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STUDY ON THE STRUCTURE AND FUNCTION OF PYROLYSIS KILNS FOR PRODUCING VARIOUS TYPES OF BIOCHAR FROM AGRICULTURAL BY-PRODUCTS

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Abstract:

The technology of anaerobic pyrolysis kilns in biochar (BC) production has demonstrated success and efficiency in recent years. Research shows that the structure of the pyrolysis kiln consists of a kiln body and a lid. The kiln body is robustly designed to withstand high pressure and temperature. The lid incorporates a condenser and activated carbon, which serve to process gases such as CO2, CH4, CnHn, etc., ensuring no air pollution. Moreover, experimental studies have outlined the "biochar production process" using anaerobic pyrolysis kilns, which includes five steps: (i) raw material preparation, (ii) raw material preprocessing, (iii) biochar burning/firing, (iv) biochar cooling, and (v) biochar preservation and storage. Notably, the biochar production process using pyrolysis kiln technology generates a by-product called wood vinegar, a type of "pyroligneous acid" solution that benefits the environment and offers commercial value. This is considered a "green" product with promising potential applications in the future.

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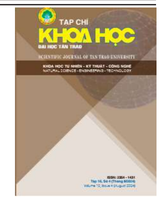

NGHIÊN CỨU ĐẶC ĐIỂM CẤU TẠO VÀ CHỨC NĂNG CỦA LÒ ĐỐT NHIỆT PHÂN ĐỂ SẢN XUẤT MỘT SỐ LOẠI THAN SINH HỌC TỪ PHẾ PHỤ PHẨM NÔNG NGHIỆP

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Lò đốt nhiệt phân yếm khí; Than sinh học; Giấm gỗ; Phế phụ phẩm nông nghiệp

Tóm tắt

Công nghệ lò đốt nhiệt phân yếm khí trong quá trình sản xuất than sinh học (TSH) đã cho thấy những thành công và hiệu quả trong những năm gần đây. Nghiên cứu cho thấy, cấu tạo lò đốt nhiệt phân bao gồm phần thân lò và nắp lò. Phần thân lò được thiết kế chắc chắn và có khả năng chịu áp suất và nhiệt độ cao. Nắp lò bao gồm bình ngưng tụ và than hoạt tính có vai trò xử lý các loại khí CO_2, CH_4, CnHn,... đảm bảo không gây ô nhiễm môi trường không khí. Hơn nữa, nghiên cứu bằng thực nghiệm cũng chỉ ra *"quy trình sản xuất than sinh học"* bằng lò đôt nhiệt phân yếm khí bao gồm 5 bước: (i) chuẩn bị nguyên liệu, (ii) sơ chế nguyên liệu, (iii) đốt/nung TSH, (iv) làm nguội TSH và (v) bảo quản và lưu trữ sản phẩm TSH. Đặc biệt, quá trình sản xuất TSH bằng công nghệ lò đốt nhiệt phân tạo ra sản phẩm phụ là giấm gỗ, là một dạng dung dịch *"Pyrolygneous acids"* có lợi cho môi trường và mang lại giá trị thương mại. Đây là một trong những sản phẩm *"xanh"* và có tiềm năng ứng dụng trong tương lai.

1. Introduction

Pyrolysis technology for biochar production is a smart solution to enhance the value of agricultural products, reduce greenhouse gas emissions, and promote the transformation of agricultural by-products into clean energy and green materials in Vietnam. Biochar (BC) is a carbon-rich product obtained by pyrolyzing organic materials such as wood, manure, leaves, and agricultural by-products (e.g., straw, rice husks) at temperatures below 700°C under oxygen-limited or oxygen-free conditions. Biochar has been proven to be an effective adsorbent for various pollutants, both organic and inorganic, due to its large surface area and unique structure, including porosity and pore size. Currently, there have been numerous studies on the technology and development of pyrolysis kilns for biochar production and application in Vietnam. For instance, Mai Thi Lan Anh et al. have innovated biochar production from straw, firewood, corn cobs, and rice husks for use as fertilizer in Bac Kan; the University of Agriculture and Forestry (Hue University) successfully researched, designed, and fabricated pyrolysis kilns capable of processing 50–300 kg of rice husks per batch from agricultural by-products; the Institute for Agricultural Environment has successfully produced biochar from wood chips, sawdust, straw, rice husks, bagasse, corn, and coffee; the Institute of Soil and Fertilizer has used rice husk biochar as a substrate, artificial soil, and organic microbial fertilizer for growing ornamental plants and specialty vegetables; and in 2007, Binh Dinh Fertilizer and General Services Joint Stock Company (Biffa) received technology transfer from Sino-Japan to produce biochar from plantation eucalyptus, introducing various biochar products to the market. Overall, existing biochar kilns on the market have advantages such as reduced labor effort, low cost, and biochar recovery efficiency exceeding 90%. However, current kiln technologies still produce smoke and some pollutant gases, have long pyrolysis times (3–5 hours per batch), consume significant energy, and lack detailed operational guidelines.

Thus, the research titled "Study on the structure and function of pyrolysis kilns for producing various types of biochar from agricultural by-products" is necessary to meet practical needs. The objectives of the study include:

(i) identifying the structural characteristics, functions, and operating principles of anaerobic pyrolysis kilns;

(ii) experimentally producing various types of biochar from agricultural and forestry by-products using anaerobic pyrolysis kilns; and

(iii) evaluating the production efficiency of biochar using anaerobic pyrolysis kilns.

2. Materials and Methods

2.1. Methods for Collecting Secondary Data

Utilizing various types of documents: internationally published articles, books, and specialized journals.

Research reports, projects, scientific theses, etc.

Using the internet to search for and compile materials.

Consulting experts, lecturers, and staff responsible for the research field at various levels through a questionnaire.

2.2. Experimental Design

2.2.1. Tools for Pyrolysis Kiln Simulation Drawing

Using software such as AutoCAD, Visio, and Photoshop to determine the structural characteristics of the pyrolysis kiln (simulation).

The AutoCAD drawing (version 2021) illustrates the structure of the kiln, including the components of the anaerobic pyrolysis kiln:

- Kiln body
- Kiln lid
- Gas recovery and treatment unit
- Gas condensation unit for producing wood vinegar
- Kiln rotation system
- Kiln support frame

2.2.2. Biochar Production from Different Waste Sources Using Anaerobic Pyrolysis Kilns

Raw material preparation: Using agricultural and forestry by-products such as wood scraps, rice husks, coconut shells, etc.

Cleaning raw materials: Washing with water to remove impurities and dirt.

Cutting/grinding and drying: Drying at 80–120°C or under sunlight for 2–3 days (raw material moisture content < 20%).

Pyrolyzing preprocessed materials: Burning in a pyrolysis kiln at 400°C under anaerobic conditions for approximately 4 hours (burning time depends on the material).

Cooling the biochar: Allowing it to cool naturally or using water.

Preserving biochar: Storing biochar samples in containers at room temperature (25°C), avoiding direct sunlight.

Some types of biochar produced using pyrolysis kiln technology:

- Biochar derived from rice husks – BC 01
- Biochar derived from coconut shells – BC 02
- Biochar derived from miscellaneous wood – BC 03
- Biochar derived from wood scraps (leftover forestry production materials) – BC 04

2.2.3. Statistical Data Processing

Compiling all data analyzed on the structural characteristics and functions of the pyrolysis kiln.

Using the aggregated data to evaluate each criterion and write the report.

Employing software such as Excel, Word, and AutoCAD during the research process.

3. Results and Discussion

3.1. Characteristics, Functions, and Operating Principles of Anaerobic Pyrolysis Kilns

3.1.1. Characteristics and Functions of Anaerobic Pyrolysis Kilns

The structure of the anaerobic pyrolysis kiln is cylindrical and consists of two main parts: (i) the kiln body and (ii) the kiln lid. Figure 1 illustrates the complete structure of the pyrolysis kiln.

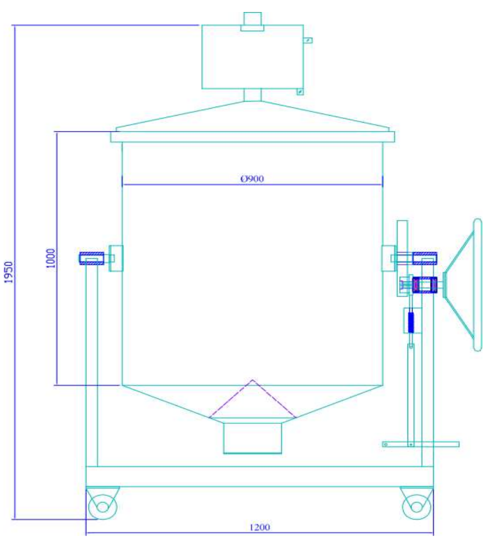

Figure 1. Structure of the pyrolysis kiln

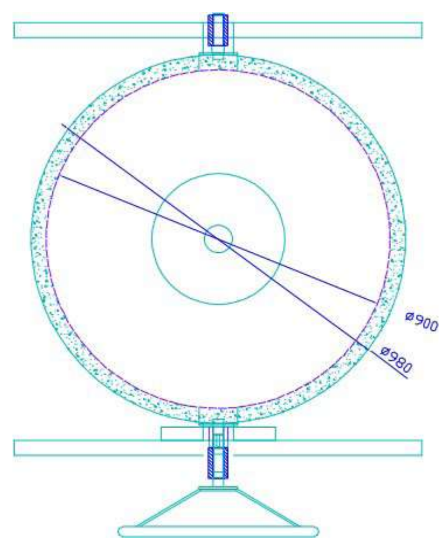

Figure 2. Structure of the Kiln Rotating Wheel

Description of the Structural Characteristics and Functions of the Anaerobic Pyrolysis Kiln:

(i) Kiln Body:

- Kiln Rotation System: The kiln rotation system has a wheel with an inner rim diameter of ø 900 and an outer rim diameter of ø 980 (Figure 2). This system plays a role in adjusting the biochar combustion chamber. After the biochar is cooled, the rotation system can be adjusted to discharge the biochar.

- Kiln Support Frame: The support frame measures 1200 cm in length and 1066 cm in width. It supports the entire kiln body and is equipped with rotating wheels, making it easy to move the kiln.

- Combustion Chamber: This is where the pyrolysis process occurs, with organic materials burned in an oxygen-deficient environment. The chamber is cylindrical, with a diameter of ø 900, a chamber body height of 1000 cm, and a total kiln height (from the rotating wheel base to the lid) of 1950 cm.

(ii) Kiln Lid

The kiln lid includes a gas filtration system and a condensation unit for wood vinegar (a secondary product obtained after biochar production). The lid measures 410 cm in length, 350 cm in width, and features a liquefied gas container for wood vinegar with a height of 21 cm.

Exhaust Gas Treatment System: To ensure compliance with environmental regulations, the anaerobic pyrolysis kiln is equipped with an exhaust gas treatment system that includes an activated carbon filter. This system filters harmful gases such as CO2 and CH4 generated during pyrolysis. The inner rim of the filter system measures ø 350, while the outer rim measures ø 430. Additionally, the gas filtration unit lid has a vent hole diameter of ø 60, matching the diameter of the gas duct (Figure 3).

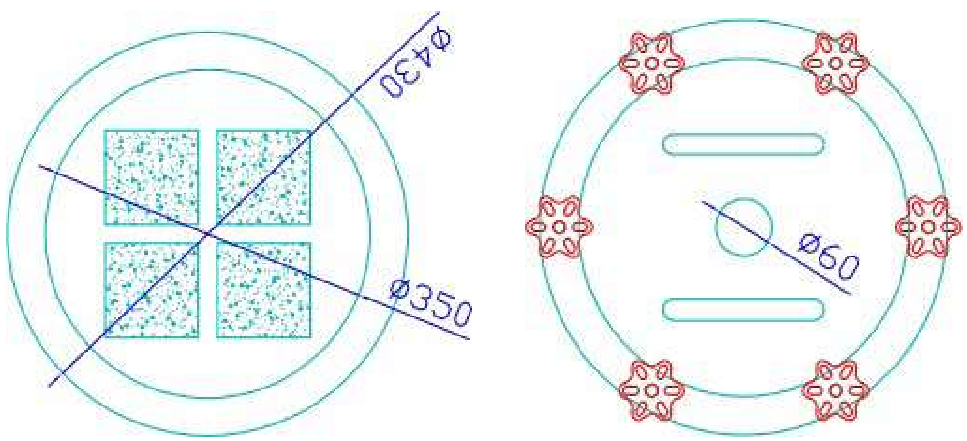

Figure 3. Structure of the Air Filtration by Activated Carbon

Gas Condensation Unit: The gas condensation unit is used to cool and condense gases generated during the anaerobic combustion process into liquid form. This liquid, known as wood vinegar (a type of aqueous solution and secondary product), has an inner circular diameter of ø 200 and an outer circular diameter of ø 350 (Figure 4).

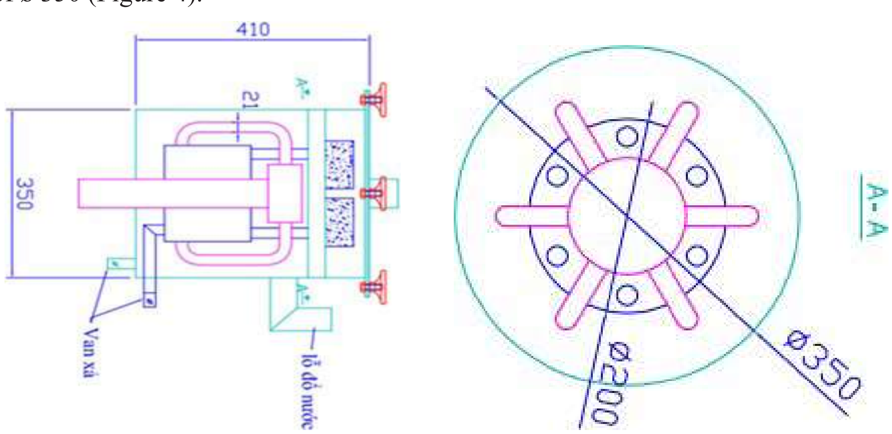

Figure 4. Structure of the Gas Condensation Unit and Liquefied Gas Release Valve

3.1.2. Operating Principles of the Anaerobic Pyrolysis Kiln

Dry materials (organic waste, agricultural by-products, wood processing residues, etc.) are placed in the combustion chamber. Next, the fan is turned on, and the air supply valve is opened at the kiln inlet. A fire is ignited at the kiln door to provide heat for the combustion chamber. After approximately 5 minutes of ignition, when the combustion chamber reaches a temperature of 400°C, the air supply valve to the chamber is closed to create an oxygen-deficient combustion environment.

During this limited oxygen combustion process, various combustible and non-combustible gases are directed through a gas pipe into a container with lime water (Ca(OH)2 solution) for filtration and condensation. The kiln is constructed with a 5-mm-thick layer of heat-resistant steel surrounding the kiln body, ensuring the kiln remains unaffected by extreme temperatures and does not crack during biochar production. This construction also ensures the biochar produced meets high-quality standards.

During biochar production, complex and simultaneous reactions occur at different locations in the kiln and on individual particles of biomass feedstock. Biomass gasification involves four stages:

Drying Stage:

Using heat, water evaporates from the material. This is beneficial as excess water reduces oxidation temperature and prevents clean gas production. Physical water separation occurs at temperatures of 90–100°C.

Pyrolysis Stage:

Carbon chains break down at 400°C, forming a mixture of gases including CO, CO_2, CH4, CnHn,..., etc.

Combustion Stage:

In the combustion chamber, with limited oxygen, heat is generated to sustain the pyrolysis process:

$C + O_2 \rightarrow CO_2 + Q$ (heat release).

Gasification Stage (Reduction):

The char reacts with water vapor in chemical reactions:

$C + H_2O \rightarrow H_2 + CO$;

$C + CO_2 \rightarrow 2CO$;

Successive reversible reactions occur, reaching equilibrium:

$CO + H_2O \leftrightarrow CO_2 + H_2$.

3.2. Development of a process for producing biochar from agricultral by-product using anaerobic pyrolysis kiln

Through experimental procedures (Figure 5), the process of trial biochar production from various waste sources using the anaerobic pyrolysis kiln is described through the following main steps:

Figure 5. Experimental Images of Biochar Production and Analysis:
(a) Raw wood materials, (b) Biochar derived from wood materials, (c) SEM image of the biochar

(i) Step 1: Material Preparation

The materials used in the anaerobic pyrolysis process in this study are wood scraps, sawdust, rice husk, and coconut shells.

Sawdust, wood waste, and wood scraps are collected from wood production workshops in Dong Hy District, Thai Nguyen Province.

Rice husk is collected from milling facilities around Dong Hy District, Thai Nguyen Province.

Coconut shells are collected from the Dong Quang market area in Thai Nguyen City.

(ii) Step 2: Material Preprocessing

Clean the materials: Wash the materials 2–3 times with clean water to ensure they are free from dirt and organic matter.

Dry the materials under direct sunlight for 2-3 days or dry them at a temperature of 80-120°C. (Note: Ensure the materials are thoroughly dried to 80-85% moisture content.)

Grinding: After drying, grind or chop the materials into small pieces. Store the materials in a dry place (avoid damp areas).

*Note: The materials, after preprocessing and treatment, should be free from unwanted impurities, cut into small pieces, or ground to the appropriate size for the pyrolysis process.

(iii) Step 3: Pyrolysis of Materials

The materials are placed into the pyrolysis kiln, where the pyrolysis process occurs. In the kiln, the materials are burned in a limited oxygen environment, meaning oxygen is either absent or restricted.

Install a fan to blow air into the kiln.

Place a layer of straw (or other flammable material such as dry wood pieces or kindling) about 10 cm thick at the bottom of the kiln and ignite it before adding the materials for biochar production.

Load the preprocessed materials into the pyrolysis kiln.

Pour water into the gap between the lid and the body of the kiln to prevent gas from escaping, ensuring the best anaerobic conditions inside the kiln. Continue adding water (limewater) to the container on top of the kiln lid until it is nearly full.

Burn the materials for 1.5-2 hours (depending on the material) at a temperature of 400°C.

(iv) Step 4: Cooling the Biochar

Allow the biochar to cool naturally for about 1 hour, then transfer it to a clean, dry tarp.

If necessary, water can be used to speed up the cooling process, but once removed from the kiln, the biochar should be dried or further heated (at 80-120°C).

(v) Step 5: Storing and Preserving the Biochar

Store the biochar in a sample container at room temperature (25°C).

Ensure the biochar container is kept dry and not exposed to moisture or mold, as this can affect the quality of the biochar.

3.3. Evaluation of the effectiveness and potential applications of Anaerobic pyrolysis kiln

In this study, the smoke emitted during the pyrolysis process, instead of being released directly into the environment causing pollution, will be rapidly cooled for condensation and recovery. The gas filtration unit recovers a very useful by-product: Wood vinegar solution – a product with many potential applications, including in the field of pollution treatment.

Wood vinegar solution *(Pyrolygneous acids)* is recovered from the pyrolysis of agricultural and forestry waste, organic waste, etc. The composition and properties of the wood vinegar solution are shown in Table 1.

Table 1. Analysis results of the chemical and physical properties of Pyrolygneous acids solution recovered from pyrolysis technology

Or.	Parameters	Unit	Results
1	Water content	g/100 mL	90,0
2	Acid acetic	g/100 mL	4,92
3	Formaldehyde	mg/L	44,9
4	Arsenic	mg/L	< LOQ (LOQ: 0.019 mg/L
5	Mercury	mg/L	KPH/ND LOD:0,003 mg/L
6	Methanol	%V/V	0,925
7	Phenol and phenol derivatives content	mg/L	39,3

Table 1 shows that the composition of wood vinegar solution mainly consists of water, acetic acid, formaldehyde, methanol, and phenol, with concentrations of 90 g/100mL, 4.92 g/100mL, 44.9 mg/L, 0.925 %V/V, and 39.3 mg/L, respectively. Additionally, wood vinegar has a characteristic smoky odor, a color ranging from reddish-brown to dark yellow, high purity, and strong anti-inflammatory, antibacterial, and antioxidant properties. Therefore, wood vinegar can be used as an organic and environmentally friendly product that can be applied across various fields.

Potential Applications of Pyrolygneous acids solution in Environmental Protection

Wastewater Treatment: Wood vinegar has the ability to adsorb pollutants in water such as heavy metals, organic compounds, and other contaminants. Using wood vinegar in wastewater treatment can help remove these pollutants and improve the quality of wastewater before it is released into the natural environment.

Soil Improvement: Pyrolygneous acids also has the ability to enhance soil fertility and improve soil quality.

Adsorption of Emissions and Odors: Wood vinegar has strong adsorption properties and can remove pollutants from emissions sources such as industrial plants, traffic, and waste treatment systems. Additionally, wood vinegar has effective deodorizing capabilities, helping to reduce unpleasant odors from pollution sources.

4. Conclusion

**** In the experimental process, the research findings include:***

Several detailed characteristics of the construction (furnace body and lid), function, and operating principle of the anaerobic pyrolysis furnace technology.

The research and improvement of the 5-step process in biochar (TSH) production from waste and agricultural by-products using pyrolysis furnace technology. These steps include: (i) raw material preparation, (ii) raw material preprocessing, (iii) pyrolysis/incineration of TSH, (iv) cooling of TSH, and (v) storage and preservation of the TSH product.

The pyrolysis process produces wood vinegar as a by-product, a form of "Pyrolygneous acids" that is beneficial for the environment and provides commercial value.

**** Future Research***

Continue to upgrade and apply advanced technologies (AI, sensors, etc.) to improve the anaerobic pyrolysis furnace.

Study the application of wood vinegar in agriculture and environmental protection.

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