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Research article

Novel eco-friendly design and fabrication: Application of low-cost, smokeless, mobile charcoal furnace and wood vinegar products for aging society

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Abstract

Importance of the work: A low-cost, smokeless, mobile charcoal furnace with a wood vinegar product condensing system was fabricated. It is environmentally friendly and suitable for the elderly. The developed furnace can increase productivity compared to existing conventional units and can be operated easily by the elderly to generate charcoal for income.
Objectives: To develop and evaluate a portable, smokeless charcoal furnace equipped with a wood vinegar condensation system to enhance the efficiency of charcoal production, reduce the required production time, and improve the quality of the charcoal produced. Additionally, the study also analyzes its economic viability.
Materials & Methods: The production of charcoal involved exposing bamboo and *Acacia auriculiformis* wood to 200°C, 250°C or 300°C for 5 hr, 6 hr or 8 hr. The quality of the resulting charcoal was determined based on several factors: heating value, weight, yield, moisture content and the amount of wood vinegar generated.
Results: The charcoal furnace system had the highest capacity, producing 7 kg/hr of charcoal. It took 5 hr to complete the burning process and an additional 15 min to remove the charcoal. Engineering economic analysis was used to determine the viability of using the portable, smokeless charcoal furnace. It was determined that the cost of production was USD 0.18 /kg. The break-even point for this operation was 12 hr/yr and the payback period was 0.021 yr.
Main finding: The charcoal kiln system could be moved to different locations and was suitable for elderly workers. The quality of charcoal products was higher than the products available on the market and their value was increased by adding a wood vinegar condensation system.

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Introduction

Bamboo is an ideal plant for the sufficiency economy system as it represents self-reliance in terms of food, shelter, medicine and clothing (Chien et al., 2011; Zhu et al., 2014). Additionally, bamboo fabric already exists (Rathod et al., 2014). Bamboo is beneficial in both economic and ecological terms as it can create forests that conserve soil and water and it is part of the natural food chain (Shao et al., 2016). Furthermore, bamboo can be used as a material for career development, starting from self-sufficiency and advancing to an industry that promotes well-being. For example, in the charcoal industry, bamboo stems can be used directly or bamboo joints can be used as residues from other industries, with the charcoal scraps being crushed and then being pressed into charcoal briquettes for sale both domestically and internationally (Mwampamba et al., 2013). In addition, burning charcoal can produce wood vinegar (Liu et al., 2014; Than and Suluksna, 2018), which can be a good substitute for pesticides (Taha et al., 2014). Wood vinegar is created by burning wood to produce charcoal, with the liquid that forms during this process condensing into brown-red droplets that can be mixed with water and allowed to settle for about 3 mth to obtain pure wood vinegar with a high level of acidity (Lu et al., 2020). In many industries, bamboo is sourced from forests as raw material. However, the quantity and quality of bamboo can be unpredictable, while obtaining it during the rainy season can present various challenges (Embaye, 2003). As a solution, bamboo is now being cultivated in farm-based plantations (Partey et al., 2017; Jusoh et al., 2021; Beshir et al., 2022), making it a more accessible and sustainable source of production in the future. Furthermore, bamboo is a versatile plant that can easily grow in almost any location and climate, with many low-income individuals and the elderly relying on charcoal as a fuel source (Woolley et al., 2021).

Bamboo charcoal has various uses in the manufacturing of carbon-based composites, nanorods, functional fabrics, silicon carbide, metal reduction and recycling, as well as being considered a natural anti-bacterial agent and a biological preservative, due to its beneficial medicinal properties, which are similar to those of bamboo vinegar (Wang et al., 2012). In addition to this, bamboo charcoal has been found to be effective when added in small amounts to the diets of poultry and farm animals (Ruttanavut et al., 2009). In many parts of the world, including the northeastern region of India, bamboo charcoal is used as a fertilizer, along with manure and compost (Rathour et al., 2022). Thus, there is huge potential for the commercial exploitation of bamboo charcoal. The purpose of this paper was to design a cost-effective, efficient and easy-to-operate pyrolysis unit to produce high-quality bamboo charcoal meeting market standards (Liu et al., 2016; Nigatu et al., 2020). Implementing an improved process for the production of bamboo charcoal would create more job opportunities and promote entrepreneurship in the rural sector. However, the traditional method of burning charcoal requires a large amount of manpower and time and produces a lot of smoke and ash. To address these challenges, mobile charcoal furnaces have been developed that are designed to be more space-efficient, require less manpower and produce less smoke (Koraïem et al., 2021). In addition, they can also be easily transported to areas with sintering materials and portable kilns are available in sizes suitable for family use (Boateng et al., 2015).

The objective of this study is to enhance the efficiency of charcoal production and minimize the production time by designing and fabricating a low-cost, smokeless, and mobile charcoal furnace that incorporates a wood vinegar condensation system. This system aims to be environmentally friendly and suitable for elderly users, facilitating easier operation and increased productivity compared to conventional units.

Materials and Methods

Method for designing and fabricating low-cost, mobile, smokeless bamboo charcoal furnace and wood vinegar products

Following an in-depth study of pertinent information regarding the design and construction of a charcoal furnace, a mobile, smokeless charcoal furnace was designed and constructed. Subsequently, testing was conducted to comprehensively assess the performance of the mobile, smokeless charcoal furnace. The set of well-defined design criteria and specifications specified: 1) a simple and uncomplicated working mechanism that is operable using human power for the rotation and lifting of the charcoal; 2) ease of maintenance, allowing for straightforward servicing and repairs; 3) convenience and safety in operation for all users, including elderly individuals; 4) constructed from materials readily available in rural areas; 5) standard parts and equipment that if damaged could be effortlessly removed and replaced; and 6) environmentally friendly, minimizing its environmental footprint (Samseemoung et al., 2024).

Low-cost, mobile, smokeless bamboo charcoal furnace

The furnace was configured as a vertically arranged double tank to facilitate the loading of raw materials and the retrieval of charcoal products. Additionally, the tank was equipped with technology aimed at reducing smoke emissions during the combustion process, thereby rendering it environmentally friendly. The structural composition comprised four main components: a 200 L tank structure, a power transmission, a transmission system and a condensation system. The main framework responsible for supporting the components of the furnace was fabricated from 5.08 cm × 5.08 cm and 7.62 cm × 3.81 cm square pipe, as presented in Fig. 1, respectively. The tank mounting apparatus was constructed using 3.81 cm flat steel, 1 cm in thickness, and a 10.16 cm square plate. These components underwent cutting, drilling,

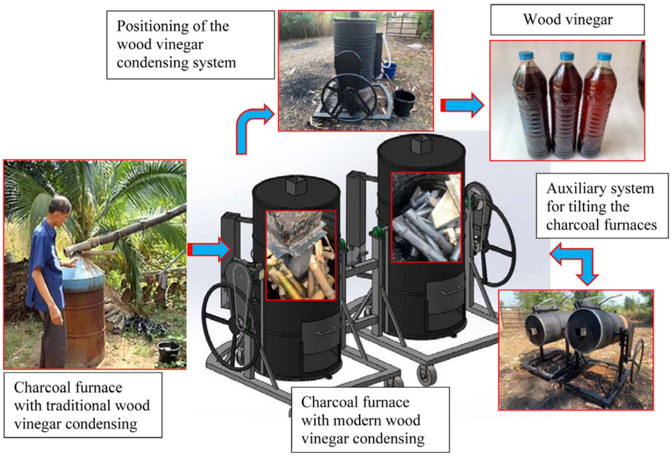

Fig. 1 Low-cost, mobile, smokeless charcoal furnace and wood vinegar products

welding and assembly processes to obtain the specified dimensions of 115 cm in width, 210 cm in length and 75 cm in height. The primary function of this component was to serve as the structural framework for housing the incineration tank, power transmission unit, wheels and supporting legs of the tank. The wood-loading section of the furnace was fabricated from a 200 L steel drum. To extend the lower tank section, a square section measuring 35 cm in width and 23 cm in height was created by cutting the front portion. In addition, a cover rail was constructed from a 2.54 cm angle bar and flat steel, measuring 3.81 cm in width and 1 cm in thickness, featuring round holes with a diameter of 1.2 cm for attachment. These elements were welded onto the steel tank to function as both the mounting legs and supporting legs for the tank.

Auxiliary system for tilting charcoal furnace

A power transmission system was incorporated into the design and construction of the low-cost, mobile, smokeless bamboo charcoal furnace to make it suitable for elderly users. The system served as the interface for power input, with the primary source being a steering wheel that facilitated the subsequent transfer of power to a reduction gear designed with a 1:2 ratio, which was directed to a shaft located on the tank supporting legs to enable the rotation of the furnace (wood-loading process), controlled by a locking plate mechanism. The power transmission used a driving gear with 20 teeth and a driven gear with 40 teeth. Additionally, steel roller chain no.60 was integrated into the system, as presented in Fig. 2.

No.	Item
1	Main construction
2	200 L fuel tank
3	Tank weight support structure
4	Guard protection chain gear sprocket
5	Wood vinegar products condensing system
6	Auxiliary system for tilting charcoal furnace
7	Gear 1
8	Gear 2
9	Inner drive chain sprocket
10	Outer drive chain sprocket
11	Roller bearing
12	Plain bearing
13	Steel wheel
14	Locker

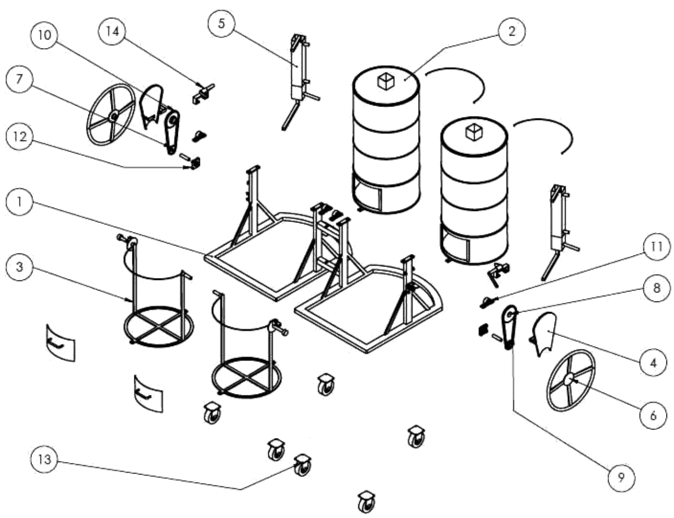

Fig. 2 Components diagram of low-cost, mobile, smokeless charcoal furnace and wood vinegar production system

Wood vinegar products condensing system

The wood vinegar condensing system was designed and constructed using 2.54 cm and 10.16 cm square pipe and 2.54 cm steel pipe. These materials were cut, drilled and welded to create a structure with dimensions of 50.16 cm × 15.16 cm × 64.80 cm (width × length × height). This wood vinegar condensing system served as a distillation unit for extracting the wood vinegar from the charcoal production process.

X-ray diffractometry

An X-ray diffractometer (XRD) (Rigaku Model SmartLab, 9 kW, X-Ray generator: Cu anode, Kα1-1,544 A° Detector: 0D, 1D, 2D; Expert Centre of Innovative Materials (InnoMat); Thailand) was used to study the internal structure of the tested wood charcoal and compare it with wood charcoal available in the market. The XRD analysis utilized X-rays to qualitatively and quantitatively analyze and identify the compounds and crystal structures in the bamboo charcoal and the acacia wood charcoal. The XRD technique operated on the principle of directing X-rays onto the charcoal sample, inducing diffraction and capturing the diffracted X-rays at various angles using a signal probe, known as a detector. This process enabled the analysis of the composition and structure of charcoal. Different degrees of X-ray diffraction occur at varying angles, depending on the composition, shape and crystal characteristics of the sample. The resulting data provided insights into the types of compounds present within the charcoal, as well as the crystal structure of the charcoal. Furthermore, it allowed for the assessment of various characteristics (crystallinity, crystal size, crystal completeness and the stress within the compounds present in the charcoal). When combined with supplementary equipment, such as a cooling-heating device, it was possible to study alterations in the crystal structure as the testing conditions were changed.

Determination of wood charcoal characteristics

The following main equipment was used:

Compound microscope

An ordinary light microscope (Iris Binocular Zoom Stereo microscope model SZM45-B8L, Eyepiece: WF10x/20mm, Objective lens: continuous zoom 0.7×–4.5× (Zoom Ratio 1:6.4); Inter Education Supplies Co., Ltd.; Thailand) was used to examine the structure, crystal components, arrangement and pore characteristics of the wood charcoal. The microscopes used consisted of two main types: 1) a compound microscope or magnifying glass that utilized only a single convex lens to magnify objects. The resulting image obtained through this type of microscope is virtual; and 2) a compound light microscope, equipped with two sets of lens systems (an objective lens and an eyepiece) that magnify images. Commonly, light field microscopes or bright field microscope are used in laboratories based on the following working principle. The light source is provided by a light bulb, with the light being focused through a condenser lens onto the specimen placed on the specimen stage. Subsequently, the objective lens magnifies the object to a larger image size, which is then directed to the eyepiece (ocular lens) to enhance the final image.

Infrared thermometer

A multipurpose infrared thermometer (-50°C to 550°C) combines the temperature measurement functions that industrial, electrical and heating, ventilation, air conditioning and refrigeration (HVAC/R) professionals need, all in one tool. It measures both the infrared and contact temperatures, replacing several other test tools. This tool is speedy, efficient and easy to use, saving time and energy. The IR thermometer can be used to measure hot, moving, electrically energized and hard-to-reach objects instantly, such as in check motors, insulation, breakers, radiant heating, pipes, corroded connections and wires (Kaya et al., 2021).

Moisture analyzer

A moisture analyzer is a measuring instrument that can measure humidity using the electrical resistance within the range of 8.5% to 23.5% with an accuracy (Signature Process Gas) and an error not exceeding 0.5%. The test can be conducted without damaging the material being measured, using a measurement speed of 3 s and an operational temperature range of 5–40°C (Gallegos et al., 2016).

Analysis of raw materials, products and gases

Study indicators

1. Yield percentage of charcoal (Equation 1)

$$C_t = \frac{W1}{W} \times 100 \tag{1}$$

where C_t is the yield percentage of charcoal, W_1 is the weight of charcoal of standard size and W is the weight of the charcoal obtained, with both weights measured in kilograms.

2. Heating value of charcoal (Equation 2)

$$Q = mc\Delta T \quad (2)$$

where Q is the heat measured in calories, m is the mass of charcoal measured in grams, c is the specific heat of charcoal (measured in calories per gram per degree centigrade) and ΔT is the temperature change measured in degrees centigrade (1 calorie equals to 4.2 Joules).

3. Wood moisture content measurement (Equation 3)

$$\text{Wood moisture content percentage} = MC = \frac{A-B}{A} \times 100 \quad (3)$$

where MC is the moisture content as a percentage, A is the green weight of wood and B is the dry weight of wood both measured in kilograms.

Necessary information for designing and constructing mobile, smokeless charcoal furnace

The results of the study on the necessary information for designing and constructing a mobile smokeless charcoal furnace are as follows:

1) Labor wages = USD 9.8/d or USD 0.03/kg charcoal production

2) Maximum burning capacity = 68 kg/d (8 working hours)

3) Current problems encountered with operating the mobile, smokeless charcoal production process include a shortage of labor for cutting trees and burning charcoal. Currently, 1 person has only 32 hr/wk available for charcoal production. The weekly demand of wood is 420 kg and the required amount of wood cannot be cut to meet the demand.

4) The required characteristics of a mobile, smokeless charcoal furnace include the ability to produce smokeless charcoal efficiently and continuously in sufficient quantities to meet demands. In addition, it should be easily movable to access the raw materials at various locations within the area.

5) The operational mechanism of the furnace should not be complicated and should be durable and easily maintainable. The successful development of a mobile, smokeless charcoal furnace will increase efficiency and operational capacity, as well as mitigate the adverse effects of air pollution in the community.

Statistical analysis

The experiments were set up following a completely randomized design. The measurements were conducted three times. Before performing statistical analyses, the data were tested for normality using the Shapiro-Wilk test and for homogeneity of variances using Levene's test to ensure assumptions were met. The data on the weight of charcoal obtained from two types of furnaces at each time point were compared using a paired samples t-test. The same method was used to compare the volume of wood vinegar produced from bamboo and acacia at each temperature. The moisture content of bamboo wood and acacia wood at different burning times and temperatures were separately analyzed using analysis of variance followed by mean comparisons using Duncan's multiple range test. All tests were considered significant at $p < 0.05$. The analyses were performed using SPSS software (version 21; IBM Corp.; Armonk, NY, USA).

Results

The operational principle of the mobile, smokeless charcoal furnace involves utilizing the transmission system to tilt the tank at the angle that facilitates easy access for opening the tank lid and loading wood. There is a locking mechanism to hold that tank at the desired angle. After loading the wood, the lid is closed and the tank is returned to the upright position. Then, the fire is ignited using the furnace fire socket. Once the wood is burning at the desired temperature, water is added to the condensing system unit and the front cover of the furnace fire socket is closed when wood vinegar distillation begins. The water circulating within the condensation system is utilized to facilitate the condensation of wood vinegar into a container until the burning process is completed.

Testing results of mobile, smokeless charcoal furnace

The test results involved burning two different types of wood (bamboo and acacia wood) using the mobile, smokeless charcoal furnace. These tests compared the quality of the two resulting charcoals from the furnace with commercially available charcoal and determined the charcoal with the highest heat output and longest burning duration. The study results were based on analysis of heating values, identification of compounds and the crystal structures of the compounds present in the samples from both qualitative and quantitative aspects, as well as microscopic examination utilizing a microscope with a magnification of 260× to observe and analyze the pore characteristics of the charcoal samples. The wood samples tested were bamboo charcoal, acacia charcoal and commercial charcoal. The specific details of the tests are discussed below.

Design results of mobile, smokeless charcoal furnace

The review of general literature identified there was no currently available mobile, smokeless charcoal furnace. Furthermore, there was a lack of information concerning the structural system, heating system, ventilation system, mobile capabilities, power transmission system and materials used in the construction of such a furnace, as presented in Fig. 3. The design results to operate a smokeless charcoal furnace involved lighting a fire at the bottom of the stove. Then, as the heat rises, it heats the wood, which initially releases moisture until the there is sufficient heat to produce white smoke, which is combustible. As burning continues, the wood is completely ignited and then a pipe is placed to allow the smoke to exit and condense into wood vinegar. This process ensures that no white smoke is emitted, making it safe to burn charcoal near community areas.

Fig. 3 Mobile, smokeless charcoal furnace

Based on the test results and observations under a microscope at a magnification of 260×, it was evident that the charcoal consisted of irregular cells and had a high degree of porosity. Notably, these characteristics varied among different types of charcoal. For example, the bamboo charcoal had minimal pores, in contrast to the acacia and commercial charcoals available from the market, both of which exhibit a higher degree of porosity. The numerous pores in charcoal are a result of the arrangement of sheets of carbon atoms. These sheets are arranged in a rather disordered manner and they are interconnected by chemical bonds, albeit sporadically. While some sections exhibit adhesion, other parts are not firmly attached to each other. Hence, there are various-sized gaps between these structural plates (Mathieson et al., 2012; Tazebew et al., 2023). There are numerous small nooks and crannies present, resulting in a structure with many pores.

This porous nature contributes to the charcoal's lower heat output. Unfortunately, it was not possible to precisely determine the size of these pores as Rajamangala University of Technology Thanyaburi lacks a microscope with the required magnification power to measure the pore size in detail, as presented in Fig. 4.

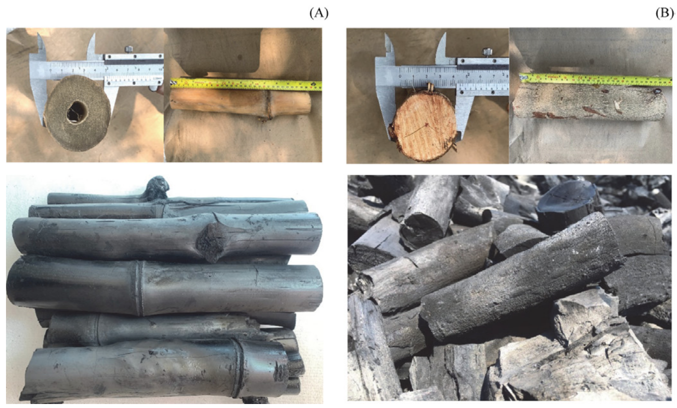

Fig. 4 Preparation of charcoal raw materials, including measuring the length and diameter of bamboo and samples of the charcoal for: (A) bamboo; (B) acacia tree

From the XRD test result images, it was evident that the bamboo charcoal had a lower peak value (64°) compared to the acacia wood and commercial charcoal, which both had higher peak values. Fig. 5 indicates that bamboo charcoal contained the least amount of ash. X-ray diffraction was used to analyze the charcoal compounds. This technique utilizes X-rays to analyze and identify compounds based on the crystal structure of the compounds present in the charcoal. In addition, a microscope with a magnification of 260× was used in the analysis. Fig. 6 presents the method applied to determine the heating value of charcoal, involving using 1 L of water that was boiled and the time required for this process while assessing the weight of 1 kg of charcoal. This approach was standardized for all three types of charcoal: bamboo charcoal, acacia charcoal and commercial charcoal. In addition, the method measured the temperature of the charcoal immediately after ignition and recorded the temperature of the charcoal when the water reached its boiling point (Zhu et al., 2014; Oduor et al., 2019).

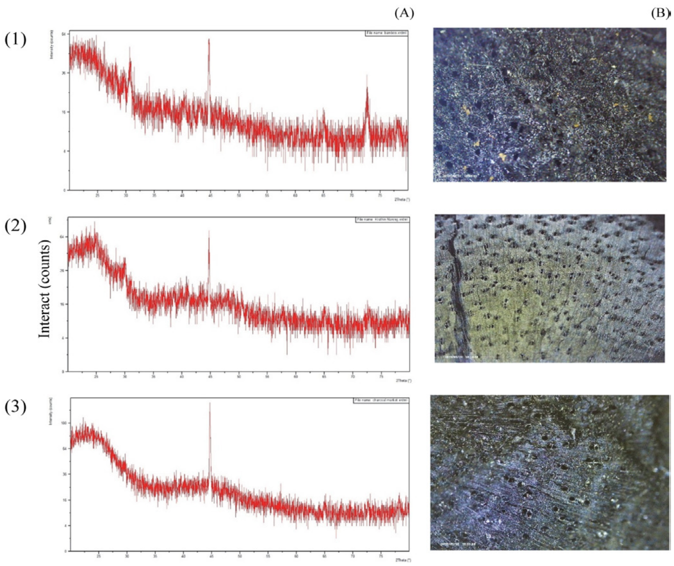

Fig. 5 Comparison of performance of ordinary charcoal and charcoal in mobile, smokeless charcoal furnace: (A) X-ray diffraction; (B) porosity measurements using X-ray diffraction; (1) bamboo charcoal; (2) activated acacia charcoal; (3) commercially available activated carbon

Fig. 6 Temperature measurement using infrared thermometer (-50 °C to 550 °C)

Table 1 shows that the bamboo charcoal had highest heating value (550°C), coupled with a low moisture content and a minimal amount of ash. Additionally, it took approximately 3.37 min for the water to reach boiling point. The acacia charcoal had a heating value of 496°C and like the bamboo charcoal, the acacia charcoal had a low moisture content and produced a small amount of ash. It took approximately 6.20 min for the acacia charcoal to boil the water. The commercially available charcoal had a heating value of 482°C and moderate levels of moisture content and ash content, taking 11.00 min to boil water. In terms of the efficiency of the bamboo charcoal, it was notable for having the highest heating value and a prolonged usage duration (lasting twice as long as the other types of charcoal tested), while being cost-effective due to its extended usability and resistance to breakage and explosions. The bamboo charcoal produced no smoke as it has a low moisture content, and it was odorless as it consisted of solely 100% natural materials without any chemicals (Berenschot et al., 1988; Bian et al., 2012).

Charcoal production duration

Experimental results of burning charcoal using mobile, smokeless charcoal furnace

The initial weight of the wood was approximately 60 kg and the initial moisture content was approximately 33.3%, as detailed in Table 2. It can be determined from Table 2 that increasing the burning hours would greatly increase the amount of wood vinegar obtained.

Table 2 Bamboo and acacia charcoal activated with moisture content of 33.3%

Properties of charcoal production	Material for producing charcoal	
	Bamboo	Acacia
Weight of wood (kg)	60	60
Calorific value of dried wood (J/g)	7160	7125
Charcoal product weight (kg)	32	34
Charcoal heating value (MJ/kg)	28.29	30.09
Product heat energy (MJ)	905.28	962.88
Charcoal yield (%)	59.77	63.57
Energy conversion efficiency (%)	97	95
Total time (hr)	5	5
Amount of wood vinegar products (L/hr)	0.64	0.72

Table 1 Experimental results of different charcoals based on time to boil water using 1 kg of charcoal and 1 L of water

Charcoal	Charcoal temperature as water was boiling (°C)	Moisture content (%)	Amount of ash	Boiling time (min)
Bamboo charcoal	550	7	Low	3.37
Acacia charcoal	496	7	Low	6.20
Commercial charcoal	482	11	Moderate	11.00

From Table 3, using 1 kg of charcoal, the bamboo charcoal requires 2.12 hr, the acacia charcoal required 1.38 hr and the commercial charcoal required 1.13 hr to boil the 1 L of water (Chien et al., 2011; Idris et al., 2012). These measurements were taken using an infrared thermometer with a range of -50°C to 550°C, as presented in Fig. 6.

Table 3 Composition of wood charcoal from bamboo and acacia wood, obtained from burning in a mobile, smokeless charcoal furnace

Composition of charcoal produced	Material for producing charcoal	
	Bamboo	Acacia
Moisture content (%)	12	8
Charcoal product weight (kg)	32	34
Fixed carbon (%)	63.08	72.93
Ash (%)	4.82	6.51
Volatile matter (%)	8.64	20
Volume of smoked vinegar products (L)	3.20	3.60
Acidity (pH)	6.72	7.16
Specific gravity (kg/m^3)	1.61	1.84
Average combustion test		
Smoke	Burnt with smoke emitted	Burnt with smoke emitted
Carbon (C)	48.90	56.54
Hydrogen (H)	7	8.09
Gas calorific value (MJ/kg)	18.72	17.52

Machine performance

According to Table 4, it was found that burning time significantly affects the weight of charcoal produced by both mobile, smokeless charcoal furnace and traditional clay furnace at a 95% confidence level. As the duration of the burning process increases, the amount of charcoal produced also increases. When comparing the two methods, the mobile, smokeless charcoal furnace yields a higher amount of charcoal than the traditional clay furnace for the same burning duration. The correlation coefficients (r) between the burning time and charcoal weight produced by the mobile, smokeless charcoal furnace and the traditional clay furnace are 0.945 and 0.979, respectively.

Table 4 Quantity of charcoal obtained from a mobile, smokeless charcoal furnace compared with a traditional clay furnace at varying burning times

Burning times (hr)	Charcoal weight (kg)	
	Mobile smokeless charcoal furnace	Traditional clay furnace
5	32.00±2.00^b	13.00±1.00^a
10	30.00±1.00^b	20.00±2.00^a
20	60.00±2.00^b	50.00±5.00^a
30	120.00±10.00^b	100.00±2.00^a

Mean±SD in each row superscripted with different lowercase letters are significantly ($p < 0.05$) different.

Fig. 7 illustrates the relationship between burning time and weight of the charcoal acquired. It was evident from the graph that the combustion characteristics obtained from the mobile, smokeless charcoal furnace differed from those of the clay furnace. Over time, there was a noticeable trend of increased charcoal weight for each type of furnace, with the weight of charcoal from the mobile smokeless charcoal furnace showing a more pronounced increase compared to the clay furnace (Dhamodaran et al., 2006; Biswas and Mahanta, 2013).

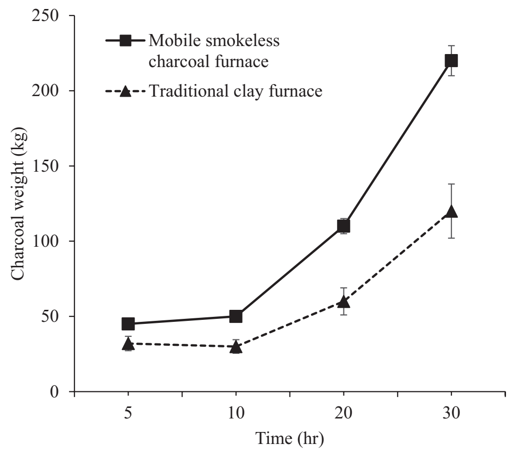

Fig. 7 Machine performances of mobile, smokeless charcoal furnace and traditional clay furnace

Characteristics of wood vinegar derived from charcoal production process

Table 5 illustrates the correlation between temperature differences and their impact on the volume of wood vinegar produced from the two different types of raw material. The temperature at which the collection of wood vinegar commenced was within the range of 200°C to 350°C and this collection occurred while the charcoal had an initial weight of 60 kg (Prianto et al., 2020; Jusoh et al., 2021).

Table 5 The volume of wood vinegar produced from bamboo and acacia at different temperatures

Temperature at which wood vinegar was collected (°C)	Volume of wood vinegar (L)	
	Bamboo wood	Acacia wood
200	13.04±0.04^b	3.42±0.02^a
240	13.65±0.05^b	4.80±0.20^a
250	13.80±0.10^b	5.00±0.10^a
280	14.84±0.04^b	5.80±0.10^a
300	15.12±0.02^b	6.67±0.07^a
350	16.83±0.03^b	6.84±0.04^a

Mean±SD in each row superscripted with different lowercase letters are significantly ($p < 0.05$) different.

Temperature affects the volume of wood vinegar produced. As the temperature increases, the amount of wood vinegar collected also increases. When comparing the two types of wood at the same temperature, bamboo wood produces a greater volume of wood vinegar than acacia wood. The correlation coefficients (r) between temperature and the volume of wood vinegar produced from bamboo wood and acacia wood are 0.980 and 0.973, respectively.

Wood vinegar obtained from burning charcoal was reddish-brown or yellowish-brown in color. Wood vinegar was collected when the charcoal was at a temperature of 200°C. The initial burning temperature at the start of collecting the wood vinegar did not impact the volume obtained. However, the burning duration did affect this, as a longer burning time resulted in a greater volume of wood vinegar being collected as shown in Table 5.

Comparative graphs are provided for the moisture profile of charcoal obtained from bamboo and acacia subjected to varying temperatures and burning times (Fig. 8), based on an initial wood moisture content of 33.3% and 60 kg of material (Sangsuk et al., 2018; Than and Suluksna, 2018).

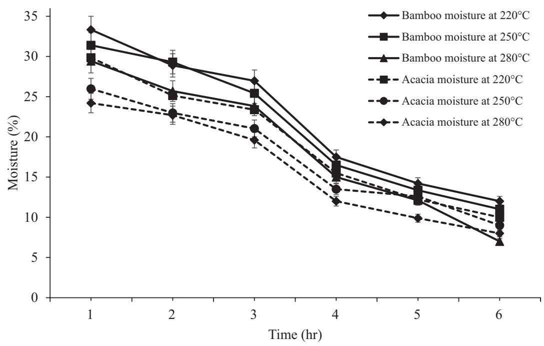

Fig. 8 Moisture profile of charcoal obtained from bamboo and acacia subjected to varying temperatures and burning times

Temperature and burning time significantly affect the moisture content at the 95% confidence level. As the temperature increases, the moisture content decreases, as shown in Tables 6 and 7. The correlation coefficients (r) between the moisture content and burning time for bamboo wood at 220°C, 250°C, and 280°C are -0.978, -0.978, and -0.984, respectively. For acacia wood, the correlation coefficients are -0.984, -0.978, and -0.971, respectively.

Engineering economy

Based on the test results, the mobile, smokeless charcoal furnace could be operated using a single person. The work expenses were calculated by considering both fixed and variable costs (Partey et al., 2017; Siyoum et al., 2022). The calculation was based on Equation 4:

1) Fixed cost

Depreciation (DP) was calculated using the straight-line method, as shown in Equation 4:

$$DP = \frac{P\text{-}S}{Lf} \tag{4}$$

where P is the price of machinery and S is the selling price or residual value of machinery both measured in US dollars and Lf is the useful life of the machinery, measured in years.

The price of the mobile, smokeless charcoal furnace was USD 392.16, with the residual (scrap) value of the furnace at the end of the fifth year assumed to be 10% of the original price. The scrap value (S) $= \frac{10}{100} \times 392.16$ = USD 39.22 and depreciation (DP) $= \frac{392.16\text{-}39.22}{5}$ = USD 70.59.

Table 6 The moisture content (%) of bamboo wood at different burning times (1, 2, 3, 4, 5 hr) and temperatures (220°C, 250°C, and 280°C)

Temperature (°C)	Time (hr)	Moisture content (%) 1	2	3	4	5	6
220		33.33±0.33^{l}	28.89±0.89^{j}	26.97±0.97^{i}	17.50±0.50^{f}	14.21±0.21^{de}	12.00±1.00^{bc}
250		31.39±0.39^{k}	29.30±0.30^{j}	25.42±0.20^{h}	16.50±0.10^{f}	13.36±0.36^{d}	11.00±1.00^{b}
280		29.43±0.43^{j}	25.69±0.01^{h}	23.83±0.03^{g}	15.00±1.00^{e}	12.10±0.10^{c}	7.00±1.00^{a}

Mean±SD in each row superscripted with different lowercase letters are significantly ($p < 0.05$) different.

Table 7 The moisture content (%) of acacia wood at different burning times (1, 2, 3, 4, 5 hr) and temperatures (220°C, 250°C, and 280°C)

Temperature (°C)	Time (hr)	Moisture content (%) 1	2	3	4	5	6
220		29.85±0.05^{l}	25.14±0.14^{gk}	23.38±0.08^{hi}	15.50±0.50^{e}	12.21±0.21^{c}	10.00±1.00^{b}
250		25.98±0.40^{k}	22.98±0.40^{h}	21.04±0.04^{g}	13.50±0.50^{d}	12.61±0.61^{cd}	9.00±1.00^{b}
280		24.20±0.20^{ij}	22.69±0.69^{h}	19.60±0.60^{f}	12.00±1.00^{c}	9.89±0.40^{b}	8.00±1.00^{a}

Mean±SD in each row superscripted with different lowercase letters are significantly ($p < 0.05$) different.

The interest on investment was calculated using Equation 5:

$$I = \frac{p+s}{2} \times \frac{i}{100} \quad (5)$$

where I is the interest on investment, p is the price of the mobile, smokeless charcoal furnace, and S is the scrap value.

The annual interest rate was set at 10%; therefore, annual interest = $\frac{392.16+39.22}{2} \times \frac{10}{100}$ = USD 21.57/yr.

2) Total fixed cost = 70.59 + 21.57 = USD 92.16/yr

The repair and maintenance cost averaged USD 0.28/d for 300 working days/yr = 0.28 × 300 = USD 84.03/yr.

The labor cost = USD 10.08/d/worker for 300 working days/yr = 10.08 × 300 × 1 = USD 3,025.21 /yr.
Hence, the total variable cost = 84.03 + 3025.21 = USD 3,109.24 /yr.

The operating cost of the mobile, smokeless charcoal furnace for 1 yr based on operating for 2,400 hr and a working capacity of 7 kg/hr = $\frac{3109.24+92.16}{2,400 \times 7}$ = USD 0.19/kg.

3) Payback period of mobile, smokeless. charcoal furnace

The variable costs consisted of the sum of repair and maintenance costs plus labor costs. Total costs encompassed variable costs and interest. Benefits received were computed by multiplying the hourly wage by the number of hours worked per year. Net benefit was defined as the difference between the benefits and the total costs. The payback period was defined as the quotient of purchase price of the machinery and net benefit, as detailed in Table 8 (Samseemoung et al., 2024).

Table 8 Construction cost for mobile, smokeless charcoal furnace

Part	Price (USD)
200 L fuel tank	42.02
Square pipe	112.04
Steel sheet	28.01
Iron wheel	39.22
Steel tube	28.01
Equal angle steel	14.01
Grinding wheel/cutting wheel	14.01
Spray paint	14.01
Gear and chain	44.82
Round shaft	28.01
Ball bearings	28.01
Total cost	392.16

For working hours of 2,400/yr, interest at USD 21.57/yr and a variable cost of USD 3,109.24/yr, the total cost = 3109.24 + 21.57 = USD 3130.81/yr; the benefit received = 2,400 × 45 × 0.20 = USD 21,176.47/yr, the net benefit = 21176.47 – 3130.81 = USD 1,8045.66/yr and the payback period = $\frac{392.16}{18045.66} \times 12$ = 0.26 mth.

4) Break-even analysis (Equation 6)

$$\text{Break even point} = \frac{\text{Fixed cost}}{\text{(Daily wage - Operating cost)}} \quad (6)$$

For fixed *costs* = USD 92.16, labor costs = USD 0.18 /kg, charcoal production capacity = 7 kg/hr, daily wage = 1.26×7 = USD 8.82/d, then the operating cost of the mobile, smokeless charcoal furnace = 0.18×7 = USD 1.26/hr.

Therefore, break even usage = $\frac{92.16}{8.82-1.26}$ = 12.19 hr/yr or approximately 12 hr/yr.

Conclusions

Based on the test results the mobile, smokeless charcoal furnace could function as intended with 200 L capacity, 2 tanks and a power transmission unit, including gears, chains, and a condensing system. It could operate at a rapid, continuous pace, thus saving time and labor in the charcoal production process. The design of the furnace enabled the smoke generated during charcoal production to be re-burned, ensuring that the wood was completely consumed and minimizing heat loss. This design effectively reduced the remaining smoke from combustion to a minimum, contributing to reduced air pollution. This in turn, promoted the health of the individuals involved in charcoal production and those in the vicinity, helping them to avoid respiratory diseases. Additionally, the furnace conserved fuel during each charcoal-burning session, resulting in a higher charcoal yield compared to previous methods and thus increasing the income from each charcoal production cycle. The advantages of the designed furnace are: 1) reduced air pollution from burning charcoal; 2) promotion of careers in charcoal production for commercial sale and increased income; and 3) enhanced energy utilization potential, with the capacity to process 7 kg/hr. Each charcoal production session lasted 5 hr, with an extra 15 min for charcoal removal from the furnace. The results of the engineering economic analysis indicated that the operating cost was USD 0.18/kg. The break-even point, assuming 12 hr of operation annually, resulted in a payback period of approximately 0.26 mth or about 0.021 yr. The mobile, smokeless charcoal furnace offered superior charcoal efficiency and a higher charcoal quality compared to conventional clay charcoal production methods due to the designed furnace being able to yield 50% of the weight of the wood as charcoal, while a clay furnace only yielded 25% of the wood weight. The convenience of relocating the mobile, smokeless charcoal furnace was enhanced through the incorporation of wheels, allowing for easy movement of the furnace to various raw material locations. Additionally, a design feature facilitated the convenient storage of charcoal by creating a structure that could be lifted and emptied, making charcoal collection more convenient. Furthermore, this design reduced the need for as much raw material as a typical clay furnace to produce the equivalent amount of charcoal. This use of a thorough research process and applying the correct research methodology suggesting that academic advancements could be relevant to the implementation of intelligent precision agriculture. Notably, this study provided in-depth analysis, presenting research findings as new knowledge beyond the original work and that can be widely utilized to assess the benefits of an aging economy and society.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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