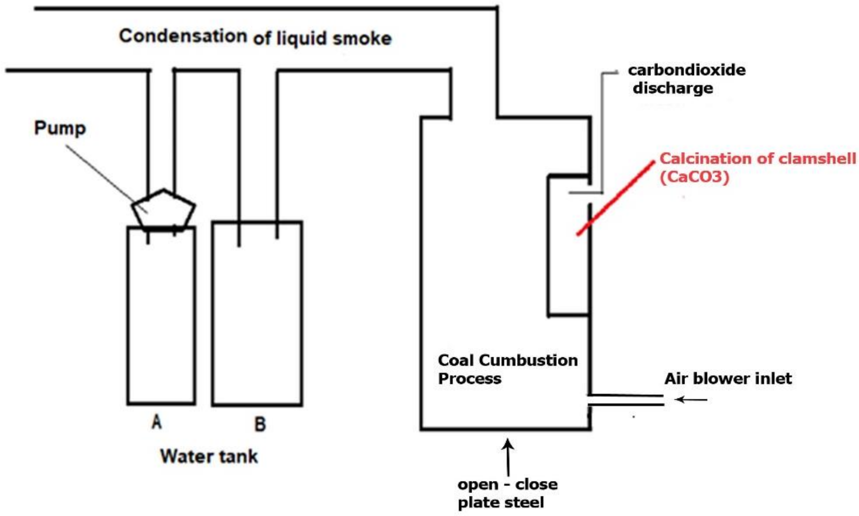

Figure 1. 3-in-1 reactor design

2.4. Preparation of Raw Materials

The preparation of raw materials was essential for efficient operation. Coal was crushed to increase its surface area, facilitating combustion and heat generation within the reactor. The shell waste was cleaned, dried, and fragmented into smaller pieces, making it more suitable for calcination into limestone. Additionally, a 0.5 M solution of H_3PO_4 was prepared to activate the carbon residue after pyrolysis, enhancing the porosity and adsorption capacity of the material.

2.5. Reactor Operation

The reactor was loaded with coal in the main chamber, which had a capacity of 150-250 kg. Shell waste was placed in a separate compartment for calcination. To initiate pyrolysis, the reactor was sealed to restrict oxygen flow, creating a low-oxygen environment necessary for the process. The blower was activated, generating high-pressure airflow to ensure optimal combustion and prevent clogging within the system. Throughout the operation, the reactor's temperature was closely monitored to ensure it reached a minimum of 550°C. This temperature facilitated both the pyrolysis of organic material and the calcination of shell waste to produce activated carbon and limestone, respectively.

2.6. Collection and Processing of By-products

The pyrolysis process produced smoke, which was directed through a piping system into a condenser. Water from a reservoir was continuously pumped to the condenser to cool and condense the smoke into liquid form, resulting in liquid smoke, which was collected in a 200-liter drum. The collected liquid smoke was further purified through distillation, performed between 130°C and 280°C. The distillation process was repeated up to three times, yielding different grades of liquid smoke (Grades 1, 2, and 3), each representing a varying level of purity.

The residual carbon was collected and immersed in water to instantly cool it and halt combustion. This carbon was then activated by soaking it in the 0.5 M H_3PO_4 solution for 24 hours. The activated carbon was subsequently dried at 110°C for six hours to eliminate moisture. Meanwhile, shell waste, subjected to high temperatures, was calcined into limestone, which was then ground to achieve nanomaterial particle sizes, enhancing its potential applications in various industries.

2.7. Testing and Analysis

Following production, each product underwent testing and analysis to determine its quality and suitability for specific applications. The activated carbon was characterized based on surface area, porosity, ash content, and adsorption capacity. Liquid smoke was evaluated for its chemical composition and purity across different grades. Lastly, the limestone was analyzed for particle size, purity, and potential uses in environmental and industrial contexts. This comprehensive testing provided a clear assessment of the reactor's efficiency and the quality of its outputs, confirming the 3-in-1 reactor's viability as a sustainable solution for converting local waste into valuable resources.

3. Result and Discussion

3.1. Reactor Design and Operational Efficiency

The innovative design of the 3-in-1 nanotechnology pyrolysis reactor enables the integration of three separate processes, namely, liquid smoke production, activated carbon creation, and limestone calcination, within a single, compact system. This multifunctional reactor allows for the simultaneous production of all three outputs, addressing the inefficiencies associated with conducting each process in isolation, which typically requires multiple units, energy sources, and operational costs. By consolidating these processes, the 3-in-1 reactor enhances efficiency and makes waste-to-product conversion feasible even in resource-limited settings.

This technology totally different with other previous studies that use single method to create only one product (Naswir et al., 2022). A major feature contributing to the reactor's efficiency is the use of glass wool insulation to replace the traditional clay insulation. A previous study informed that the use of clay insulation in the carbonization reactor notably enhanced the efficiency and productivity of the corn cob charcoal production process (Mangallo and Joni, 2024). By reducing heat loss, clay insulation demonstrated a significant improvement in the reactor's thermal management. In the uninsulated reactor, heat loss reached as high as 3,611.94 W, which accounted for 55.64% of the total energy supplied during the carbonization process. In comparison, the clay-insulated reactor reduced heat loss to 2,320.69 W, lowering it to 35.75% of the energy input (Mangallo and Joni, 2024). This 8.61% reduction in heat loss underscores the effectiveness of clay as an insulator, particularly given its low cost and natural abundance (Mangallo and Joni, 2024). These findings highlight that clay insulation is not only a feasible but also an economically viable solution for mitigating energy loss in biomass carbonization processes.

Furthermore, the implementation of clay insulation contributed to a significant reduction in the carbonization time required to produce charcoal from corn cobs. The clay-insulated reactor completed the process in 170 minutes, which is 50 minutes (or 22.73%) faster than the 220 minutes required by the uninsulated reactor (Mangallo and Joni, 2024). But, in this study, we tried to improve the insulation in the reactor using better insulator such as glass wool. As shown in Table 1, the insulation material significantly affects the reactor's heat retention capabilities. The table indicates that clay insulation only allowed the reactor to reach a maximum temperature of 280°C on the outside surface, which is insufficient for optimal pyrolysis and calcination. By contrast, glass wool insulation enabled the reactor to achieve and maintain an external temperature of 550°C. This substantial increase in thermal efficiency underscores the superiority of glass wool as an insulating material.

Table 1. Effect of different insulator in outside surface reactor temperature

Insulator Type	Temperature (°C)
Land	280
Glass wool	550

Glass wool is known for its high thermal insulation properties due to its fibrous structure, which minimizes heat loss and improves energy efficiency in reactors. For example, the use of glass wool as an insulating material in high-temperature environments has shown to significantly retain heat in applications such as reactor containment (Department of Urban Environment Systems, Graduate School of Engineering, Chiba University, Japan et al., 2019). Glass wool's enhanced heat retention minimizes energy loss, allowing the reactor to sustain the high temperatures necessary for both pyrolysis and calcination (Jones and Wade, 2000). Studies show that glass wool retains its insulating properties over time under various thermal conditions, making it a stable choice for reactors that require consistent insulation performance (Soltész et al., 2008). Insulation methods and materials like glass wool contribute to reduced heat loss in reactors, supporting a sustainable energy-efficient design that enhances overall process outcomes in thermal and pyrolysis applications (Beknazaryan et al., 2021). In addition, pyrolysis requires a high temperature environment to thermally decompose organic materials, like coal, into activated carbon, while calcination needs similar temperatures to convert clamshells into calcium oxide (CaO) (Wibowo et al., 2023b). The consistent temperature stability achieved with glass wool insulation allows these transformations to proceed efficiently, yielding high-quality by-products with minimal resource wastage. This insulation upgrade has made the reactor not only more energy-efficient but also capable of achieving the temperatures required for high-quality conversion of materials in a single cycle.

The reactor's design also includes an airflow control system facilitated by a blower, which plays a crucial role in maintaining an oxygen-restricted environment essential for pyrolysis. Effective control of airflow, essential for maintaining the low oxygen conditions necessary for pyrolysis, is facilitated through blower placement and inlet design. This control enhances combustion consistency and heat distribution throughout the reactor, which is vital for efficient pyrolysis and calcination processes (Getahun Dessie et al., 2020). The controlled airflow, as illustrated in Figure 1, is achieved by placing a blower at the air inlet, with the inlet size reduced to 0.5 inches to increase internal air pressure. This design adjustment ensures a steady but limited supply of oxygen, preventing complete combustion of the organic material and instead enabling pyrolysis. The blower system thus supports controlled combustion, allowing the reactor to operate under low-oxygen conditions optimal for the conversion of coal into activated carbon and for generating the necessary heat for calcination. Moreover, the placement of the blower system ensures consistent combustion without blockages within the reactor, promoting uniform heat distribution. The airflow control, combined with the effective insulation provided by the glass wool, maximizes the reactor's operational efficiency by reducing energy loss and maintaining the conditions required for each phase of the process. This setup enables the reactor to process both coal and shell waste simultaneously, producing activated carbon, liquid smoke, and calcined limestone within a single cycle.

3.2. Production and Purification of Liquid Smoke

The production and purification of liquid smoke using the 3-in-1 pyrolysis reactor technology demonstrate an efficient, multi-functional approach to biomass processing. This technology enables the production of three primary products—activated carbon, limestone, and liquid smoke—from a single reactor setup, enhancing both resource utilization and sustainability. Figure 2 illustrates these products: (a) displays the activated carbon produced from coal, (b) shows the limestone derived from clamshell waste, and (c) depicts the raw liquid smoke collected from the pyrolysis process. This multi-product system represents a sustainable solution that reduces waste by generating valuable byproducts, each of which can serve distinct applications across industries.

The liquid smoke produced in this process originates from the condensation of pyrolytic gases, which form a complex mixture of organic compounds, including phenols, carbonyls, and organic acids. These compounds impart antimicrobial, antioxidant, and flavoring properties, making liquid smoke suitable for a range of applications. However, raw liquid smoke contains various impurities and unwanted compounds that can affect its efficacy and safety in specific applications. To address this, a multi-stage distillation process was employed to refine the liquid smoke into different grades, each tailored for unique uses based on purity levels.

A previous study details the pyrolysis of cacao pod husks in a steel reactor to produce liquid smoke (Putri et al., 2019). Key components such as acetic acid and phenol were identified, which contribute to the smoke's preservation properties (Putri et al., 2019). In other study, Research on biomass pyrolysis shows that nitrogen flow into the reactor enhances the quality of both charcoal and liquid smoke products, improving yield and maintaining low oxygen conditions (Aladin et al., 2021). Additionally, oxygen supplied through a blower was used in this study to sustain efficient pyrolysis of coal, serving as the primary energy source.

Figure 2. Product of 3-in-1 Technology including activated carbon from coal (a), limestone from clamshell waste (b) and liquid smoke (c)

The distillation process involved heating the liquid smoke to temperatures between 130°C and 280°C, with each stage selectively removing impurities and concentrating beneficial compounds. This multi-step purification enabled the separation of liquid smoke into three distinct grades—Grade 1, Grade 2, and Grade 3—each with different purity levels, as shown in Figure 3. Supporting these findings, a prior study on oil palm empty fruit bunches demonstrated that varying pyrolysis temperatures significantly impact the concentration of valuable compounds, such as phenols and acetic acid, in liquid smoke, offering insights into temperature optimization for desired liquid smoke qualities (Faisal et al., 2020). Similarly, a study using coal as a resource for liquid smoke production complements research on simplified pyrolysis tools, which effectively produce liquid smoke from rubber seeds and shells with basic purification steps, making it suitable for food preservation (Ali and Al Fiqri, 2020). Additionally, a review highlighted biomass pyrolysis as a sustainable alternative to traditional smouldering for liquid smoke production, emphasizing its higher efficiency, environmental benefits, and broader application potential (Xin et al., 2021).

Figure 3. Liquid smoke from the 3-in-1 reactor technology

3.2.1. Grade 1 Liquid Smoke (Highest Purity)

Grade 1 liquid smoke is the product of three rounds of distillation, resulting in a high-purity liquid that contains a concentrated amount of bioactive compounds and minimal impurities. As shown in Figure 3, this grade appears almost clear, reflecting its low impurity content. The high purity of Grade 1 liquid smoke makes it suitable for applications requiring stringent standards, such as in the food industry. Here, its natural antimicrobial properties are highly beneficial for preservation, as phenolic compounds in the smoke can inhibit the growth of spoilage-causing bacteria and fungi (Lingbeck et al., 2014). Moreover, due to its clean profile and lack of contaminants, Grade 1 liquid smoke is often used as a flavoring agent, imparting a smoky taste to foods without the potential health risks associated with traditional smoking methods (Putranto et al., 2020).

Beyond food applications, high-purity liquid smoke has been explored for use in agricultural and environmental applications. Its antimicrobial properties make it a viable option for natural pest control, reducing the need for synthetic chemicals in crop management (Dewi et al., 2021). In addition, the organic acids and phenols in Grade 1 liquid smoke can enhance soil health by contributing to organic matter, promoting plant growth, and improving nutrient availability (Santiyo Wibowo et al., 2023). This adaptability to both food and agricultural applications underscores the versatility of high-purity liquid smoke and its potential to replace chemical-based preservatives and pesticides with a natural alternative.

3.2.2. Grade 2 Liquid Smoke (Moderate Purity)

Grade 2 liquid smoke, which undergoes two rounds of distillation, retains a moderate level of purity and is shown in Figure 3 as having a faint color due to a slightly higher level of residual impurities. This grade is suitable for applications where a certain level of purity is needed but where the standards are less rigorous than those required for direct food contact. In the food processing industry, Grade 2 liquid smoke can be used as a flavoring agent in non-human food products, such as pet food or animal feed, where it provides a natural smoky flavor and mild preservative effects (Montazeri et al., 2013).

In agriculture, Grade 2 liquid smoke serves as a natural pesticide or soil conditioner, thanks to its moderate concentration of bioactive compounds. It can be applied to crops as a biodegradable pest deterrent, offering an eco-friendly alternative to conventional pesticides. Additionally, the phenolic compounds in this grade can improve soil organic content, enhancing fertility and supporting sustainable farming practices (Dewi et al., 2021). In environmental management, Grade 2 liquid smoke has applications in odor control, particularly in waste treatment facilities, where its disinfectant properties help manage microbial activity and unpleasant odors (Lingbeck et al., 2014). The use of Grade 2 liquid smoke in these applications demonstrates its economic and environmental value for sectors seeking cost-effective, natural solutions.

3.2.3. Grade 3 Liquid Smoke (Lowest Purity)

Grade 3 liquid smoke, which undergoes a single distillation process, contains the highest level of impurities among the three grades, as depicted in Figure 3 with a darker color indicative of residual compounds. Although less refined, this grade is still valuable for industrial and agricultural uses where high purity is not required. For example, in composting facilities, Grade 3 liquid smoke can be used to control odors and suppress microbial activity. Its natural deodorizing properties are effective for such applications, where slight impurities do not compromise the functionality (Budaraga et al., 2016). In large-scale agriculture, Grade 3 liquid smoke can serve as a soil amendment, contributing organic content to the soil and supporting long-term soil health (Santiyo Wibowo et al., 2023). Although it may not be as effective as higher-grade liquid smoke in promoting plant growth, it still offers benefits as a biodegradable soil additive. Additionally, Grade 3 liquid smoke can be integrated into biochar production, where it acts as an enhancer in biochar-based fertilizers. By utilizing even the lower-grade byproduct of the pyrolysis process, this approach maximizes resource efficiency and minimizes waste, making the most out of the biomass conversion process (Maulina and Sinaga, 2020). The grading system for liquid smoke production allows for precise targeting of its applications across different industries. By refining liquid smoke into multiple grades, the process maximizes resource efficiency and addresses diverse market needs. For instance, Grade 1 liquid smoke, with its high purity, is ideal for food preservation and sensitive applications, while Grade 3 is better suited for industrial purposes where lower purity is acceptable (Yulistiani et al., 2020). This grading approach not only reduces waste but also broadens the scope of liquid smoke's usability across various sectors.

The economic benefits of graded liquid smoke production are also significant. Higher purity levels require more energy and processing steps, increasing production costs. By segmenting liquid smoke into multiple grades, manufacturers can allocate resources efficiently, providing premium, high-purity liquid smoke for applications that demand it, while offering lower-cost options for less demanding uses. This flexibility enhances the economic feasibility of liquid smoke production and supports a sustainable model by minimizing waste (Montazeri et al., 2013). The 3-in-1 reactor technology and the grading system for liquid smoke production offer environmental and economic advantages. Pyrolysis, as a method of biomass utilization, generates minimal emissions and produces valuable byproducts, supporting global sustainability goals and promoting a circular economy (Xin et al., 2021). By producing liquid smoke, activated carbon, and limestone from renewable biomass sources, this approach reduces dependence on synthetic chemicals and fossil fuels, contributing to a more sustainable future. Economically, the multi-grade production of liquid smoke increases the value of biomass resources that might otherwise be discarded as waste. This value addition benefits local economies, particularly rural communities involved in biomass production, by creating additional revenue streams. Furthermore, the availability of graded liquid smoke supports sustainable agricultural practices, potentially lowering costs associated with synthetic pesticides and fertilizers (Santiyo Wibowo et al., 2023).

3.3. Properties and Performance of Activated Carbon

The activated carbon produced from coal in the 3-in-1 reactor demonstrated excellent properties that support its use as an effective adsorbent. Activated carbon is widely recognized for its extensive use in environmental applications, particularly for removing contaminants from air, water, and other industrial processes (Girhe et al., 2021). In this study, the activation of coal-derived carbon with 0.5 M H_3PO_4 resulted in an activated carbon with desirable structural and chemical characteristics that enhance its adsorption capacity. This section discusses the specific properties of the activated carbon, as well as the implications for its performance in practical applications (Kurniawan and Kim, 2021).

Table 2. Activated carbon specification

Type	Result
Ash content	0.93 %

Type	Result
Water content	2 %
Adsorption of Blue Methylene	24.5221 gr/ml
Surface area	9.2 m^2/g
Iodine	2,918.7 mg/g
Type	Powdered
Nominal size	80% min finer than 150 μm

One of the critical factors influencing the adsorption efficiency of activated carbon is its surface area and porosity. A higher surface area generally indicates more available sites for contaminant molecules to adhere, making it more effective in adsorption processes (Stavropoulos et al., 2015). In this study, the activated carbon achieved a surface area of 9.2 m^2/g. While this value may appear modest compared to certain commercially produced activated carbons, it exceeds the minimum requirement set by the Indonesian National Standard (INS), indicating its suitability for various industrial and environmental applications (Davini, 2001).

The phosphoric acid (H_3PO_4) activation process plays a significant role in enhancing the porosity and surface area of the carbon. Acidic activation facilitates the formation of a more extensive pore network within the carbon structure by promoting the development of micropores and mesopores (Stavropoulos et al., 2015). This improved pore structure is crucial for adsorption, as it allows a greater volume of contaminants to interact with the carbon surface. The resulting microporous structure is especially beneficial for adsorbing smaller molecules, such as gases and dissolved ions, while mesopores enhance accessibility to larger molecules. The activated carbon produced in this study is thus well-suited for applications requiring the adsorption of various contaminants, including heavy metals and organic compounds (Maneerung et al., 2016).

The iodine number is a widely used indicator of activated carbon's adsorption capacity, particularly for small molecules. A high iodine number reflects a large surface area and a substantial number of micropores capable of adsorbing iodine molecules. The activated carbon in this study exhibited an impressive iodine number of 2,918.7 mg/g, demonstrating its high adsorption efficiency and ample accessible surface area (Wu et al., 2010). The iodine number in this study showed higher than other previous study such as cross-linked chitosan microspheres achieved an iodine adsorption capacity of up to 879.2 mg/g, showing its application in wastewater treatment (Zhang et al., 2019). This value significantly exceeds typical iodine numbers for activated carbons intended for general adsorption applications, underscoring the potential of this material for more demanding environmental and industrial uses.

The high iodine number indicates that the activated carbon has a well-developed microporous structure, which is crucial for adsorbing small pollutants, such as dissolved organic contaminants in water or volatile organic compounds in air (Zhang et al., 2023). In water purification, for instance, a high iodine number suggests that the activated carbon will be effective in adsorbing organic contaminants and other small molecules, which are often the target pollutants in water treatment applications. Additionally, the high adsorption capacity makes this activated carbon a viable choice for heavy metal removal, as heavy metal ions can readily be captured within the microporous and mesoporous network of the carbon structure.

The ash content of activated carbon is another essential factor influencing its performance as an adsorbent. High ash content indicates the presence of non-carbon impurities, which can interfere with the adsorption process by occupying active sites on the carbon surface or contributing to unwanted chemical interactions (Davini, 2001). In this study, the activated carbon exhibited an ash content of 0.93%, which is significantly below the Indonesian National Standard limit of 10%. This low ash content highlights the purity of the activated carbon, as well as the effectiveness of the carbonization and activation process in removing non-carbon materials (Mohan and Singh, 2002). The minimal ash content indicates a high degree of carbonization, meaning that the coal feedstock was efficiently converted into pure carbon with few residual impurities. This high purity enhances the adsorption capabilities of the activated carbon, as a greater proportion of its surface area is available for contaminant removal. Furthermore, the low ash content reduces the likelihood of unwanted chemical reactions that could decrease the material's stability or contaminate treated media, such as water or air. The activated carbon's low ash content thus supports its use in sensitive applications, such as drinking water purification and environmental remediation.

Moisture content is another critical parameter affecting the performance of activated carbon, particularly in adsorption applications. High moisture levels can block the pores of the carbon, reducing the available surface area for adsorption and diminishing its effectiveness. In this study, the water content of the activated carbon was recorded at less than 2%, which is significantly below the Indonesian National Standard threshold of 15% (Wibowo et al., 2023a, 2022a). This low moisture content suggests that the activated carbon's pores are largely free from water molecules, allowing maximum adsorption capacity for other contaminants. Low moisture content is especially important in applications where the activated carbon is exposed to humid environments or aqueous solutions, as excess water can saturate the material and reduce its efficacy. The low water content of the activated carbon produced in this study ensures that it is prepared for high-performance applications in water treatment and air purification, where maintaining optimal pore accessibility is crucial for efficient adsorption.

The adsorption of methylene blue is often used as a measure of activated carbon's effectiveness in adsorbing larger organic molecules. In this study, the activated carbon displayed a methylene blue adsorption capacity of 24.5221 g/mL. This value indicates the material's ability to adsorb relatively large organic molecules, which is beneficial for treating industrial wastewater and other applications involving organic contaminants (Urano and Kato, 1972). The methylene blue adsorption capacity reflects the presence of mesopores in the carbon structure, which provide sites for larger molecules to attach and be retained. The methylene blue adsorption test supports the use of this activated carbon in wastewater treatment, where the removal of dyes and other organic pollutants is essential. Many industrial processes, such as textile and dye manufacturing, produce wastewater containing organic dyes that must be removed before discharge. The activated carbon's capacity to adsorb methylene blue thus makes it a suitable choice for such applications, contributing to pollution control and supporting environmental protection initiatives. The activated carbon produced in this study is in powdered form, with a nominal size where 80% of the particles are finer than 150 µm. The small particle size of powdered activated carbon enhances its adsorption kinetics, as the large surface-to-volume ratio allows contaminants to quickly reach and interact with the carbon's active sites. This feature makes powdered activated carbon highly effective in applications where rapid adsorption is required, such as in emergency water treatment and air purification systems. The fine particle size also facilitates the dispersion of activated carbon in aqueous solutions, allowing it to be evenly distributed throughout the treatment medium. This improves contact efficiency between the carbon particles and contaminants, leading to faster and more effective purification. The powdered form of activated carbon produced in this study is thus ideal for various environmental applications, including water and wastewater treatment, air purification, and soil remediation. The activated carbon's favorable properties—high surface area, low ash and moisture content, high iodine number, and strong methylene blue adsorption capacity—suggest that it is a viable option for environmentally beneficial applications. In water treatment, for example, this activated carbon can effectively remove a range of contaminants, from heavy metals to organic pollutants, reducing the need for synthetic chemicals and supporting sustainable purification practices (Kosheleva et al., 2019). Additionally, the use of coal-derived activated carbon promotes the valorization of coal byproducts, reducing waste and creating value from otherwise low-value materials. Economically, the production of high-quality activated carbon through the 3-in-1 reactor technology is a cost-effective approach to generating a versatile adsorbent with broad market appeal. Given its specifications, this activated carbon can be applied in various sectors, from municipal water treatment to industrial pollution control, offering an economically viable solution for large-scale environmental management.

3.4. Production and Applications of Limestone

The 3-in-1 nanotechnology pyrolysis reactor demonstrates remarkable versatility by transforming shell waste into high-purity limestone through an integrated calcination process. Limestone production from shell waste, such as clamshells, highlights the reactor's capacity to repurpose organic and inorganic materials into valuable products, aligning with the principles of sustainable resource management and waste-to-product conversion (Lim et al., 2021). This transformation leverages the high temperatures generated in the reactor, allowing for efficient calcination and creating limestone with characteristics suited for various industrial and environmental applications (Lee et al., 2019).

Calcination, the thermal decomposition of calcium carbonate ($CaCO_3$) into calcium oxide (CaO) or quicklime, requires temperatures typically exceeding 800°C. In this reactor, the calcination process is achieved using the residual heat generated during coal pyrolysis. The thermal energy released from the combustion of coal effectively drives the calcination of shell waste, a process that would otherwise demand separate energy input in conventional systems. This synergy between pyrolysis and calcination represents an energy-efficient approach to producing high-quality limestone, as it optimally utilizes the heat generated within the reactor without the need for additional fuel or external energy sources (Sanahuja-Parejo et al., 2019).

The effectiveness of this integrated approach is evident in the properties of the produced limestone. The high temperature within the reactor promotes a thorough decomposition of calcium carbonate into calcium oxide, resulting in a product with high purity and reactivity. Furthermore, the calcination process in the 3-in-1 reactor enables control over the particle size, allowing the limestone to be ground down to nanomaterial scales. These nano-sized particles offer a higher surface area and increased reactivity, which are advantageous in applications that require rapid chemical reactions, such as neutralization in acidic environments (Hai et al., 2021). The production of limestone with nanomaterial particle sizes significantly enhances its application potential. Nano-sized limestone has a considerably larger surface area compared to traditional limestone, which directly impacts its reactivity. The increased surface area allows for greater contact with reactants, making the limestone highly effective in neutralizing acidic solutions and adsorbing contaminants. This characteristic is particularly valuable in environmental remediation, where rapid and efficient chemical reactions are essential for treating large volumes of acidic wastewater, such as those resulting from mining or industrial processes (Lim et al., 2021).

In the context of acidic wastewater treatment, nano-limestone acts as a neutralizing agent, effectively raising the pH of acidic effluents to acceptable levels. Mining operations, for example, frequently generate acidic wastewater, also known as acid mine drainage, which contains heavy metals and other contaminants. The high reactivity of nano-limestone allows it to quickly neutralize the acidic conditions and precipitate metals, preventing them from entering natural water systems. This application of nano-limestone thus contributes to environmental protection, making it an effective and sustainable solution for mitigating the impact of industrial effluents on ecosystems (Abnisa et al., 2014; Abnisa and Wan Daud, 2014). The pyrolysis-based approach to calcination in the 3-in-1 reactor offers several advantages over conventional limestone production methods. Traditional calcination methods typically involve separate kilns or furnaces specifically dedicated to limestone processing, which are both energy-intensive and require substantial fuel input to reach the necessary temperatures. By contrast, the 3-in-1 reactor uses the waste heat from coal pyrolysis to drive the calcination of shell waste, maximizing energy efficiency and reducing the overall carbon footprint of the process (Sanahuja-Parejo et al., 2019).

This dual-process system not only minimizes resource consumption but also reduces emissions associated with conventional limestone production. By repurposing waste materials (coal for pyrolysis and shells for calcination) into valuable products, the reactor contributes to a circular economy model, where waste is minimized, and resources are reused. This aligns with sustainable development goals by reducing the environmental impact of limestone production, which is traditionally associated with high greenhouse gas emissions. The reactor's ability to produce limestone without the need for additional combustion or fossil fuel sources highlights its potential as an eco-friendly alternative to conventional calcination methods (Lee et al., 2019). The high reactivity and fine particle size of the limestone produced in the reactor make it suitable for a wide range of industrial and environmental applications. One of the most prominent uses of nano-limestone is as a neutralizing agent for acidic soils. Agricultural soils can become acidic due to factors such as acid rain, overuse of chemical fertilizers, or industrial pollution. When applied to soil, nano-limestone can quickly increase the pH, creating a more balanced and fertile environment for plant growth. Its high surface area allows for a faster reaction with soil acids, making it an efficient choice for agricultural soil amendments (Hai et al., 2021).

Additionally, the reactivity of nano-limestone is beneficial in water treatment applications. In wastewater treatment facilities, nano-limestone can be used to adjust the pH of effluents before discharge, ensuring that water released into the environment meets regulatory standards. Its use in treating acidic industrial effluents, such as those from petrochemical or textile industries, helps to reduce the environmental impact of these activities. The fine particle size also enhances the limestone's dispersibility in water, allowing it to interact more effectively with dissolved acids and contaminants (Lim et al., 2021). Moreover, limestone's applications extend to industrial processes that require quicklime (CaO), such as in the production of glass, steel, and cement. Quicklime acts as a flux, reducing the melting point of silica and other materials, thereby improving the efficiency of these industrial operations (Chuakham et al., 2021). The high purity of the quicklime produced in the 3-in-1 reactor ensures that it meets the quality requirements for these applications, making it a competitive alternative to commercially sourced limestone (Yasuro Katsuyama et al., 2005; Y Katsuyama et al., 2005). The production of high-purity, nano-sized limestone from shell waste in the 3-in-1 reactor presents economic advantages, particularly for rural and resource-limited areas. Utilizing locally sourced shell waste, such as discarded clamshells, reduces reliance on commercial limestone mining, which is often costly and environmentally damaging (Heriyanto et al., 2018). By converting a waste material into a valuable commodity, this reactor provides an additional revenue stream for local communities, promoting economic growth while fostering sustainable practices. The low operating costs of the 3-in-1 reactor further enhance its economic feasibility. The reactor's reliance on waste heat from coal pyrolysis means that limestone production incurs minimal additional fuel costs, making it an affordable solution for producing nano-limestone in small-scale operations. This cost-effectiveness is particularly relevant for small industries or agricultural operations that require limestone for soil or water treatment but may lack the resources to purchase commercial-grade limestone. By enabling local production, the reactor supports self-sufficiency and reduces the financial burden of importing materials (Akram et al., 2018).

3.5. Environmental and Economic Implications

The 3-in-1 pyrolysis reactor offers substantial environmental and economic benefits by transforming waste materials into valuable products such as liquid smoke, activated carbon, and limestone. This innovative reactor system represents a sustainable approach to waste management, addressing the dual issues of waste disposal and resource scarcity. The reactor's ability to integrate multiple production processes into a single, efficient unit not only reduces environmental pollution but also provides economic opportunities for communities, especially in rural or resource-constrained areas (Zheng et al., 2021).

One of the most significant environmental benefits of the 3-in-1 reactor is its capacity to repurpose local waste materials that would otherwise contribute to environmental degradation. Traditional waste disposal methods, such as landfilling and open burning, are associated with serious environmental issues, including greenhouse gas emissions, leaching of contaminants into the soil, and pollution of water bodies. By processing materials like coal and shell waste, the 3-in-1 reactor diverts these materials from landfills and minimizes the need for open burning (Campuzano et al., 2019). The closed-loop system of the reactor ensures that potentially harmful by-products are contained, captured, and converted into useful forms, rather than being released into the environment (Aladin et al., 2021).

The production of activated carbon within the reactor is particularly noteworthy in terms of environmental impact. Activated carbon is a highly effective adsorbent material used to remove pollutants from air and water. By enabling local production of activated carbon, the reactor supports environmental remediation efforts, offering a sustainable way to manage water and air quality (Xu et al., 2020). Communities can use this locally produced activated carbon to treat contaminated water, remove heavy metals, and reduce organic pollutants, thus improving local environmental health. In areas where access to commercial activated carbon is limited due to high costs, the reactor provides an affordable alternative, empowering communities to address their own environmental challenges (Agar et al., 2018). Another environmental benefit of the reactor is its production of liquid smoke, a by-product of the pyrolysis process that can be used as a natural preservative and antimicrobial agent. High-purity liquid smoke, produced through a multi-stage distillation process, offers an eco-friendly alternative to chemical preservatives and pesticides. Traditional synthetic preservatives and pesticides are often associated with environmental and health risks, including soil and water contamination, adverse effects on non-target organisms, and human health concerns. Liquid smoke, on the other hand, provides a natural solution with fewer negative impacts. Its antimicrobial properties allow it to be used in food preservation, extending shelf life without the use of synthetic additives (Lingbeck et al., 2014). Additionally, when applied as a biopesticide, liquid smoke can reduce reliance on chemical pesticides, promoting safer and more sustainable agricultural practices (Aladin et al., 2021).

The production of limestone from shell waste in the 3-in-1 reactor further highlights the system's environmental relevance. Nano-sized limestone, produced through the calcination of shell waste, has applications in soil and water remediation. For instance, it can be used as a neutralizing agent to treat acidic soils, improving soil health and promoting agricultural productivity. Acidic soils, which are common in many agricultural regions due to acid rain, excessive use of chemical fertilizers, and industrial pollution, hinder plant growth and reduce crop yields. Applying nano-limestone to such soils can rapidly increase pH levels, creating a more favorable environment for crops (Hai et al., 2021). Furthermore, in water treatment, nano-limestone effectively neutralizes acidic wastewater from industrial processes such as mining, reducing the impact of acid mine drainage on aquatic ecosystems (Lim et al., 2021). This capability positions the reactor as a valuable tool in environmental management, especially for industries that generate acidic effluents.

In addition to its environmental benefits, the 3-in-1 reactor offers considerable economic advantages, especially for rural or economically disadvantaged regions. By combining multiple production processes into a single unit, the reactor eliminates the need for separate, specialized equipment, which would typically require individual installations, maintenance, and energy sources. This consolidation significantly reduces both capital and operational costs, making the reactor a cost-effective solution for small-scale or community-level operations (Campuzano et al., 2019). Communities can achieve multiple outputs—activated carbon, liquid smoke, and limestone—using a single reactor, maximizing their resource utilization while minimizing expenses. This efficiency makes the reactor accessible to areas with limited financial and technical resources, enabling them to benefit from advanced waste-to-product conversion technology.

The simplicity and versatility of the 3-in-1 reactor also contribute to its economic feasibility. Unlike more complex systems that require skilled operators and extensive maintenance, the reactor can be operated with minimal technical expertise, making it suitable for rural and remote communities. The reliance on readily available raw materials, such as coal and shell waste, further enhances the reactor's practicality (Zheng et al., 2021). These materials are often inexpensive or even free in many regions, particularly where shell waste is abundant due to local seafood industries. By converting this waste into valuable products, the reactor provides communities with a new revenue stream while reducing reliance on external resources.

The economic value of the products generated by the reactor is another important factor. Activated carbon, for instance, is in high demand in sectors such as water treatment, pharmaceuticals, and chemicals. Its widespread use in filtration and purification processes ensures a stable market, providing communities with an opportunity to generate income from its sale (Xu et al., 2020). The availability of locally produced activated carbon at a lower cost than commercially available alternatives could also encourage its adoption within the community, supporting local environmental improvement initiatives.

Similarly, liquid smoke has multiple commercial applications, particularly in the food processing industry, where it serves as a flavoring agent and natural preservative. The production of different grades of liquid smoke—ranging from high-purity for food applications to lower-purity grades for agricultural use—broadens its market potential. High-grade liquid smoke can be marketed to food producers, while lower-grade variants can be sold to farmers as a natural biopesticide or soil amendment (Xin et al., 2021). This versatility allows communities to reach different market segments, maximizing revenue potential and increasing the economic resilience of the reactor system.

Nano-limestone, the third product of the reactor, also holds significant market value due to its effectiveness as a soil amendment and neutralizing agent in wastewater treatment. Agricultural sectors in particular can benefit from the availability of locally produced nano-limestone to improve soil health and increase crop yields. Additionally, industrial sectors that produce acidic effluents can use nano-limestone to neutralize their wastewater, reducing the environmental impact of their operations and potentially complying with environmental regulations (Mystrioti et al., 2020). By offering a locally produced, cost-effective alternative to commercial limestone, the reactor not only supports environmental goals but also provides an economic opportunity for communities (Abd El-Halim and Omae, 2019).

The reactor's ability to produce these three valuable products—activated carbon, liquid smoke, and limestone—from local waste materials fosters a circular economy model in which resources are continuously repurposed rather than discarded. This model promotes sustainable consumption and production practices by encouraging the use of waste as a resource, reducing the need for raw material extraction, and minimizing environmental harm. The economic benefits generated through this model support local livelihoods, creating jobs and providing new income streams in areas where employment opportunities may be limited (Judy et al., 2015). By offering a practical and scalable solution for waste-to-product conversion, the 3-in-1 pyrolysis reactor has the potential to transform rural economies and support environmental sustainability. Its integration of waste management with product generation reduces the financial burden of waste disposal, mitigates pollution, and creates valuable resources that meet the needs of local communities. This reactor aligns with global efforts to promote sustainable development, supporting cleaner production methods, reducing reliance on non-renewable resources, and contributing to a healthier environment (Xue et al., 2021).

Thus, the 3-in-1 pyrolysis reactor provides a comprehensive approach to sustainable waste management and resource utilization. Its environmental benefits stem from its ability to convert organic and inorganic waste into products that aid in pollution control, soil improvement, and sustainable agriculture. Economically, the reactor offers a low-cost, high-value solution for communities to generate revenue from local waste, making it particularly beneficial for resource-limited regions. The accessibility, efficiency, and versatility of the 3-in-1 reactor make it a promising technology for addressing waste challenges, enhancing economic resilience, and supporting environmental stewardship across diverse settings.

3.6. Limitations and Future Directions

While the 3-in-1 pyrolysis reactor offers numerous environmental and economic benefits, certain limitations need to be addressed to further improve its efficiency, product quality, and applicability across diverse materials and processes. These limitations highlight areas for optimization and provide a foundation for future research and development to make the technology more versatile, scalable, and sustainable in the long term (Oyedun et al., 2013). One of the primary limitations of the current 3-in-1 reactor design is the temperature restriction. The maximum achievable temperature of around 550°C, while sufficient for certain pyrolysis and calcination processes, may not be ideal for all materials, particularly those that require higher temperatures for complete decomposition or calcination. In the case of limestone production, for example, the reactor's current temperature limitation may result in lower-quality calcium oxide when compared to products obtained from traditional high-temperature calcination methods (Veses et al., 2016). Conventional calcination of calcium carbonate into calcium oxide typically requires temperatures above 800°C, which allows for more efficient and complete conversion. Operating at lower temperatures may produce limestone with residual impurities or a less reactive form of calcium oxide, limiting its effectiveness in applications such as wastewater treatment or soil amendment. In other side, this study need to analysis the operation condition, it essential to get the holistic information including the input and output of raw materials

Future improvements to the reactor's design could focus on enhancing its insulation and combustion systems to achieve and maintain higher internal temperatures. Upgrading the insulation material or increasing its thickness may help retain more heat within the reactor, allowing it to reach higher temperatures without significantly increasing fuel consumption (Solar et al., 2018). Additionally, optimizing the airflow and combustion design could improve the efficiency of heat generation and distribution, ensuring that all parts of the reactor reach and maintain uniform temperatures. Such enhancements would expand the range of materials that can be effectively processed, allowing the reactor to produce higher-quality products and compete more directly with traditional calcination technologies. Another limitation of the current reactor design relates to the activation process used for producing activated carbon. While phosphoric acid activation has proven effective in increasing the surface area and adsorption capacity of the resulting activated carbon, this method has certain drawbacks. Phosphoric acid is a chemical agent that, if not handled and disposed of properly, could pose environmental risks. Additionally, phosphoric acid activation may not achieve the same level of pore development and surface area enhancement as other chemical or physical activation methods, potentially limiting the adsorption efficiency of the activated carbon for certain applications (Ahmed Hared et al., 2007).

To address these concerns, future studies could explore alternative activating agents, such as potassium hydroxide (KOH) or zinc chloride ($ZnCl_2$), which have been shown to enhance pore structure and surface area in activated carbon production (Fadhil and Kareem, 2021). These alternative chemicals could potentially create a more effective adsorbent material, depending on the desired properties of the activated carbon. Physical activation methods, such as steam activation, could also be investigated as a more environmentally friendly option, as they avoid the use of chemical activators altogether. Steam activation, for instance, involves exposing carbonized material to high-temperature steam, which develops a well-connected pore network without introducing chemical residues. Research into these alternative methods could improve the reactor's activated carbon production, making it suitable for a broader range of applications, from water treatment to air filtration (Chen et al., 2016).

The environmental impact of large-scale implementation of the 3-in-1 reactor technology also warrants further investigation. While the reactor offers a sustainable approach to waste conversion, scaling up this technology may introduce challenges related to resource use, emissions, and waste management. Conducting a life cycle assessment (LCA) would provide valuable insights into the environmental footprint of the reactor over its operational lifetime, from raw material acquisition and energy consumption to product distribution and end-of-life disposal. An LCA would help identify areas where environmental impacts could be minimized, such as through improved fuel efficiency, reduced emissions, or better management of by-products (Antoniou and Zabaniotou, 2015). This assessment would be essential for determining the long-term sustainability of the reactor and its alignment with environmental standards. In addition to environmental impact studies, economic analyses are necessary to evaluate the viability of large-scale adoption of the 3-in-1 reactor. While the reactor is designed to be cost-effective and accessible for rural or resource-constrained areas, scaling up the technology might involve additional costs, such as infrastructure upgrades, maintenance, and energy demands. Assessing these costs in relation to potential revenue from the products generated (activated carbon, liquid smoke, and limestone) would provide a clearer understanding of the reactor's economic potential (Yang et al., 2017). Studies on operational costs, market demand for the products, and potential revenue streams would aid in developing a sustainable business model for scaling up the technology, ensuring that it remains economically feasible in diverse contexts (Yang et al., 2017).

Moreover, as the reactor technology matures, research could explore additional uses for the by-products generated during the pyrolysis, calcination, and activation processes. For instance, exploring the potential applications of any gaseous emissions from the reactor could lead to new avenues for resource recovery. If the gases produced during pyrolysis and calcination contain useful compounds, they could be captured, purified, and marketed, further enhancing the economic viability of the reactor. Such advancements would allow for more comprehensive utilization of the reactor's outputs, contributing to a zero-waste model (Zheng et al., 2021).

Thus, while the 3-in-1 pyrolysis reactor offers a promising solution for sustainable waste conversion, there are several areas where further optimization and research are needed. Enhancements to insulation and combustion design could increase the achievable temperature, improving the quality of products like limestone. Investigating alternative activation methods for carbon could yield activated carbon with enhanced properties and potentially lower environmental impact (Kulas et al., 2018). Environmental and economic assessments of large-scale adoption would ensure the technology's long-term sustainability and viability. Addressing these limitations will enable the 3-in-1 reactor to reach its full potential as a transformative tool for sustainable resource management and environmental conservation.

4. Conclusion

The 3-in-1 pyrolysis reactor demonstrates an innovative, sustainable approach to waste management by transforming local waste materials into valuable products—liquid smoke, activated carbon, and limestone—within a single, integrated system. This multifunctional reactor addresses environmental and economic challenges by repurposing coal and shell waste into high-demand products with applications in agriculture, water treatment, and various industries. Through the use of glass wool insulation and a controlled airflow system, the reactor optimizes thermal efficiency and resource utilization, enabling effective pyrolysis, calcination, and activation processes within a compact design. The environmental benefits of the reactor are notable, as it reduces waste and lowers reliance on synthetic chemicals for food preservation, water purification, and soil treatment. By producing high-quality activated carbon, natural liquid smoke, and nano-sized limestone, the reactor supports sustainable practices in rural and economically disadvantaged regions, offering an affordable and accessible solution for communities seeking to manage waste sustainably and generate income. Despite its benefits, the reactor's temperature limitations and reliance on phosphoric acid for activation present areas for improvement. Future research should explore alternative activation methods, higher temperature capabilities, and life cycle assessments to enhance the reactor's efficiency, scalability, and environmental impact. Thus, the 3-in-1 pyrolysis reactor offers a practical, sustainable technology that aligns with circular economy principles, providing a viable model for transforming waste into resources. Its potential for economic empowerment and environmental conservation makes it a promising tool for sustainable development in various settings

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