OPTIMIZING CHARCOAL PRODUCTION: A COMPARISON OF THREE WOOD SPECIES AND METHODS

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Received: 09 February 2023, Revised: 26 May 2023, Accepted: 02 January 2024

OPTIMIZING CHARCOAL PRODUCTION: A COMPARISON OF THREE WOOD SPECIES AND METHODS. For sustainable forestry management and environmental protection, it is crucial to compare three wood types and processes in order to optimise charcoal production. The purpose of this study was to evaluate the viability of using diverse waste materials and carbonization techniques to produce wood charcoal. The upcountry wet zone and low-country dry zone regions of Sri Lanka provided the samples, which were each repeated ten times and came in three different sample sizes. To make charcoal, these samples were put through the barrel and pit processes. The results showed that the barrel method produced 28% charcoal instead of the 21% produced by the pit method, demonstrating its higher efficiency and cost-effectiveness. This improvement was ascribed to the barrel's enhanced ability to regulate airflow and temperature during pyrolysis. The study emphasizes the use of wood off-cuts and the barrel method to increase efficiency, save costs, and improve charcoal quality. It provides helpful advice for small charcoal producers.

Keywords: Barrel method, charcoal, off cuts, pit method

OPTIMASI PRODUKSI ARANG: PERBANDINGAN TIGA JENIS KAYU DAN METOD. Untuk pengelolaan hutan berkelanjutan dan perlindungan lingkungan, penting untuk membandingkan tiga jenis dan proses kayu guna mengoptimalkan produksi arang. Tujuan dari penelitian ini adalah untuk mengevaluasi kelayakan penggunaan beragam bahan limbah dan teknik karbonisasi untuk menghasilkan arang kayu. Daerah zona basah pedalaman dan daerah dataran rendah kering di Sri Lanka menyediakan sampel, yang masing-masing diulang sepuluh kali dan datang dalam tiga ukuran sampel berbeda. Untuk membuat arang, sampel ini dimasukkan melalui proses tong dan lubang. Hasilnya menunjukkan bahwa metode barel menghasilkan 28% arang dibandingkan dengan 21% yang dihasilkan metode lubang, sehingga menunjukkan efisiensi dan efektivitas biaya yang lebih tinggi. Peningkatan ini dianggap berasal dari peningkatan kemampuan laras untuk mengatur aliran udara dan suhu selama pirolisis. Kajian tersebut menekankan penggunaan metode potongan kayu dan metode tong untuk meningkatkan efisiensi, menghemat biaya, dan meningkatkan kualitas arang. Laporan ini memberikan saran yang bermanfaat bagi produsen arang kecil.

Kata kunci: Metode tong, arang, potongan kayu, metode lubang

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 doi:10.59465/ijfr.2024.11.2.139-153

I. INTRODUCTION

Wood has intertwined itself with the story of humanity, serving as a vital companion since the dawn of our existence. From the earliest sparks of civilization, humans have embraced this versatile resource, shaping its essence to fulfil our most fundamental needs. Humans have used wood for the construction of tools, machinery, furniture, fuel wood, and charcoal (Olorunnisola, 2023). Lightweight black carbon made by burning wood with minimal air which is known as Charcoal can be the best domestic fuel (Fraga et al., 2022). Almost any organic material, including wood, straw, coconut shells, rice husks, and bones, can be used to make charcoal (Nyemba et al., 2018). The hardwood types of wood such as acacia and mangroves are typically selected for manufacturing charcoal. The largest production can be found in Nigeria, Ethiopia, and Brazil but coconut shells are commonly applied in Sri Lanka (Allué et al., 2021). In the past, charcoal was an important fuel for metalworking. With the introduction of coal and raw coal for the smelting of iron, charcoal lost almost all of its importance and was only used as fuel in a specific metallurgical process where a higher fuel purity was needed (Crewe, 2020).

The need for technological innovation in charcoal production will be important and should be encouraged in areas where there is a significant demand for better quality (charcoal with a higher carbon content) for industrial uses. In many cities and towns, charcoal is needed for industrial and commercial uses as well as for domestic use as fuel (e.g., cooking and food processing) (Borowski, 2021). Charcoal production optimization in existing charcoal production techniques needs to be improved for both quality improvement and better production recoveries (Gebremariam & Marchetti, 2018). Wood charcoal makes a great fuel at home, and it can also be used to create bioenergy. Plus, even things like leaves and food scraps can be turned into charcoal. Wood charcoal is the most important commercial fuel derived from wood. Charcoal, a lightweight black carbon made from burning wood or other organic matter, falls into distinct types based on source and purpose: wood charcoal for fuel, industrial charcoal from coal or shells, and activated charcoal for purification. Wood charcoal is used as a domestic fuel for cooking and heating in many developing countries. Its advantages when used as a domestic fuel are that it produces less heat while burning, has a higher energy content per unit mass, can be easily transported and stored, and can be reused after cooking (Woolley et al., 2020). Charcoal production relies on thermochemical conversion through slow pyrolysis or carbonization, both under limited oxygen. Slow pyrolysis, in this method slowly heats biomass (mostly wood) in closed ovens to around 400-500°C, driving off volatile gases and leaving behind charcoal. It creates high-quality charcoal with high fixed carbon content.

Carbonization involves heating biomass in earth pits, kilns, or retorts to even higher temperatures (up to 800°C) with minimal air access. While faster than slow pyrolysis, it often yields lower quality charcoal with more ash and impurities. The specific process and temperature range used depends on the charcoal type being produced and the desired properties. Some methods also utilize byproducts like wood tar and pyroligneous acid. Wood is burned in sealed kilns or retorts, chambers with different gases and controlled and regulated airflow to create charcoal. By all methods, high-temperature heating transforms the wood into gases, a liquid tar combination and the well-established solid carbon compound known as charcoal (Zeng et al., 2017).

Despite the general trend away from using charcoal as a fuel for producing iron, some countries, most famously Sweden which has a large amount of native forest land and no coal, continued to use charcoal to produce the highest-quality iron and steel products well into the 20th century. Earlier this century, Sweden stopped producing charcoal iron due to a number of reasons including depleted forest supplies, higher labor expenses in rural areas, and easily available, cheap hydroelectric power. The second part of the country is where most developing markets with young steelmaking industries have discovered the advantages of melting iron in simple, reduced blast furnaces that burn charcoal as fuel (Cottrell, 2019). Waste wood has historically served as the primary raw material source for charcoal manufacture. A number of regularly wasted forestry and agricultural wastes appear to be potential major raw materials for the production of charcoal, considering that wood sources are frequently limited (Asare, Owusu & Gazo, 2022). Analyze wood species' charcoal quality, crowning the champion to guide lab selection and market decisions. (Kongprasert et al., 2019).

The characteristics of charcoal made from waste of wood species were being studied and the quantity and quality of the charcoal produced were evaluated. Ash content, moisture content, volatile matter, fixed carbon, and calorific value were collected from the selected species in order to determine the characteristics of charcoal yield. Eucalyptus charcoal stood out with the highest fixed carbon content (70%) and calorific value (22.5 MJ/kg), indicating its potential for generating more heat and lasting longer (Protásio et al., 2017). Charcoal's high volume and low value per unit of weight make it akin to transporting cotton balls versus diamonds. While a truckload of cotton balls might be less valuable than a handful of diamonds, the cotton balls would occupy significantly more space. For this reason, long-distance transportation may not be cost-effective without special containers or further compression to produce hardwood charcoal (Bao et al., 2019).

Charcoal yields can fluctuate dramatically due to seemingly minor variations in production. The pace of heating, the size and moisture content of the wood, and the precise temperature spectrum during the burn can all subtly influence the final output. Like a recipe with delicate measurements, even slight changes in these parameters can yield surprisingly different outcomes. Additionally, there are inevitable variations in fuel volume, moisture content, and energy value estimation (Motta et al., 2018). Charcoal flies under the domestic radar, possibly due to folks' thin wallets. To meet their domestic cooking fuel requirements, people frequently look for free supply sources. Such areas won't have any potential for charcoal production or trade so, it should not be promoted (Doggart & Meshack, 2017). Navigating the present crisis requires overcoming significant hurdles in importing LPG, from battling currency shortages and soaring fuel costs to confronting logistical bottlenecks and the looming risk of a burdened consumer and a shadowy black market. Alarming recent practices to fill domestic energy gaps call for immediate action. We must move beyond these shadowy solutions and embrace the sunshine of green energy options. The already identified environmentally friendly charcoal production offers a beacon of hope, paving the way for a sustainable future fuelled by responsibility and cleaner horizons.

Considering the fact that supplies of wood are often limited, a variety of agricultural and forestry residues that often remain unused appear to be potentially important raw materials for charcoal production. In 2020, Sri Lanka exported $ 28.1M making it the 100th largest exporter of wood charcoal in the world (Cornot-Gandolphe, 2017). In the same year, wood charcoal was the 42nd most exported product in Sri Lanka. From tea wood in Middle East markets to Chinese logs crossing oceans, global wood destinations dance to the tune of species and shifting economic winds (Alvesdias et al., 2018). In order to ascertain the most appropriate strategy for sustainable and economical charcoal production, a thorough investigation should be carried out to compare the efficacy of teak root, off-cut, and Eucalyptus spp. waste timber materials for wood charcoal production. Additionally, the efficiency of various production methods should be assessed, and the cost-benefit ratio should be examined.

II. MATERIAL AND METHOD

A. Study Area

Sri Lanka State Timber Corporation (SLSTC) is a government-owned organization responsible for managing and controlling the country's timber resources. It was established in 1979 and operates under the Ministry of Mahaweli Development and Environment. SLSTC is responsible for logging, processing, and marketing of timber products, as well as reforestation and afforestation efforts in Sri Lanka. The corporation also manages and maintains several forest reserves and national parks in the country. This study was carried out at the State Timber Complex in Boossa (6°0"60"N 80°1'80"E) and the State Timber Corporation's Boralanda depot (6°4'24"N 80°9'28"E).

B. Waste Wood Samples Selection

The selection of waste wood samples for analysis depends on the specific research or study being conducted. However, there are a few general guidelines that should be followed when selecting waste wood samples such as representativeness in which the samples should represent the waste wood population being studied. This means that the samples should be randomly selected from different sources, such as different types of wood or different stages of decay. Storage and handling: the samples should be properly stored and handled to avoid contamination or degradation during transportation or storage. In this study, different wood waste materials were selected from the low-country dry zone and upcountry wet zone areas which are upstream of Sri Lanka with consideration above factors (Table 1). Three samples were gathered and replicated three times for the study's sample size. In the end, samples were burned and charcoal was gathered utilizing two different techniques, including the pit and barrel methods.

C. Collection of Waste Wood Samples

The samples should be collected using a method that is appropriate for specific research or study. For example, if the study is focused on the chemical composition of the waste wood, small core samples may be collected. If the study is focused on the physical properties of the waste wood, larger samples may be

Table 1. Selected waste offcut timber species for the experiments

No	Botanical name	Common name	Family
1.	*Azadirachta indica*	Margosa	Meliaceae
2.	*Artocarpus heterophyllus*	Jack	Moraceae
3.	*Eucalyptus grandis*	Grandis	Myrtaceae
4.	*Swietenia macrophylla*	Mahogany	Meliaceae
5.	*Tamarindus indica*	Tamarind	Fabaceae
6.	*Tectona grandis*	Teak	Lamiaceae
7.	*Terminelia arjuna*	Kumbuk	Combretaceae

Figure 1. Waste wood samples, A- Sample of *Eucalyptus* spp.; B- Sample of teak root; C- Sample of offcuts according to Table 1.

collected. By considering the above factors waste wood samples small sized for chemical composition and big offcuts were used to identify the physical factors were collected from the furniture factory in State Timber Complex Boossa and Boralanda Timber depot (Figure 1).

D. Charcoal Production Methods

I) Barrel method

The barrel method for charcoal production utilized two nested metal barrels. The larger barrel acted as a kiln, while the smaller held tightly packed hardwood. A fire in the larger barrel heated the wood within the smaller one to around 450-500°F (232-260°C) for several hours, driving out water and gases and leaving behind pure carbon to make the charcoal.

II) Pit method

In the pit method of charcoal production, a dug hole was lined with wood, ignited at one end, and then tightly sealed with layers of soil and leaves. This created a smothering environment where the wood slowly carbonized without burning away entirely. Monitoring for cracks and maintaining temperature through ventilation holes was crucial throughout the process, which can take a day or two. Once the smoke stopped and the pit cooled, the resulting charcoal was then unearthed.

E. Data Collection

All the produced charcoal from samples of *Eucalyptus* spp. teak root, and wood offcuts were tested by Industrial Technology Institute, Colombo 7, Sri Lanka. Data was collected on the moisture content, volatile matter, ash content, and fixed carbon, which were proximally resolved using the BS EN1860-2:2005 method and gross calorific value/kcal/kg using the ASTM D5865-13 test method (Benin et al., 2021).

III. RESULT AND DISCUSSION

A. The Yield of Charcoal

The physical properties of waste wood-charcoal production significantly varied among different species (Figure 3). Wood charcoal made from off-cuts of wood species recorded the highest yield of charcoal (28%) followed by Eucalyptus spp. (22%). Wood charcoal produced from Tectona grandis species showed the lowest yield of charcoal (14%). Pit and barrel processes can produce varying amounts of charcoal. Due to less regulated conditions, pit carbonization often has a lower yield, ranging from 15 to 25 percent of the initial biomass (Heidarinejad et al., 2020). The average yield of the three wood species (21.33%) is slightly higher than the average yield of pit carbonization (20%). Off-cuts of wood species (28%) significantly exceed the average pit carbonization yield. Tectona grandis (14%) is below the pit carbonization range, indicating it is less efficient even compared to the least efficient pit carbonization process. Better temperature control during barrel carbonization often results in increased yields of 20–30% of the original biomass (Heidarinejad et al., 2020). In this recent study, *Eucalyptus* spp. charcoal yield could reach 30%, Tectona grandis could reach 22%, and wood offcut obtained 35% of yield.

Figure 2. Charcoal production: A.Sketch of a barrel; B. Barrel method; C. Pit method

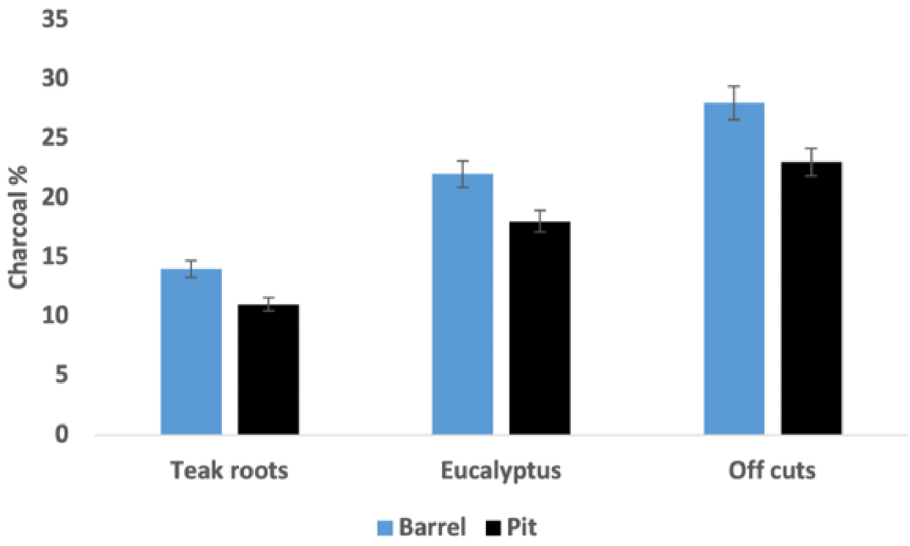

Figure 3. Charcoal yield of Barrel and Pit Method

Causal factors for low charcoal yield in barrel methods can include high moisture content, inadequate temperature control, limited oxygen supply, and wood density/species (Heidarinejad et al., 2020). The highest yield of charcoal production was given by offcuts due to the use of various high-density timber species such as *Azadirachta indica*, *Artocarpus heterophyllus*, *Swietenia macrophylla*, *Tamarindus indica*, *Tectona grandis*, and *Terminalia arjuna* (Hashim et al., 2015). It's also worth noting that the yield will also vary based on the type of wood used for example Teak roots charcoal production is low due to suboptimal. Hardwoods such as oak, hickory, and beech typically have higher charcoal yields than softwoods such as pine or spruce. Additionally, the moisture content of the wood will also affect the charcoal yield, with lower moisture content resulting in higher yields (Heidarinejad et al., 2020). The yield of wood-charcoal varies greatly depending on the species, with off-cuts offering the largest output. Because of the less controlled environment, pit carbonisation yields are typically lower and more variable. This emphasises the value of choosing particular wood species and maybe more controlled methods like barrel carbonisation for higher and more consistent yields.

B. Moisture Content

As seen in Figure 4, the moisture content of the resulting wood charcoal differed significantly between the samples. Charcoal made from Eucalyptus species had the highest moisture level (7%) whereas charcoal made from wood offcuts had the lowest moisture content (5%). The moisture percentage of charcoal derived from the wood species Tectona grandis was found to be 6%.

It is important to note that the moisture content in charcoal should be as low as possible, as high moisture content can lead to problems such as spontaneous combustion, decreased energy density, and difficulty to light (Darmstadt et al., 2000). It is also worth noting that the moisture content of charcoal can vary depending on the method of production and the type of wood used. Charcoal made from freshly cut wood or wood with a high moisture content will have a higher moisture content than charcoal made from seasoned wood or wood with a lower moisture content (Danish and Ahmad, 2018).

This is because the high content of moisture makes fine wood charcoal and lowers its calorific value (Yaseen et al., 2020). Open drying in the pit process might reduce the moisture content

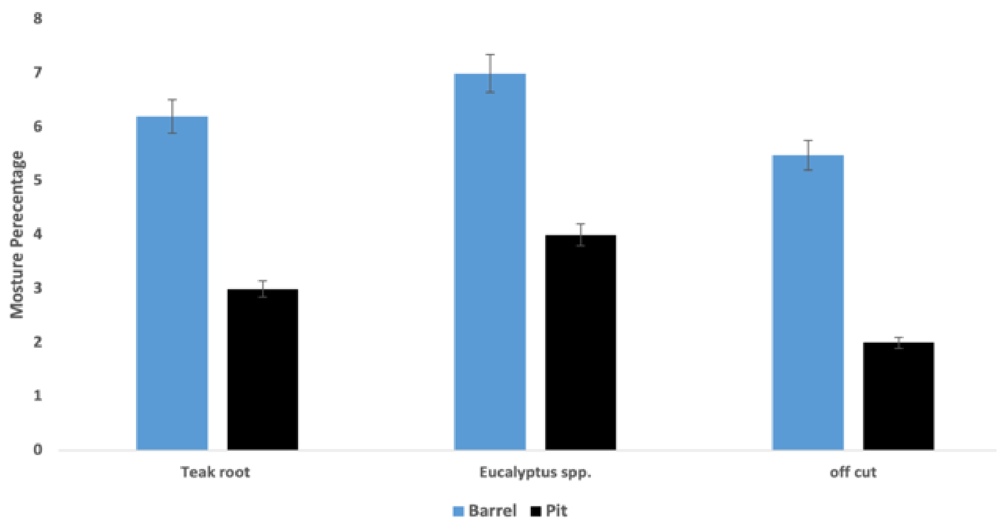

Figure 4. Moisture content percentage in the charcoal produced by barrel and pit method

of *Eucalyptus* charcoal from 7% to somewhere between 4% (Darmstadt et al., 2000). Similarly, *Tectona grandis* charcoal could reach a range of 3% moisture content, and wood offcuts might have their moisture level drop to as low as 2%. The moisture content values of wood charcoal manufactured from various wood species utilized for this study were within the acceptable criteria established by the FAO (1985) which stated that the highest limit for moisture content is 7% (FAO 1985). The average yield of the three wood species (21.33%) being slightly higher than the pit carbonization yield (20%) suggests that, on average, specific wood species can be slightly more efficient. Off-cuts of wood species (28%) provide a significantly higher yield, making them highly efficient. *Tectona grandis* (14%), however, falls below even the minimum efficiency of pit carbonization. The reduction in moisture content through open drying in the pit process further enhances the quality of the charcoal, making it more energy-dense and efficient. Therefore, selecting appropriate wood species and managing moisture content are crucial factors in optimizing charcoal production.

The moisture percentage in the pit and barrel method was not a fixed value, but rather a range that depended on the specific type of wood charcoal and the drying conditions. However, as a general rule of thumb, the moisture content of wood charcoal produced using the pit and barrel method is typically between 1-5% (Darmstadt et al., 2000). This is significantly lower than the moisture content of fresh wood, which can be as high as 50% (Darmstadt et al., 2000).

C. The content of Volatile Matter

The wood charcoal from *Eucalyptus* spp. had the highest volatile matter level at 17%, which was almost equal to *Tectona grandis*'s volatile matter content of 16.5%. On the other hand, Figure 5 shows that charcoal made from wood offcuts had the lowest volatile matter level, at 14%. Charcoal made from wood offcuts, *Tectona grandis*, and *Eucalyptus* species had a volatile matter percentage of 12%, 14%, and 15% in the pit method, respectively. Notably, charcoal made by the pit and barrel techniques might have different volatile matter contents. According to FAO (1985), wood charcoal can have a volatile matter percentage of anywhere from 5% to 40%. (FAO 1985). *Eucalyptus* spp. has the highest volatile matter content at 17%, closely followed by *Tectona grandis* at 16.5%. Wood offcuts have the lowest volatile matter content at 14%.

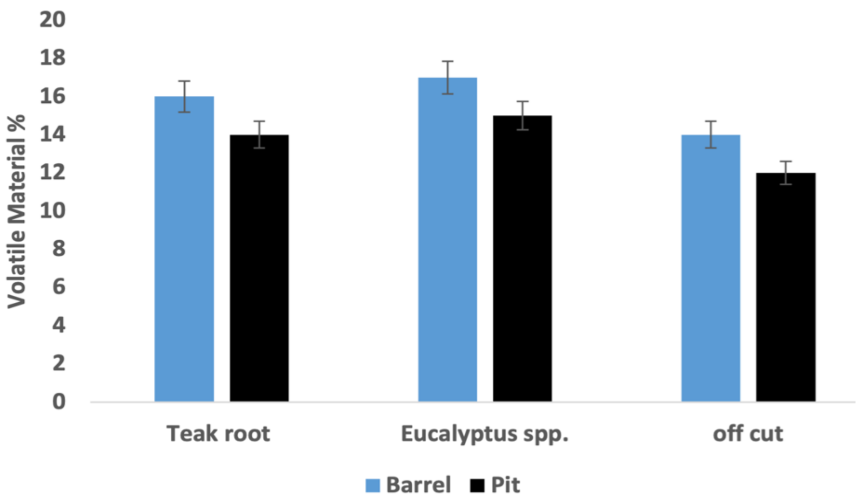

Figure 5. Volatile matter content of the charcoal in the barrel and pit method

The pit method generally reduces volatile matter content in all wood species. Wood offcuts show a reduction from 14% to 12% (2% decrease). *Tectona grandis* shows a reduction from 16.5% to 14% (2.5% decrease). Eucalyptus spp. shows a reduction from 17% to 15% (2% decrease).

Charcoal made from offcuts, or small pieces of wood that are left over from other woodworking processes, can have a higher volatile matter content than charcoal made from larger pieces of wood. Volatile matter is the portion of charcoal that is composed of gases and other volatile compounds that are released during the carbonization process. Offcuts usually have a higher volatile matter content due to their small size which causes an increase in the ratio of surface area to volume, leading to higher evaporation of volatile compounds. This can result in charcoal with a lower energy density and higher ash content. Additionally, offcuts may have a higher moisture content which also results in higher volatile matter(Ge et al., 2023).

It's worth noting that the volatile matter content of charcoal can also be affected by the method of production, with traditional pit methods generally producing charcoal with a higher volatile matter content than more modern methods such as retort kilns. Charcoal with higher volatile matter content is not always a disadvantage, as it can be used in certain industrial applications such as activated carbon production where the presence of volatile matter can be beneficial (Kumar et al., 2021).

The components of the biomass that are emitted as gases during carbonization are referred to as volatile matter. The charcoal produced by the pit method frequently has a greater volatile matter concentration due to slower carbonization and lower temperature control. As a result of superior temperature control, the barrel process typically results in charcoal that contains less volatile materials (Deenik, 2011). Regarding wood charcoal quality, low levels of volatile matter in wood charcoal are associated with higher lignin levels and lower extractive levels in the wood species (Massuque et al., 2021). The high value of the volatile matter in wood charcoal makes it light easily but may burn with a little smoke (Deenik, 2011). Charcoal with lower volatility is hard to ignite and burn cleanly. Moreover, higher volatile matter in wood charcoal is favored for some uses like barbecue, while other uses like purification of chemicals and metal production need wood charcoal with a lower content of volatile matter. Good commercial wood charcoal has a net content of volatile matter (moisture-free) around 30%. High-volatile wood (charcoal) is normally hard (Ahamad et al., 2020). The volatile matter other than water in charcoal comprises all those liquid and tarry residues not fully forced off in the carbonization process. If the time and temperature of carbonization increase, then the volatile matter content is low (Üner & Bayrak, 2018).

D. Ash Content

The ash contents were significantly different among the produced wood charcoals (Figure 6). In the barrel method, wood-charcoal of *Eucalyptus* spp had the highest value (13%), while wood-charcoal of *Tectona grandis* and offcuts showed low ash content values, each was 12% and 11%, respectively. In the pit method ash content was higher than in the barrel method which was 17.3% and was observed in *Eucalyptus* spp Claims that the presence of high mineral composition in wood is expensive because the minerals do not degrade after carbonization and remains in charcoal as undesirable residues that also contribute to a reduction in the calorific value of charcoal (Ahmad et al., 2020). The ash content of wood charcoal can vary from around 0.3 percent to 16 percent or more, depending on the wood species used to make the charcoal. High-quality wood charcoal has a content of about 3% (FAO, 1985). Fine wood charcoal may have a very high ash content; buyers naturally suspect fine wood charcoal, and it is unfortunately difficult to sell and use (Ahmad et al., 2020). Statistically, *Eucalyptus* spp. has the highest ash content, making it less desirable for charcoal production due to lower calorific value and higher residues. The barrel method is more effective in reducing ash content compared to the pit method, particularly for *Eucalyptus* spp. Wood offcuts are the best option among the species studied, as they produce charcoal with the lowest ash content, indicating higher quality and efficiency. The pit method results in significantly higher ash content (4.3% increase) compared to the barrel method.

Charcoal made in a pit or a barrel might have varying amounts of ash. Due to exposure to outside pollutants, the open-air carbonization process used in the pit method frequently produces greater ash contents. The barrel method, on the other hand, can provide charcoal with a lower ash level due to its regulated environment. Ash content in both techniques can be reduced through cautious handling and good feedstock selection. The ash content of charcoal typically ranges from 1-5%. The process of making charcoal involves heating wood in the absence of oxygen, which causes the wood to release its moisture, gases, volatile compounds, and mineral matter that don't burn and remain as ash. Factors that can affect ash

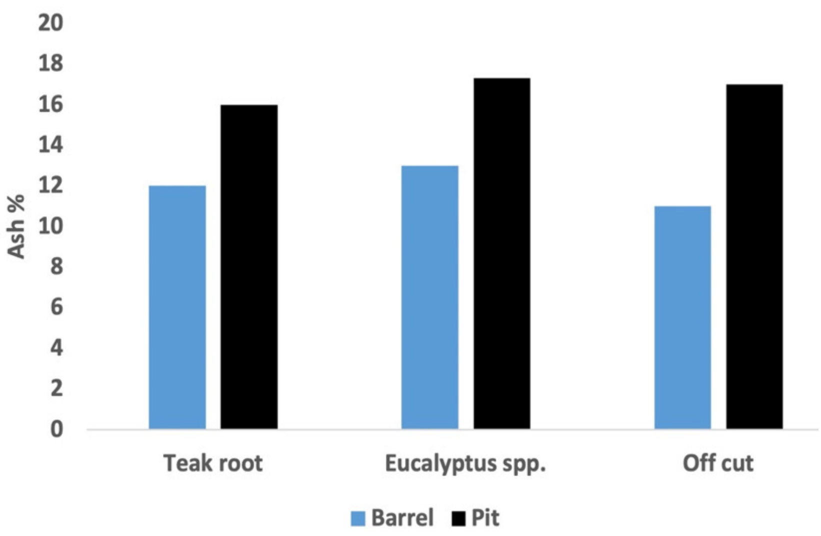

Figure 6. Ash content percentage in the charcoal produced by the barrel and pit method

content in charcoal include the type of wood used, the moisture content of the wood, and the method of charcoal production. Hardwoods such as oak, hickory, and beech typically have lower ash content than softwoods such as pine or spruce. Additionally, the moisture content of the wood will also affect the ash content, with lower moisture content resulting in lower ash content.

Charcoal made from offcuts also tends to have higher ash content. The ash content of charcoal can be important in certain applications such as metallurgy and ceramics where a low ash content is desirable, while in others like agriculture, the presence of certain mineral elements can be beneficial (Ramos et al., 2019).

E. Content of Fixed Carbon

There was a significant variance in the content of fixed carbon among the charcoal samples. In the barrel method, the highest fixed carbon was found in *Eucalyptus* spp. (82.7%), while the lowest was noticed in *Tectona grandis* (67.8%). Charcoal produced by offcuts showed a fixed carbon content of 78.8% (Figure 7). Wood charcoal has a fixed carbon content that ranges from a low of 50% to a high of roughly 95% (FAO 1985). Furthermore by the pit method of carbonization practices, *Eucalyptus* spp. 88.8%; *Tectona grandis*: 73.5%; and Offcuts: 84.7% were observed. Statistically, *Eucalyptus* spp. demonstrates the highest fixed carbon content, making it the best choice for efficient and high-quality charcoal production. The pit method further enhances the fixed carbon content for all species, with *Eucalyptus* spp. achieving the highest increase. *Tectona grandis* consistently shows the lowest fixed carbon content, indicating its lower suitability for high-quality charcoal production. The choice of wood species and carbonization method significantly impacts the fixed carbon content and, consequently, the quality and economic value of the charcoal produced. In determining the quality of the charcoal, high grades of fixed carbon and high grades of lignin combine with low grades of extractives and holocellulose in wood to provide better chemical attributes of charcoal (Do Rosário et al., 2020). By altering the carbonizing process's temperature and duration, the amount of fixed carbon might be adjusted. This method reduces the production of charcoal while simultaneously increasing the fixed carbon content of the wood charcoal (Ren et al., 2020).

The type of biomass utilized and the carbonization process are two variables that can affect the fixed carbon content of charcoal made using the pit and barrel method. However,

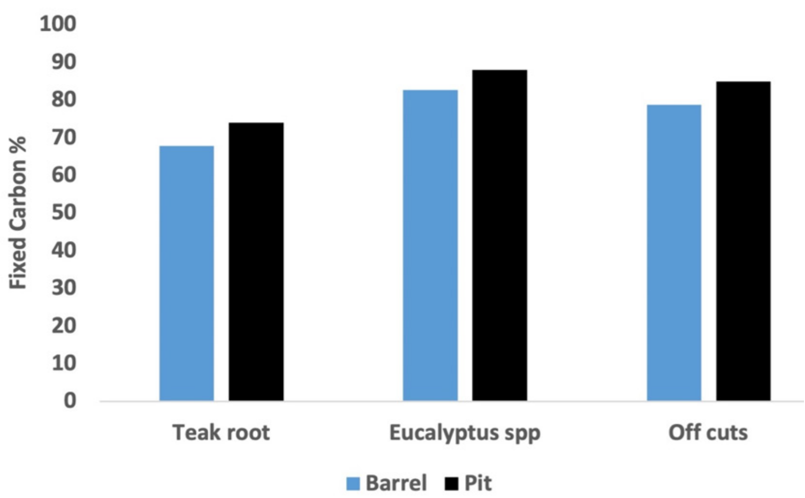

Figure 7. Fixed carbon content in the charcoals produced by the barrel and pit method

compared to charcoal generated using the barrel method, charcoal produced using the pit method may often have a lower fixed carbon content. The barrel method tends to encourage more carbonization and higher fixed carbon content due to its controlled temperature and oxygen supply. The fixed carbon content of charcoal is typically between 60-80%. Fixed carbon is the portion of the charcoal that remains after the volatile matter (gases and other volatile compounds) has been released during the carbonization process. It is called "fixed" because it is not released when the charcoal is heated. Fixed carbon content is an important characteristic of charcoal as it is directly related to the heating value of charcoal, meaning that charcoal with higher fixed carbon content will have a higher energy density and will produce more heat when burned (Ajimotokan et al., 2019).

The type of wood used, the moisture content of the wood, and the method used to produce the charcoal all affect its fixed carbon content. Hardwoods, such as oak, hickory, and beech, usually have a higher fixed carbon content than softwoods, like spruce or pine. Moreover, a higher fixed carbon content is generally correlated with lower wood moisture levels. Notably, the method of production can also affect the fixed carbon concentration; charcoal produced using conventional pit methods frequently has a lower fixed carbon percentage than charcoal produced using more contemporary techniques like retort kilns. Furthermore, charcoal made from leftovers often has a lower fixed carbon concentration.

F. Calorific Value

The calorific values of the charcoal were significantly different between different types of wood and between different producing methods with $P<0.05$ (Figure 8). The highest calorific value was noted in charcoal produced from *Tectona grandis* wood (7047 kcal/kg), followed by charcoal produced from *Eucalyptus* spp. (6848 kcal/kg) and wood offcuts (6755 kcal/kg0). However, although wood charcoal of *Tectona grandis* showed the highest calorific value, it had a higher production cost. The calorific values of charcoal produced by pit carbonization practices were 88.8%, 73.5%, and 84.7% each for *Eucalyptus* spp. *Tectona grandis*, and wood offcuts, respectively.

Wood offcuts had the lowest calorific values which presumably was due to their smaller size. The offcuts were mostly composed of roots and large root pieces were difficult to turn into charcoal, therefore, those pieces were cut into small pieces prior to the carbonization process. Although offcuts had the lowest calorific value,

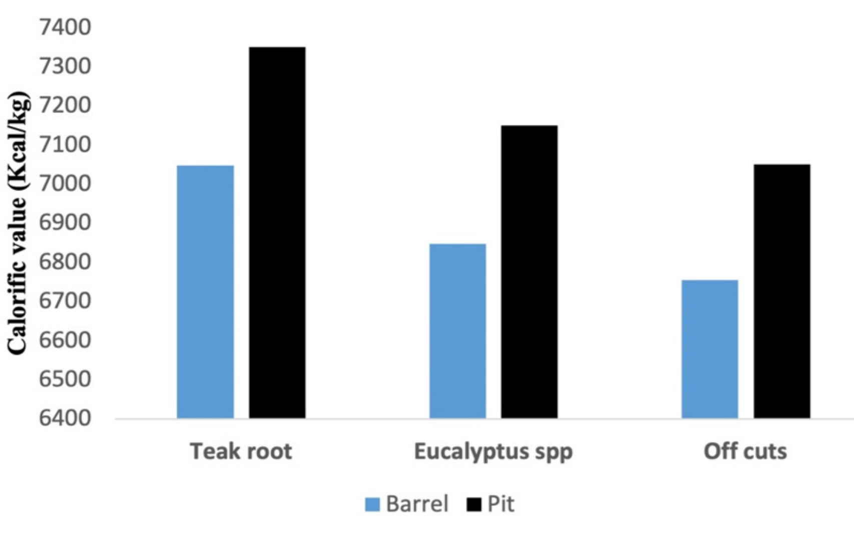

Figure 8. Calorific value of charcoals made by barrel and pit method

the chemical properties of the resulted charcoal were superior to those of other species, it also had a higher production percentage, the lowest moisture content, and the highest fixed carbon value.

The calorific value of charcoals made from different types of wood can vary depending on the specific type of wood used and the method of charcoal production. Hardwoods such as oak, hickory, and beech often have higher calorific values than softwoods like pine or spruce. This is explained by hardwoods' higher density, lower moisture content, and higher fixed carbon content, all of which add to their higher calorific value.

For example, charcoal made from oak has a calorific value of around 29,000-30,000 kcal/kg, while charcoal made from pine has a calorific value of around 25,000-27,000 kcal/kg (Qian et al., 2020). The calorific value of charcoal can also be affected by the method of production utilising more contemporary techniques, including retort kilns, creating charcoal with a higher calorific value than old pit processes.. Charcoal made from offcuts also tends to have lower calorific value. The calorific value of charcoal is important because it determines the amount of energy that can be released when the charcoal is burned. It is measured in units of energy per unit of mass and is often expressed in units such as kilocalories per kilogram (kcal/kg) or joules per kilogram (J/kg).

G. Effective Method of Charcoal Production

In the barrel method, the highest cost of wood charcoal production was from the root of *Tectona grandis* and the lowest was for *Eucalyptus* spp.

The yields and costs of producing charcoal varied significantly, according to the study. A 28% yield was obtained from the production of charcoal, and the cost of production was found to be minimal. There were notable variations in the amount of charcoal produced by the several wood species that were investigated.

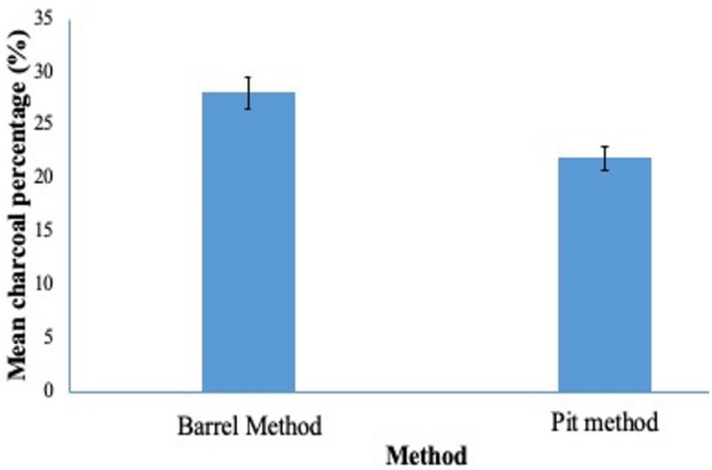

Figure 9. The yield of charcoal produced by the barrel and pit method

Table 2. Cost-effective analysis of charcoal production in barrel method

	Teak	mix-wood Offcuts	Eucalyptus offcuts
Production of Charcoal			
Weight (Kg)	896	523	1000
Partially burned charcoal (Kg)	20	12	35
Total Charcoal Production (Kg)	129	89	89

Table 2. Contunued

	Teak	mix-wood Offcuts	Eucalyptus offcuts
Cost			
Teak root transport/loading and unloading	$58.14		
Chain saw fuel	$05.81		
Chain saw 02	$20.34		
Chain saw operator hire	$08.72		
Row material		$02.90	$05.81
Labour cost	$15.11	$07.56	$11.34
Other expenses	$05.81	$05.81	$05.81
Total Cost	$113.95	$16.28	$22.96
Cost for 1Kg of charcoals (without packing cost)	$00.83	$ 0.17	$ 0.1
Cost in $ (1$=344 Rupees)	$0.83	$ 0.17	$ 0.1

Overall, these results show how economical and efficient the production process was, and they also show how the type of wood used can affect efficiency differently.

IV. CONCLUSION

For optimal charcoal production, selecting appropriate wood species and carbonization methods is crucial. *Eucalyptus* spp. and wood offcuts are preferable due to their higher fixed carbon content and yield, respectively. The pit method enhances fixed carbon content but requires careful management to control ash content. These findings guide the selection and processing of biomass for efficient, high-quality charcoal production, balancing yield, fuel quality, and economic value.

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