Contemporary Agriculture, Vol. 73, No. 3-4 (2024): 134-144
DOI: https://doi.org/10.2478/contagri-2024-0017
UDC: 634.616

Original scientific paper

UTILIZATION OF COCONUT PLANTATION WEEDS AS A SUSTAINABLE FEEDSTOCK FOR BIOCHAR PRODUCTION

ISSN 2466-4774
https://www.contagri.info/

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Submitted: 28.10.2023.
Reviewed: 07.05.2024.
Accepted: 12.06.2024.

SUMMARY

Biochar, a carbon-rich and highly porous material, is created through the process of pyrolysis, a thermal decomposition of raw materials conducted in a controlled, low or no oxygen environment. Our research aimed to investigate the feasibility of utilizing coconut plantation weeds as a potential source for biochar production. The study encompassed two essential phases: a laboratory experiment conducted at the Agronomy Division of the Coconut Research Institute and a field experiment at the Rathmalagara Research Center, affiliated with the same institute. In the laboratory experiment, biochar was produced from six distinct types of coconut plantation weeds, including Megathyrsus maximus, Imperata cylindrica, Lantana camara, Chromoleana odorata, Stachytarpheta jamaicensis, and Urena lobata. The biochar was produced at a temperature of 500°C, with a residence time of 30 minutes. The resulting biochar samples underwent comprehensive analysis to evaluate various characteristics, such as conversion efficiency, pH, electrical conductivity (EC), moisture content, volatile matter content, ash content, and fixed carbon content. The biochar derived from Megathyrsus maximus demonstrated the highest conversion efficiency of 32.76% and displayed high-quality characteristics. In the field experiment, biochar was produced using a double-chamber pyrolyzer and employed three different stocking densities, with Megathyrsus maximus as the primary feedstock. The outcomes revealed that the biochar generated at a high stocking density of 72.10 kgm^{-3} yielded a remarkable conversion efficiency of 32% and exhibited high-quality biochar. Based on the experimental findings, Megathyrsus maximus demonstrates strong potential as an ideal feedstock for biochar production at the field level using a double-chamber pyrolyzer. These results emphasize the potential for sustainable biochar production from readily available, renewable resources, such as weed biomass from coconut plantations, further highlighting the environmental and agricultural benefits of this approach.

Key words:
Biochar, pyrolysis, Megathyrsus maximus, double chamber pyrolizer, coconut plantations

INTRODUCTION

Coconut (*Cocos nucifera* L.) is an invaluable palm, well-known for its multifaceted contributions to humanity. In 2021, the global coconut production amounted to an impressive 63 million metric tons. As of 2022, Indonesia has solidified its position as the world's leading coconut producer, contributing 17.16 million metric tons, i.e. an impressive 31.45% share of the worldwide coconut output (Shahbandeh, 2023). Conversely, Sri Lanka ranks as the fourth-largest global producer of coconuts, with an impressive annual yield of 3,120 million nuts. The coconut industry in Sri Lanka is not only pivotal for the national foreign exchange earnings but also plays a significant role in generating employment opportunities. A vast expanse of land, totaling 1,095,982 acres, is devoted to the coconut cultivation in Sri Lanka. Of this area, 178,675 acres fall under the estate sector, whereas 917,307 acres are managed by smallholders. King coconut cultivation also contributes significantly, with an allocated area of 34,063 acres (Central Bank Report, 2021). The coconut cultivation in Sri Lanka is a diverse enterprise, thriving across various soil types, nutrient profiles, and agro-climatic zones (Nuwarapaksha et al., 2023; Udumann et al., 2024). This dynamic diversity has led to the coining of the term "Coconut Triangle," an area formed by the convergence of Gampaha, Puttalam, and Kurunegala districts, which have become synonymous with coconut cultivation (Nuwarapaksha et al., 2022).

Coconut cultivation is frequently confronted with soil water stress, primarily due to inadequate precipitation, limited water infiltration, suboptimal water retention, and rapid drainage. Moreover, atmospheric water stress arises from a high vapor pressure deficit from low relative humidity and elevated temperatures (Gomes & Prado, 2007). As coconuts rely on rain-fed systems and have a lengthy productive life span, these adverse climatic conditions significantly threaten their growth and productivity. Recent climate fluctuations have further intensified concerns, potentially hindering crop growth and development. Furthermore, there has been an increase in the frequency and intensity of extreme weather events. These changing weather patterns are particularly worrisome for coconut palms, as their reproductive organs are exquisitely sensitive to water stress and high temperatures. To safeguard and optimize coconut production, it is imperative to implement effective strategies.

Biochar has captured the interest of researchers due to its potential benefits in rejuvenating and enhancing the water-retention capacity and overall health of degraded soils (Dissanayake et al., 2023b; Nuwarapaksha et al., 2024). This carbon-rich material, produced by pyrolyzing organic matter, has gained significant attention recently as a versatile tool for soil amendment and environmental management (O'Laughlin & McElligott, 2009; Dissanayake et al., 2023a). Research exploring the many applications of biochar has yielded promising findings. Studies have demonstrated its capacity to improve soil fertility (Ding et al., 2016), augment water retention, and sequester carbon (Jeffery et al., 2011), presenting a sustainable solution for addressing soil degradation and combating climate change. Furthermore, biochar has shown potential in mitigating greenhouse gas emissions (Zhang et al., 2010), positioning it as an appealing choice for promoting sustainable agriculture and environmental conservation. Nevertheless, it is essential to acknowledge that the effectiveness of biochar can vary significantly based on factors such as the choice of feedstock, production methods, and specific soil conditions.

Biochar production techniques have seen ongoing modernization efforts to enhance production rates and product quality. These advancements and adaptations can be broadly categorized into two main classes: traditional and modern approaches. It includes technologies like gasification, carbonization, fast pyrolysis, slow pyrolysis with low temperature, and slow pyrolysis with high temperature (Dissanayaka et al., 2023a; Vithanage et al., 2017). Both input (feedstock) and output (end product) will vary with the production technology. One critical factor influencing the efficiency and cost-effectiveness of biochar production is the availability and composition of the feedstock. Globally, a wide array of feedstock sources is utilized for biochar production, including agricultural crop residues, forest residues, woody biomass, aquatic biomass, animal and human excreta, industrial waste, food and kitchen waste (Wani et al., 2022). Avoiding highly moisture-absorbent materials is of great importance.

The utilization of weed biomass for biochar production has gained global attention, with various weed species undergoing testing for this purpose. Notable examples include the *Ageratum conyzoides*, *Lantana camara*, *Gynura* species, *Setaria* species, *Avena fatua* (Mandal et al., 2015), and *Pennisetum purpureum* (George et al., 2019). Novak et al. (2009) observed that biochar derived from mixed weed biomass exhibited the capacity to enhance soil nutrient retention and bolster crop yields in southeastern coastal plain soils. Further insights from Leng et al. (2015) delved into the influence of weed-based biochar on sweet corn growth and soil characteristics, revealing positive outcomes from this approach. Mao et al. (2012) contributed by discussing the stability and long-term benefits of biochar, emphasizing its pivotal role in soil fertility and carbon sequestration, even when sourced from weeds.

Omondi et al. (2016) explored the potential of biochar, including that derived from weed biomass, to curtail nutrient leaching in volcanic ash soils, thus fortifying nutrient retention. López-Mosquera et al. (2019) conducted a field study showcasing weed-based biochar as a soil amendment for carrot cultivation, noting favorable impacts on crop yield and soil properties. These studies collectively underscore the potential of weed biomass-derived biochar to enhance soil fertility, diminish nutrient losses, and enhance crop performance. Such an approach offers a sustainable solution for the effective management and utilization of weed biomass.

The Coconut Research Institute of Sri Lanka (CRISL) is actively engaged in research aimed at assessing biochar production using readily available materials found in the major coconut-growing regions of the country, such as king coconut husk, coconut husk, coconut spathe, and *Gliricidia sepium* wood (Dissanayaka et al., 2023b; Nuwarapaksha et al., 2024). One of the primary challenges faced in biochar production is the scarcity of suitable feedstock to meet production requirements. The study herein adopted a novel approach by utilizing weed biomass from coconut plantations as feedstock for biochar production. These weeds, recognized for their vigorous growth even in the presence of grazing and cutting, offer a practical solution to address the feedstock shortage.

MATERIAL AND METHODS

Experimental locations

The study was structured into two distinct experiments. The initial experiment was conducted in a controlled laboratory setting within the Agronomy Division at CRISL, located in Lunuwila, North Western Province, Sri Lanka. For this laboratory experiment, the feedstocks were sourced from the Bandirippuwa Research Centre in Lunuwila. The subsequent experiment was carried out in an outdoor field environment at the Rathmalagara Research Centre, also under the jurisdiction of CRISL, situated in Madampe. The feedstock used in this field experiment was gathered directly from the Rathmalagara Research Centre.

Preparation of biochar under laboratory conditions

In this study, biochar production involved the utilization of six different types of weeds: *Megathyrsus maximus* (Guinea grass), *Imperata cylindrica* (Illuk), *Lantana camara* (Gandapana), *Chromoleana odorata* (Podisinghomaran), *Stachytarpheta jamaicensis* (Balunaguta), and *Urena lobata* (Apala).

The process began with the preparation of the feedstock. Once the feedstock had been suitably dried, it was packed into steel containers equipped with lids, and weighed using a top-loading balance. The biochar production was performed in a muffle furnace. The process commenced with an initial temperature setting of 30 ℃, which was then raised to 500 ℃ over a span of 15 minutes. During the pyrolysis phase, the temperature was consistently maintained at 500 ℃ in an airtight environment for duration of 30 minutes. Following the completion of pyrolysis, the biochar samples were allowed to cool within a desiccator. All the biochar samples underwent comprehensive examination to assess their physical and chemical characteristics such as conversion efficiency, pH, EC, moisture content, volatile matter content, ash content, and fixed carbon content, without undergoing any further treatment at the end of this experiment. This procedure was repeated three times.

Preparation of biochar under field conditions

Megathyrsus maximus, the weed species that exhibited the highest conversion efficiency under laboratory conditions of all the samples in the first experiment, was chosen as the feedstock. The feedstock was prepared by cutting it into small pieces, approximately 7-10 cm in length, and then allowing it to air-dry in the field for a period of five days.

The process of biochar production in this field experiment involved the use of a double-chamber pyrolysis reactor. To initiate the process, the inner chamber was removed from the reactor. The empty inner chamber was weighed, and the dried feedstock was carefully packed into it. The weight of the inner chamber, including the feedstock, was then measured using a portable electronic balance. The feedstocks were packed into the inner chamber at three different densities (Tab. 1).

After packing, the inner chamber was placed back into the pyrolysis reactor. The outer chamber of the reactor was filled with dried king coconut husk, which served as the fuel source for the pyrolysis process. Each batch utilized approximately 14 kg of dried king coconut husk to initiate the process. The reactor was ignited from the top, and the reactor lid was closed. The following day, the reactor was opened, and the inner chamber was removed. The biochar samples were carefully extracted from the inner chamber and weighed using a portable electronic balance. These samples were subsequently transported to the laboratory for further analysis, ensuring a thorough evaluation of the resulting biochar.

Table 1. Treatments of the field experiment

Treatments	Volume of the chamber	Weight of the feedstock	Weight percentage of feedstock	Density
T_1	0.0548 m^2	4 kg	100%	72.10 kgm^{-3}
T_2	0.0548 m^2	3 kg	75%	54.74 kgm^{-3}
T_3	0.0548 m^2	2 kg	50%	36.49 kgm^{-3}

Biochar samples analysis

The biochar samples were initially weighed and then ground into finer particles using a mortar and pestle. Subsequently, the ground biochar material was sifted through a 0.2 mm mesh sieve to ensure uniform particle size. To assess the conversion efficiency of each biochar sample, the following equation was employed:

$$\text{Conversion Efficiency} = \frac{\text{Weight of Biochar Produced}}{\text{Weight of Feedstock Used}} \times 100$$

From the collected biochar samples, one sample with the highest conversion efficiency was selected from each set. This process ensures the identification of the most efficient biochar samples derived from the various feedstock sources.

In the analysis process, two grams of biochar were first placed into 50 ml screw-cap bottles to measure electrical conductivity. After adding 40 ml of distilled water, the sample was stirred for two minutes using a glass rod and then allowed to settle for 30 minutes. Subsequently, the sample was filtered into a test tube using cotton wool, and electrical conductivity (EC) was measured at 25 °C with an electrical conductivity meter.

For the pH assessment, another two grams of biochar were measured and placed in similar screw-cap bottles, along with 40 ml of distilled water. After stirring for two minutes and a 10-minute settling period, the pH was measured using a pH meter.

To determine the moisture content, an empty porcelain crucible was ignited in a muffle furnace at 750 °C for 10 minutes. After cooling in a desiccator for one hour, the weight of the empty crucible was recorded. Then, one gram of biochar sample was weighed into the crucible, which was subsequently placed in an oven at 105 °C for two hours. Following a two-hour drying period, the crucible with the oven-dried biochar sample was moved to the desiccator, and after one hour, its weight was recorded (Aller et al., 2017).

$$\text{Moisture content} = \left\{\frac{\text{A} - \text{B}}{\text{A}}\right\} \times 100$$

A = Weight of air-dry sample used
B = Weight of sample after drying at 105 °C

To determine the volatile matter content, a sample previously assessed for moisture was subjected to further analysis. The muffle furnace was preheated to a temperature of 950 °C. The sample was swiftly introduced into the preheated muffle furnace, and it was subsequently heated at 950 °C for a duration of 10 minutes. Following this heating period, the sample was carefully removed from the muffle furnace and placed on a brick to cool until it was safe to transfer into a desiccator. Once the sample had sufficiently cooled, the crucible was weighed, and the measurement was duly recorded, as detailed in the methodology of Aller et al. (2017).

$$\text{Volatile matter content} = \left\{\frac{\text{B} - \text{C}}{\text{B}}\right\} \times 100$$

C = Weight of sample after drying at 950 °C

To determine the ash content, a sample previously assessed for volatile matter was used. The muffle furnace was preheated to a temperature of 950 °C. The sample was carefully introduced into the preheated muffle furnace, and then it was heated at 730 °C for a period of 6 hours. After this extended heating process, the sample was removed from the muffle furnace and placed on a refractory brick to cool, ensuring it was safe for transfer into a desiccator. Once the sample had sufficiently cooled down, the crucible was weighed, and the measurement was recorded, as per the procedure outlined in Aller et al. (2017).

$$\text{Ash content} = \left\{\frac{\text{D}}{\text{B}}\right\} \times 100$$

D = Weight of the residue

The fixed carbon content was determined by performing calculations using the data obtained from the previous steps (Aller et al., 2017).

$$\text{Fixed carbon content} = 100 - (\text{Moisture content} - \text{volatile matter content} - \text{Ash content})$$

Data analysis was conducted using Minitab 20 and MS Excel 2021. The mean values of the data were statistically compared using a one–way analysis of variance (ANOVA) at a 5% significance level, along with the Fisher pairwise comparison test.

RESULTS AND DISCUSSION

Laboratory experiment

Figure 1 illustrates the conversion efficiency of biochar produced from six different weed biomass, specifically *Chromoleana odorata, Imperata cylindrica, Lantana camara, Megathyrsus maximus, Stachytarpheta jamaicensis,* and *Urena lobata*.

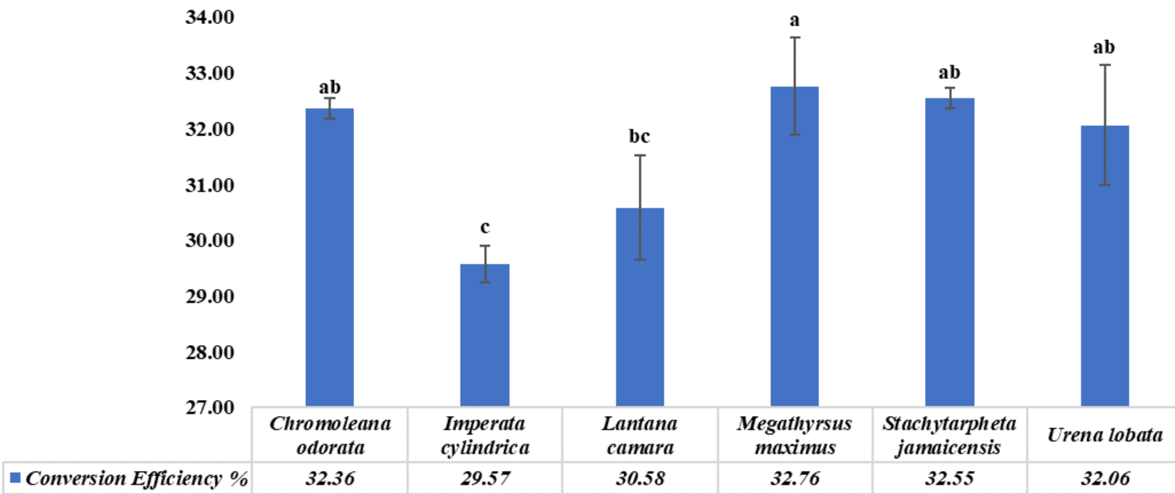

Figure 1. The conversion efficiency of biochar produced from different weed biomass (Means that do not share a letter are significantly different at $p < 0.05$)

The study reveals that all biochar samples were produced under identical conditions, maintaining a constant temperature (500 °C) and residence time (30 minutes). Notably, there was a significant influence of different weed species on the feedstock conversion efficiency of the resulting biochar. The data indicates that the biochar produced from *Megathyrsus maximus* exhibited the highest conversion efficiency, reaching 32.76%, among the six biomass types under investigation. Following closely were *Stachytarpheta jamaicensis* (32.55%), *Chromoleana odorata* (32.36%), and *Urena lobata* (32.06%), all displaying notable conversion efficiencies. In contrast, *Lantana camara* produced biochar with a slightly lower efficiency of 30.58%, while *Imperata cylindrica* yielded the lowest conversion efficiency at 29.57%. Even though, the conversion efficiency and biochar yield do not have a direct linear relationship, higher conversion efficiency generally leads to a higher biochar yield, as more of the biomass is converted into biochar rather than being lost as volatiles or gases.

These variations in feedstock conversion efficiency are likely attributable to the differing physicochemical properties inherent to each biomass type (Ghodake et al., 2021). Factors such as lignocellulosic content, ash content, and the presence of specific organic compounds within the biomass can significantly influence the yield and properties of the biochar produced (Ekanayaka et al., 2023; Dissanayaka et al., 2023a). As an example, feedstocks with higher lignin and fixed carbon content generally yield more biochar with high conversion efficiency (Kapoor et al., 2022). Furthermore, it is important to recognize that, while uniform temperature and residence time were maintained, other variables such as heating rate, final quenching temperature, and pyrolysis atmosphere may also impact the yield and characteristics of the resulting biochar, as discussed by Yaashikaa et al. (2020).

The pH and EC of the prepared biochar samples were measured (Tab. 2). The data highlights notable variations in the pH levels of biochar, which significantly depend on the type of biomass employed. Across all treatments, the pH of the biochar ranged from 8.66 to 10.37. The biochar produced from *Megathyrsus maximus* displayed the highest pH value at 10.37, followed closely by *Chromoleana odorata* (9.92) and *Lantana camara* (9.85). In contrast, the biochar produced from *Imperata cylindrica* (8.66) and *Stachytarpheta jamaicensis* (9.18) exhibited relatively lower pH values, whereas the biochar generated from *Urena lobata* had an intermediate pH value of 9.31. These variations in pH values are likely influenced by the unique physicochemical properties inherent to each type of biomass, as indicated by Tomczyk et al. (2020).

Table 2. Characteristics of the produced biochar

Biomasses (Weed Species)	pH	EC (mS/cm)
Chromoleana odorata	9.92[ab*]	3.44[b]
Imperata cylindrica	8.66[c]	0.70[d]
Lantana camara	9.85[ab]	2.12[c]
Megathyrsus maximus	10.3[a]	10.56[a]
Stachytarpheta jamaicensis	9.18[c]	1.64[cd]
Urena lobata	9.31[bc]	1.40[cd]

Legend: *Means that do not share a letter are significantly different at $p < 0.05$

The data underscore significant variations in the EC of biochar, a parameter closely associated with the type of biomass used. The biochar produced from *Megathyrsus maximus* exhibited the highest EC value at 10.56 mS/cm, indicating a notable concentration of dissolved salts and minerals. In contrast, the biochar derived from *Imperata cylindrica* displayed the lowest EC value at 0.70 mS/cm. The EC values of biochar produced from the other biomass types fell within this range, with *Chromoleana odorata* recording the highest among them at 3.44 mS/cm, followed by *Lantana camara* (2.12 mS/cm), *Stachytarpheta jamaicensis* (1.64 mS/cm), and *Urena lobata* (1.40 mS/cm).

Higher EC values indicate a greater salt content in biochar, potentially affecting soil health. To enhance its effectiveness, it may be necessary to dilute biochar with elevated EC values. Additionally, the EC of biochar is a critical factor to consider when evaluating its use as a soil amendment, as elucidated by Lehmann et al. (2011). Biochar with high EC can improve soil quality and promote plant growth by increasing the soil's capacity to retain and transfer nutrients and water, thus reducing the risk of nutrient leaching. Moreover, it can be used as a filler in composite materials for electromagnetic shielding and interference prevention (Fenta & Ali, 2024). However, combining biochar with organic materials can enhance its nutrient retention capacity. This information underscores the importance of understanding and managing the EC of biochar in soil applications.

Figure 2 illustrates no significant variations in the moisture content of biochar, which displays distinct dependencies on the type of biomass used. The moisture content of the produced biochar ranged from 3.77% to 4.77% across the various treatments. The biochar derived from *Megathyrsus maximus* exhibited the lowest moisture content at 3.77%, whereas the biochar produced from *Chromoleana odorata* and *Urena lobata* displayed the highest moisture content at 4.77%. The moisture content of the biochar generated from other biomass types fell within this range, with *Imperata cylindrica* and *Lantana camara* showing similar values of 3.97% and 3.92%, respectively, while *Stachytarpheta jamaicensis* had a slightly higher value of 4.31%.

This variation in moisture content can significantly influence the physical and chemical properties of biochar, as well as its stability and storage characteristics. Moreover, higher moisture content can potentially promote microbial activity and decomposition, as highlighted by Ellison et al. (2017). Understanding and managing the moisture content of biochar is crucial for optimizing its effectiveness and longevity across various applications.

Volatile matter content is a critical parameter in assessing biochar quality, as it reflects the quantity of organic compounds that can readily vaporize and be released during combustion or other high-temperature applications. Notably, the biochar produced from *Imperata cylindrica* exhibited the highest volatile matter content at 37.57%. A higher volatile matter content often indicates a greater potential for emissions and reduced stability during storage, while a lower content implies a more stable and potentially more effective biochar, as emphasized by Enders et al. (2012). Therefore, optimizing pyrolysis conditions (temperature, residence time, heating rate) is essential for maximizing biochar production from some of these feedstocks.

Megathyrsus maximus exhibited the lowest volatile matter content (26.97%), suggesting increased stability during storage with lower emissions. The volatile matter content of the biochar derived from other biomass types fell within this range, with *Chromoleana odorata* recording the second highest value at 33.32%, followed closely by *Urena lobata* and *Stachytarpheta jamaicensis*, which displayed similar values of 27.91% and 28.02%, respectively. *Lantana camara* exhibited the second lowest volatile matter content at 30.10%. Understanding these variations in volatile matter content is crucial for assessing the potential emissions and stability of biochar across various applications, thus enabling more informed decisions regarding its utilization.

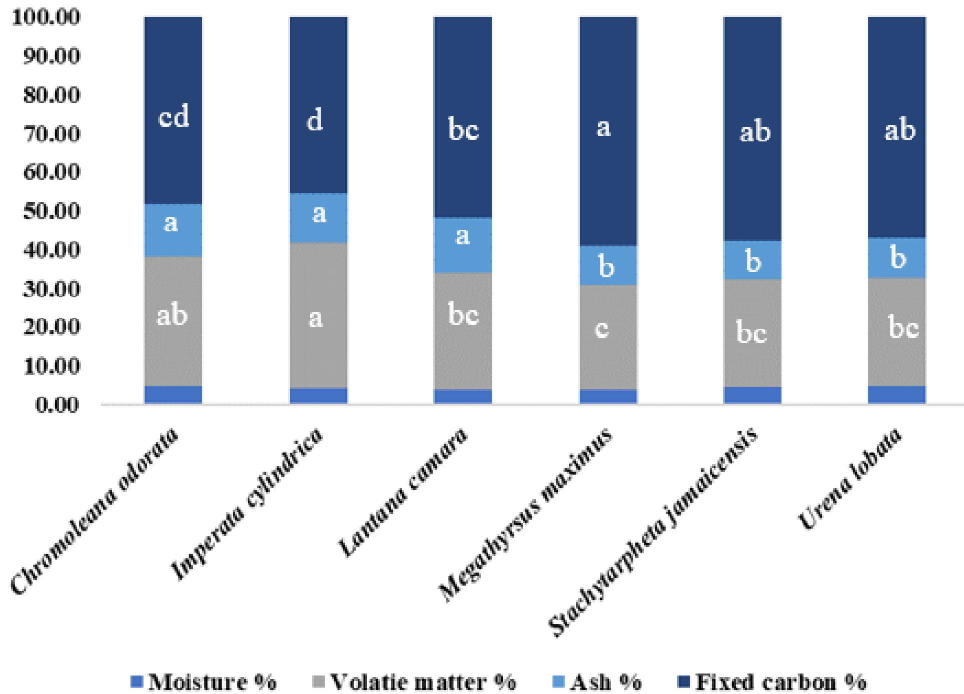

Figure 2. Proximate analysis results of the biochar produced from different weed biomass (Means that do not share a letter are significantly different at $p < 0.05$)

Ash content in biochar is a critical parameter as it plays a significant role in influencing nutrient availability and the cation exchange capacity of the biochar. Biochar with a higher ash content can contain elevated amounts of mineral matter, potentially contributing to soil fertility (Chan & Xu, 2012; Smider & Singh, 2014). However, an excessively high ash content may adversely affect soil quality by increasing the soil pH and potentially leading to nutrient deficiencies, as elucidated by Tomczyk et al. (2020).

Among the biomass types studied, *Megathyrsus maximus* showcased the lowest ash content at 10.37%, followed by *Stachytarpheta jamaicensis* and *Urena lobata*, which displayed values of 9.99% and 10.29%, respectively. Biochar with low ash contents may contain fewer nutrients, but can be more suitable for soil amendment without significantly impacting the soil pH, as suggested by Tomczyk et al. (2020). In contrast, *Chromoleana odorata* presented the highest ash content at 13.62%, with *Lantana camara* and *Imperata cylindrica* following at 14.10% and 13.08%, respectively. Understanding and managing the ash content in biochar is vital for optimizing its effectiveness as a soil amendment and preventing potential disruptions in soil quality.

The fixed carbon content of the biochar samples exhibited significant variations across different feedstock types, ranging from 45.38% to 58.89%. The highest fixed carbon content was observed in the biochar sample produced from *Megathyrsus maximus* at 58.89%. This was followed closely by the samples from *Stachytarpheta jamaicensis* (57.67%) and *Urena lobata* (57.02%), indicating their classification as high-quality biochar with elevated fixed carbon contents.

The biochar sample produced from *Lantana camara* displayed a moderate fixed carbon content of 51.88%. Conversely, the biochar samples from *Imperata cylindrica* (45.38%) and *Chromoleana odorata* (48.29%) had lower fixed carbon contents in relation to the other samples. A lower fixed carbon content suggests incomplete pyrolysis, which can potentially impact both the quality and quantity of biochar, as discussed by Battle et al. (2014). Understanding and managing the fixed carbon content is critical for assessing the quality and suitability of biochar across various applications.

Field Experiment

The effects of stocking densities on the feedstock conversion efficiency are shown in Table 3.

Table 3. Characteristics of the biochar derived from *Megathyrsus maximus* at three different feed stocking densities

Treatment	Feed stocking density (kgm^{-3})	Conversion efficiency (%)	pH	EC (mS/cm)
1	72.10	32.00^{a*}	8.52^{b}	3.17^{c}
2	54.74	29.11^{b}	10.16^{a}	5.86^{a}
3	36.49	26.36^{c}	9.95^{a}	4.54^{b}

Legend: *Means that do not share a letter are significantly different at $p < 0.05$

The impact of stocking density on the conversion efficiency, pH value, and EC of biochar production is evident in the study. The results reveal a substantial effect of three different stock densities on biochar characteristics.

The highest conversion efficiency was recorded in T1 at 32.00%, whereas the lowest was in T3 at 26.36%. The substantial difference of 19.32% between the highest and lowest conversion efficiency values suggests that conversion efficiency decreases as stocking density decreases. Under conditions of high stocking density (T1), the proximity of feedstock particles limits oxygen availability in the pyrolizer. This leads to a more uniform and complete pyrolysis process, resulting in higher conversion efficiency. Conversely, low stocking density (T3) allows for increased oxygen availability, potentially leading to feedstock combustion and a subsequent reduction in conversion efficiency. These findings underscore the significant impact of stocking density on biochar production efficiency, indicating that controlling stocking density can optimize the production process.

The study also shows the effect of stocking density on the pH value of biochar. The highest pH value (10.16) was observed in T2, while the lowest pH value (8.52) was in T1. T3 had a pH value of 9.95. Low feedstock density (T2 and T3) may have resulted in the formation of higher levels of alkaline inorganic compounds during the pyrolysis process, leading to higher pH values. Conversely, high stocking density (T1) might have generated lower levels of alkaline inorganic compounds, resulting in lower pH values.

The EC value of biochar was also affected by stocking density. T2 had the highest EC value at 5.86 mS/cm, while T1 had the lowest at 3.71 mS/cm. Biochar can contain varying levels of inorganic compounds like calcium, potassium, and sodium, contributing to its EC value. The levels of these inorganic compounds may vary based on pyrolysis conditions, including temperature and stocking density. Low stocking density (T2) may have led to the formation of higher levels of inorganic compounds during pyrolysis, resulting in a higher EC value. Conversely, high stocking density (T1) might have generated lower levels of inorganic compounds, resulting in a lower EC value.

Figure 3 reveals the influence of stocking density on various parameters of biochar produced using *Megathyrsus maximus*.

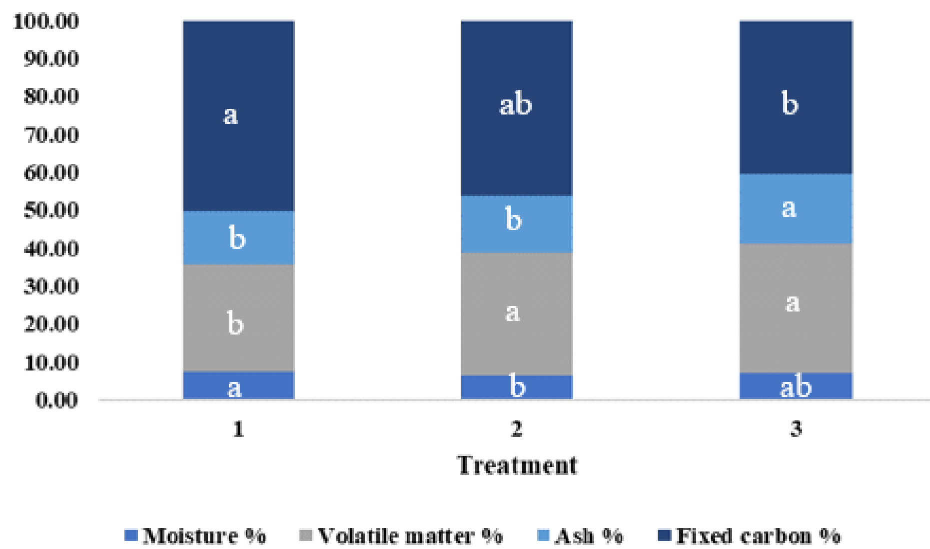

Figure 3. Proximate analysis results of biochar derived from *Megathyrsus maximus* at three different feed stocking densities (Means that do not share a letter are significantly different at $p < 0.05$)

Stocking density had a minimal effect on the moisture content of biochar. T1 exhibited the highest moisture content at 7.50%, while T2 had the lowest at 6.38%. Similarly, the effect of stocking density on the volatile matter content of biochar was relatively minor. T3 had the highest volatile matter content at 34.12%, while T1 had the lowest at

28.45%, with T2 falling in between at 33.45%. The higher stocking density in T1 may have led to a longer residence time for feedstock in the pyrolysis reactor, resulting in higher temperatures and a more complete breakdown of organic materials into volatile gases and liquid condensates, contributing to the lower volatile matter content. Conversely, lower stocking density in T3 may have led to a shorter residence time, lower temperatures, and less complete breakdown of organic material, resulting in higher volatile matter content.

The ash content of biochar was significantly influenced by stocking density. T3 exhibited the highest ash content at 18.25%, while T1 had the lowest at 13.99%, with T2 recording 14.88%.

The study indicates that stocking density significantly affects the fixed carbon content of biochar. T1 had the highest fixed carbon content at 50.06%, while T3 had the lowest at 40.51%, with T2 falling in between at 45.29%. Generally, increasing feedstock density during biochar production leads to higher fixed carbon content, as a greater feedstock density promotes more efficient heating and pyrolysis, resulting in less volatile matter being released and a higher proportion of carbon being retained in the biochar.

These findings underscore the importance of stocking density in influencing various biochar characteristics, emphasizing the potential to optimize biochar production by adjusting stocking density to meet specific application requirements.

CONCLUSION

In conclusion, this comprehensive study on biochar production under controlled conditions, maintaining consistent temperature and residence time, has provided critical insights into the influence of different biomass types and stocking densities on various biochar characteristics. These findings hold significant implications for optimizing biochar production and enhancing its suitability for diverse applications.

The study demonstrates significant variability in feedstock conversion efficiency among different weed species. Megathyrsus maximus emerged as the most efficient biomass for biochar production, underscoring the importance of feedstock selection in achieving high conversion rates. The physicochemical properties inherent to each biomass type, such as lignocellulosic content, ash content, and the presence of specific organic compounds, play a crucial role in determining the yield and properties of the resulting biochar. This insight is critical for tailoring biochar production to meet specific needs and applications.

The study also highlights the substantial impact of pH, EC, moisture content, volatile matter content, ash content, and fixed carbon content on the quality and suitability of biochar for various applications. These characteristics are closely linked to the type of biomass used and can significantly influence the effectiveness of biochar in applications such as soil amendment and environmental remediation. Effectively managing these properties is essential to optimizing the benefits of biochar while mitigating potential drawbacks.

The study confirmed the significant influence of stocking density on biochar characteristics. Variations in stocking density can affect conversion efficiency, pH, electrical conductivity (EC), moisture content, volatile matter content, ash content, and fixed carbon content. Controlling stocking density offers a strategic approach to tailoring biochar production to meet specific application requirements, such as maximizing conversion efficiency or adjusting pH levels to suit particular soil conditions.

Overall, the study provides valuable insights into the production and properties of biochar, shedding light on the important role of biomass selection and stocking density. These findings offer a foundation for more efficient and targeted biochar production, potentially enhancing its utility in agriculture, environmental conservation, and various other applications. Moreover, they underscore the importance of fully considering the feedstock and the process variables in biochar production to unlock its potential as a sustainable resource.

RECOMMENDATIONS AND FUTURE DIRECTIONS

Based on the findings of the study, it is recommended that farmers consider utilizing a double-chamber pyrolyzer to produce biochar from coconut plantation weeds, which serve as a sustainable feedstock rich in essential nutrients. This method offers several advantages, including ease of operation with minimal technical knowledge, low construction costs, and efficient feedstock conversion within a short time frame, making it an economically viable choice for farmers. To optimize biochar production, further experimentation with various weed types, temperature ranges, and residence times is advisable, allowing for the identification of the most effective combinations to maximize biochar yield and quality. This research presents a practical and cost-effective solution for biochar production and highlights its potential as a valuable tool in sustainable farming practices, contributing to waste management and enhancing soil fertility.

Acknowledgements**:** We would like to express our appreciation to the technical staff of the Agronomy Division of the Coconut Research Institute. We would like to express our deep gratitude to the editor and anonymous reviewers for their valuable comments and critical evaluation.

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Conflict of interest: The authors declare that they have no conflict of interest.

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