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ORIGINAL ARTICLE

Development, evaluation, and optimization of portable pyrolysis system for the production of biochar from tender coconut husk

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Abstract

Tender coconut husk (TCH) is a prominent part of coconut fruit, and it is discarded after consumption of tender coconut water. TCH is made of fibers that comprise lignin (30–42%) and cellulose (54–65%) and also contains traces of tannin and potassium. In this study, development of most feasible and adaptable method for production of biochar from TCH is reported. The method opted for the production of biochar is pyrolysis, and temperature of pyrolysis has a direct correlation with the characteristics of resultant biochar. The main parameters investigated are the size of the reactor, type of fuel, and positioning of the drum. Biochemical parameters of biochar such as moisture content, ash content, pH and electrical conductivity, and total nitrogen content of the product were studied. The results reveal that sample collected from the upper layer of the large-sized reactor kept in upright position and using mature coconut husk as a fuel for biochar production was found to be the best considering the yield and physicochemical properties.

Keywords Biochar · Carbon content · Coconut husk · Pyrolysis · Lignin

1 Introduction

Coconut water is a popular and natural beverage. It contains numerous bioactive components. It is a great rehydrating and refreshing drink that can help to prevent and treat a variety of ailments [1]. India exports coconut water to United Arab Emirates, USA, and UK. The sale of tender coconuts along the highways and cities is most common in India. However, the tender coconut husk (TCH) or exocarp is discarded after consuming water inside, as a waste and large quantum of TCH gets accumulated along the roadsides. Chemical composition of TCH suggests cellulose fibers (44–45%), hemicellulose (7–8%), lignin (37% approx.), pectin (4–4.5%), and waxy substances (3–3.5%) are the major components [2]. Presence of high lignin content in TCH delays the decomposition process causing environmental pollution. In this context, conversion of these cellulosic fibers to value added product such as biochar is imperative to avoid the environmental pollution. It not only ensures safe disposal but also adds value to the TCH since the biochar produced could serve as a very good soil amendment, especially for cultivation of vegetables. Similarly, Maroušek and Gavurová [3] developed silver nanoparticles from coir pith. Coir pith is a lignocellulosic biomass obtained from coconut husk.

Biochar, the solid material formed during the thermochemical decomposition of biomass, is defined, by the International Biochar Initiative (http://www.biochar-international.org/biochar), as “a solid material obtained from the carbonization of biomass.” Initially, it was used only in agriculture; however, the range of utility of biochar varies from diverse fields such as animal farming, building sector, decontamination, biogas production soil conditioner, and wastewater treatment [4]. These applications provide a scope for conversion of plant-based raw material to biochar.

Biochar can be produced by the thermochemical degradation of biomass in a zero or limited oxygen environment through the process of pyrolysis. Anaerobic fermentation and pyrolysis are the two major methods of waste

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management [5]. Maroušek [6] verified the concept of anaerobic fermentation followed by pyrolysis as economically feasible to manage urban green. It is perhaps the most recalcitrant form of organic matter in soil, whose sustenance extends from a few hundreds to thousands of years, rendering it an excellent means for carbon sequestration. It improves the chemical properties of soil. Owing to the highly porous nature of biochar, soil application of biochar would ultimately lead to enhancement of a wide range of soil physical, chemical, and biological properties [7]. Biochar application can enhance organic matter content in soil which leads to increased soil fertility [8]. Also, biochar can reduce soil acidity and increase soil electrical conductivity (EC) and cation exchange capacity (CEC), resulting in higher nutrient availability [9].

The growth of this body of knowledge as well as advances in pyrolysis technology and other ways to modify biochar will allow the deliberate control of the biochar production variables which ensures creation of a biochar with specific properties [10][11]. The pyrolysis process parameters affect the physicochemical characteristics of the biochar [12][13]. Studies have been conducted regarding the conversion and application of coconut shell, leaves, and husk-based biochar. Studies on the influence of TCH-derived biochar on nutrient use efficiency, yield, and economics of banana (*Musa. spp*) were analyzed by Sainath et al. [14]. Gopal et al. [15] converted the lignin-rich recalcitrant biomass residues of mature coconut husk, coconut leaf petiole, and coir pith by pyrolysis into porous biochars. Maroušek and Gavurová [3] activated the charred fermentation residue via calcium chloride and found that it is capable of capturing 37.5 ± 4.7 kg P t^{-1}. However, these studies have explored the preparation of biochar using simple charring kiln. The basic problems associated with the conventional charring kiln are unequal and improper pyrolysis of the biomass residues [15]. However, the quality of biochar depends on the process parameters of pyrolysis (temperature, residence time, and oxygen conditions in the combustion chamber) and chemical properties of the biomass [16]. To the best of our knowledge, there are no studies on the design, development, and standardization of pyrolysis chamber for the production of biochar from TCH. Also, the production cost of biochar is high in the case of traditional method (roughly 500 USD t^{-1}) that prevents its expansion in commercial scale [17]. The production costs depend on the production process, operational cost, type of feedstock, and transportation charges for feedstock. However, the main cost is involved in production process [18].

In this context, the present study was conducted with varying sizes of pyrolysis chamber, type of fuel, and positioning of the pyrolysis chamber within the pyrolysis setup.

2 Materials and methods

2.1 Sample preparation

The TCH was collected from the street vendors, Kasaragod, India. The raw materials collected were subjected to sun drying to reach a considerable minimum level of moisture content (< 10%).

2.2 Biochar production

Figure 1 presents the biochar production setup or the pyrolysis apparatus used in this study. The pyrolysis unit consists of a combustion chamber (larger outer drum) and pyrolysis chamber (inner smaller drum) along with an exhaust tube attached for the free flow of flue gasses and smoke out of the system. The temperature developed by burning the fuel placed in the space between the combustion chamber and pyrolysis chamber causes the carbonization of dry TCH kept in the pyrolysis chamber without resorting to direct burning of the sample. The whole setup was maintained in such a way to create a proper and controlled flow of oxygen so as to maintain the pyrolysis condition. The experimental setup consists of three different sizes (small, medium, and large as shown in Table 1) of pyrolysis chamber to optimize the suitable size for the production of TCH biochar. The dried TCH was loaded in the pyrolysis chamber and heated at a temperature of 350–380 °C for 2–4 h to produce biochar. The color of the smoke was used as a visual indicator to identify the completion of the process. The temperature profile was recorded throughout the process using an infrared thermometer at every 10-min interval to assess the process conditions. It was observed that the maximum temperature developed during the process was 380 °C. The fuel used for pyrolysis was dried mature coconut husk or dried tender coconut husk. The experiments were conducted at three different conditions such as by varying the positions of the combustion chamber (upright and inverted), size of the pyrolysis chamber, and type of fuel (dried mature coconut husk and dried TCH). The biochar obtained was further ground to fine powder (~ 0.2 mm) prior to physicochemical analysis.

2.3 Physicochemical analysis

The major physicochemical properties evaluated were moisture content, bulk density, ash content, pH, electric conductivity, and total major and micronutrients content. The moisture content of biochar was estimated according to AOAC method. Bulk density of biochar was estimated

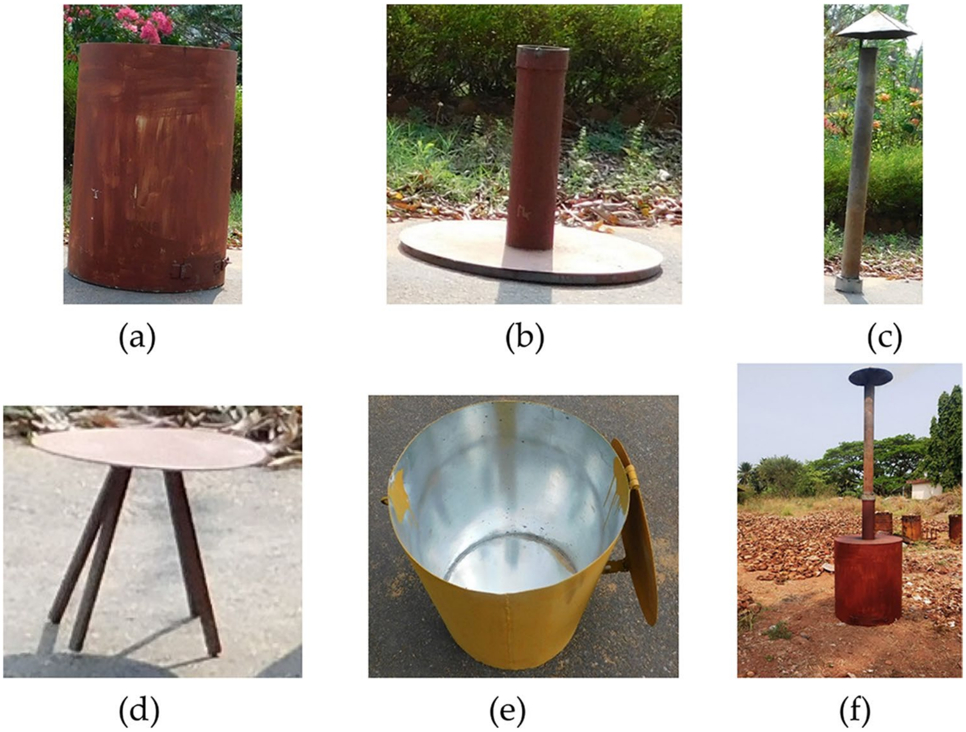

Fig. 1 Components of pyrolysis unit used for production of biochar from tender coconut husk. **a** Combustion chamber. **b** Lid for combustion chamber. **c** Exhaust pipe. **d** Stand of pyrolysis tank. **e** Pyrolysis (inner) chamber. **f** biochar production setup

Table 1 Technical specification of pyrolysis chambers employed in this study

Pyrolysis chamber	Height (mm)	Diameter (mm)	Volume (m^3)	Weight (kg)
Large	600	400	0.07536	11.14
Medium	500	300	0.03533	5.35
Small	400	200	0.01256	3.27

as per the procedure outlined by Ahmedna et al. [19]. Ash content of the sample was measured using pH/mV/Conductivity/°C/°F meter from Eutech Instruments (PC 2700; Waltham, MA, USA) [20]. The total nitrogen content was evaluated by wet digestion using concentrated sulfuric acid and other nutrients by di-acid digestion method [21]. All the experiments were replicated three times.

3 Results and discussion

3.1 Physicochemical properties

The physicochemical properties of biochar are presented in Table 2. The variables of experiment can be represented as follows: T1—large reactor, T2—medium reactor, T3—small reactor, M—middle portion, B—bottom portion, U—upper portion, M—mature coconut husk fuel, t—tender coconut husk fuel, (A)—sides of the different layers of biochar, and (B)—center of different layers of biochar obtained.

3.1.1 Effect of independent parameters on moisture content

The moisture content of the biochar samples obtained at the end of the process is in the range of 2–6. The highest moisture content was observed for $\mathrm{ItT_2M}$ (inverted, tender coconut husk as fuel, medium size pyrolysis chamber, middle layer) in which the sample obtained from the middle layer of the medium-sized pyrolysis chamber that used tender coconut husk as a fuel and the pyrolysis chamber was kept inverted. It is clearly evident that the moisture content was comparatively high for the samples which were derived from the pyrolysis chambers that were kept inverted during processing (Table 2). The temperature distribution within the chamber during the pyrolysis process has direct correlation with the final moisture content of the biochar obtained. Gopal et al. [15] reported that while producing biochar from various parts of coconut palm, the mature coconut husk biochar was found to have a moisture content of 10.0%. Contrarily, the moisture content of biochar derived from agricultural residues such as wheat straw, maize cop, and sugarcane baggase was in the range of 3.0–4.5% [22]. Moisture content

Table 2 Physiochemical properties of tender coconut husk-based biochar

SLNo	Treatments	Moisture (%)	Bulk density (g/cc)	Ash content (%)	pH	EC (mS/cm)	Total nitrogen (%)
1.	MT1B	3.65 ± 0.09	0.47 ± 0.005	6.88 ± 0.18	10.55 ± 0.02	8.05 ± 0.02	0.66 ± 0.12
2.	MT1M	4.15 ± 0.03	0.52 ± 0.005	6.79 ± 0.30	10.40 ± 0.005	7.36 ± 0.04	0.95 ± 0.20
3.	MT1U	2.89 ± 0.16	0.45 ± 0.001	8.68 ± 0.20	10.51 ± 0.02	6.39 ± 0.03	0.77 ± 0.03
4.	MT2B	3.42 ± 0.16	0.48 ± 0.005	9.55 ± 0.42	10.27 ± 0.01	6.58 ± 0.09	0.71 ± 0.04
5.	MT2M	3.19 ± 0.19	0.44 ± 0.001	11.36 ± 0.38	10.26 ± 0.02	5.43 ± 0.07	0.75 ± 0.08
6.	MT2U	2.76 ± 0.28	0.50 ± 0.01	6.44 ± 0.23	10.15 ± 0.05	5.23 ± 0.18	0.68 ± 0.04
7.	MT3B	5.48 ± 0.19	0.43 ± 0.004	6.40 ± 0.17	10.54 ± 0.01	7.93 ± 0.22	0.57 ± 0.03
8.	MT3M	5.91 ± 0.03	0.46 ± 0.005	6.68 ± 0.16	10.57 ± 0.01	7.26 ± 0.11	0.71 ± 0.02
9.	MT3U	5.73 ± 0.14	0.47 ± 0.001	10.56 ± 0.20	10.51 ± 0.02	3.70 ± 0.06	0.55 ± 0.01
10.	NtT1B(A)	4.62 ± 0.12	0.43 ± 0.01	7.32 ± 0.10	9.98 ± 0.02	7.08 ± 0.07	0.74 ± 0.02
11.	NtT1B(B)	5.43 ± 0.15	0.45 ± 0.02	7.89 ± 0.01	10.20 ± 0.006	9.21 ± 0.07	0.79 ± 0.02
12.	NtT1M(A)	3.89 ± 0.08	0.40 ± 0.005	8.89 ± 0.16	10.31 ± 0.006	6.35 ± 0.13	0.84 ± 0.01
13.	NtT1M(B)	4.17 ± 0.1	0.46 ± 0.003	7.45 ± 0.2	10.06 ± 0.006	6.93 ± 0.08	0.85 ± 0.02
14.	NtT1U(A)	4.19 ± 0.12	0.33 ± 0.005	6.51 ± 0.36	10.03 ± 0.02	6.94 ± 0.33	0.63 ± 0.01
15.	NtT1U(B)	4.12 ± 0.07	0.37 ± 0.01	3.51 ± 0.34	10.11 ± 0.03	7.49 ± 0.15	0.73 ± 0.01
16.	ItT1B(A)	4.87 ± 0.04	0.38 ± 0.0005	4.53 ± 0.10	10.16 ± 0.03	8.70 ± 0.23	0.73 ± 0.01
17.	ItT1B(B)	5.49 ± 0.03	0.45 ± 0.004	6.42 ± 0.25	10.35 ± 0.03	8.10 ± 0.17	0.71 ± 0.01
18.	ItT1M(A)	5.0 ± 0.08	0.41 ± 0.004	4.66 ± 0.17	10.15 ± 0.006	7.43 ± 0.30	0.68 ± 0.02
19.	ItT1M(B)	5.27 ± 0.09	0.40 ± 0.004	5.50 ± 0.35	10.23 ± 0.02	8.90 ± 0.16	0.7 ± 0.01
20.	ItT1U(A)	4.17 ± 0.18	0.42 ± 0.01	4.54 ± 0.13	10.20 ± 0.01	8.25 ± 0.22	0.90 ± 0.01
21.	ItT1U(B)	5.93 ± 0.03	0.45 ± 0.01	4.61 ± 0.14	10.46 ± 0.02	8.41 ± 0.06	0.76 ± 0.02
22.	ItT2B	4.98 ± 0.06	0.38 ± 0.01	4.51 ± 0.07	10.23 ± 0.03	9.20 ± 0.04	0.78 ± 0.01
23.	ItT2M	6.57 ± 0.14	0.41 ± 0.03	5.43 ± 0.26	10.11 ± 0.006	9.87 ± 0.34	0.67 ± 0.01
24.	ItT2U	5.49 ± 0.16	0.40 ± 0.005	5.26 ± 0.21	10.01 ± 0.02	10.66 ± 0.23	0.65 ± 0.02

of biochar varied according to the pyrolysis temperature and time, size of the pyrolysis chamber, and nature of the biomass material [23].

3.1.2 Effect of independent parameters on bulk density

The bulk density of the TCH biochar was in the range of 0.3 to 0.5 g/cc. From the set of values listed in Table 1, it was observed that the highest bulk density was recorded for biochar obtained in MT$_1$M (mature coconut husk as fuel, large-sized pyrolysis chamber, and middle layer) setup wherein the samples were collected from the middle layer of the large-sized reactor kept in upright position with mature coconut husk as fuel. The bulk density varied for the different types of fuel and differences in positioning of the reactor. The range of value of bulk density for the samples from the reactors kept upright was 0.4 to 0.5 g/cc, whereas the range of value for the samples from the reactors kept inverted was 0.3 to 0.4 g/cc. The bulk density of matured coconut husk-based biochar was reported to be in the range of 0.3 g/cc [15]. The density of a substance is inversely proportional to temperature; thus, as the temperature increases, the density decreases and vice versa. Biochar has a low bulk density [24] and a high water retention capacity [25], making it an appropriate substrate for light-weight soil mixtures that need to retain moisture. Pastor-Villegas et al. [26] discovered that biochar generated from several types of woods processed in various types of traditional kilns had bulk densities ranging from 0.30 to 0.43 g cm^{-3}.

3.1.3 Effect of independent variable on ash content

The ash content of the biochar ranges from 3 to 11% (Table 2). However, the percentage of ash in TCH biochar produced by traditional kiln was found to be as high as 22.3% [15], whereas the ash content of the chickpea plant, maize cobs, wheat straw, and sugarcane bagasse–based biochar produced at a temperature of 300–500 °C for 3–4 h was in the range of 20–23% [22]. The ash content showed a steady decrease when tender coconut husk was used as fuel. Also, the ash content values were lower when the pyrolysis chamber was kept in inverted position than upright position. The ash content of the biochar obtained is positively correlated with the pyrolysis temperature. Pyrolysis temperature and residence time may influence on the ash content and maximum surface area of biochar [27]. Mohammad et al. [28] and Zhang et al. [29] observed that increase in the temperature increases the ash content.

Biochar's ash content is mostly determined by the ash content of the parent biomass. This varies significantly based on the type of biomass used, as well as the harvesting methods used.

3.1.4 Effect of independent variable on pH

It was observed that the pH of the biochar did not show much variation as it was in the range of 9 to 10. Gopal et al. [15] reported that the pH of the various coconut waste-based biochar is alkaline ranging from 7.9 to 9.7. The pH of the biochar is directly proportional to the temperature profile of combustion chamber during pyrolysis. The concomitant increase in pH with an increase in pyrolysis temperature could be attributed to the reduction of organic functional groups such as –COOH and –OH [28, 29]. Similarly, the Matamba fruit shell has functional groups such as hydroxyl, carbonyl, and the carboxylate (C–O–O-) groups [27]. However, no trend in pH was observed with the varying position or size of pyrolysis chamber or the kind of fuel employed. High pH of biochar makes it a suitable soil amendment. Biochar is typically prepared in a slow pyrolysis manner with more residence periods that are longer than what is reported in the present study. As a result, the practical significance of the influence of residence time on pH-value is restricted. Apart from the obvious association of pH with the residence period, the heating rate and/or heat distribution pattern appears to have no effect on the pH value [30].

3.1.5 Effect of independent variable on electric conductivity (EC)

The EC of the biochar samples showed a wide range of values from 3 to 10 mS/cm, respectively. The changes in EC did not show any pattern with the changes in type of fuel, position, or with varying pyrolysis chamber size. The EC of a solution gets primarily affected by the concentration of ions, the type of ions, and the temperature of the solution. The electric conductivity for tender coconut husk-based biochar was around 2.81 mS/cm [15]. Tasim et al. [22] recorded a maximum EC for the chickpea-derived biochar and minimum EC value for the biochar prepared from Sesbania stem. The EC of biochar samples is dependent on the feedstock composition and pyrolysis temperature [31]. The pyrolysis temperature exhibits positive correction with EC [32, 33]. It could be due to the increasing concentration of ash or residues caused by volatile material loss during pyrolysis process [33]. Also, differences in the ash content in the composition of feedstocks could influence EC of the resultant biochar [32].

3.1.6 Effect of independent variable on total nitrogen content

The total nitrogen content of the TCH biochar recorded is in the range of 0.5 to 1%. The nitrogen content in different coconut waste biochar was ranging from 0.6 to 1.0%, and for tender coconut husk-based biochar, the nitrogen content was 0.9% [15]. The nitrogen content does not appear to be an obvious determinant. There was no clear association between treatment temperature and nitrogen content. A small rise in nitrogen concentration with rising temperature can be detected when the same feedstock is utilized for the production of biochar. The decrease in concentration of other components throughout the devolatilization process is responsible for this relative rise [34].

3.1.7 Effect of independent variable on total phosphorus content

The total phosphorus content of the tender coconut husk biochar was in the range of 0.15 to 0.35% (Table 3). The different coconut biomass residue biochar were reported to have a total phosphorus content ranging from 0.15 to 0.50% [15]. In another study, it was reported that the total phosphorus content of sun-dried coconut husk biochar was as low as 0.07% [35]. Total phosphorus content increased with pyrolysis temperature in different types of biochar [36]. Organic materials when charred the organic phosphorus bonds will break, and the resulting charred substance may contain more soluble phosphorus salts. In general, increased pyrolysis temperature increased the total phosphorus content [37]. The occurrence of multivalent metal cations, like Al, Ca, Mg, and Fe, is responsible for the making of insoluble phosphate in the resultant biochar [38]. But high temperature beyond the volatilization threshold of phosphorus (above 760 °C) often reduces the amount of total and extractable phosphorus in biochar [39, 40]. Phosphorus sorption via biochar is becoming a widespread technique that allows for the turning of biowaste into fertilizer [41].

3.1.8 Effect of independent variable on total potassium content

The total potassium in tender coconut husk biochar ranges from 1.29 to 2.74% (Table 3). According to Gopal et al. [15], the total potassium content of various coconut biomass residues varies from 2.8 to 3.6%. Zemriyetti et al. [42] reported that the total potassium content of coconut husk biochar was about 2.37%, and it was higher than the other feed stocks (cassava pulp and sugarcane bagasse) under study. Pyrolysis temperature has no significant impact on total potassium concentration of the biochar, but the feed stock potassium concentration is the major factor deciding

Table 3 Major nutrients content of TCH-based biochar

SL No	Treatments	Total P (%)	Total K (%)	Total Na (%)	Total Ca (%)	Total Mg (%)	Total S (%)
1.	MT1B	0.18 ± 0.01	1.51 ± 0.02	2.27 ± 0.08	0.66 ± 0.00	0.26 ± 0.00	0.07 ± 0.01
2.	MT1M	0.22 ± 0.01	1.55 ± 0.02	2.30 ± 0.01	0.66 ± 0.00	0.31 ± 0.08	0.08 ± 0.01
3.	MT1U	0.30 ± 0.00	1.70 ± 0.03	2.19 ± 0.13	0.66 ± 0.00	0.40 ± 0.00	0.09 ± 0.01
4.	MT2B	0.32 ± 0.01	1.71 ± 0.02	2.01 ± 0.09	0.59 ± 0.00	0.26 ± 0.00	0.08 ± 0.01
5.	MT2M	0.31 ± 0.00	1.60 ± 0.02	1.99 ± 0.09	0.44 ± 0.00	0.26 ± 0.00	0.08 ± 0.01
6.	MT2U	0.31 ± 0.01	1.72 ± 0.03	1.92 ± 0.09	0.66 ± 0.00	0.26 ± 0.00	0.10 ± 0.01
7.	MT3B	0.35 ± 0.00	2.02 ± 0.03	2.20 ± 0.10	0.66 ± 0.00	0.40 ± 0.00	0.09 ± 0.01
8.	MT3M	0.32 ± 0.01	1.63 ± 0.02	1.89 ± 0.08	0.66 ± 0.00	0.26 ± 0.00	0.08 ± 0.01
9.	MT3U	0.27 ± 0.01	1.29 ± 0.05	1.25 ± 0.11	0.59 ± 0.013	0.31 ± 0.00	0.08 ± 0.01
10.	NtT1B(A)	0.17 ± 0.00	2.21 ± 0.00	2.07 ± 0.09	0.44 ± 0.00	0.26 ± 0.00	0.09 ± 0.00
11.	NtT1B(B)	0.18 ± 0.00	2.29 ± 0.01	2.10 ± 0.11	0.44 ± 0.00	0.26 ± 0.00	0.10 ± 0.00
12.	NtT1M(A)	0.17 ± 0.00	2.05 ± 0.01	1.94 ± 0.10	0.44 ± 0.00	0.26 ± 0.00	0.11 ± 0.00
13.	NtT1M(B)	0.19 ± 0.00	2.32 ± 0.01	2.16 ± 0.10	0.66 ± 0.00	0.26 ± 0.00	0.13 ± 0.00
14.	NtT1U(A)	0.20 ± 0.00	2.23 ± 0.01	2.06 ± 0.09	0.66 ± 0.00	0.26 ± 0.00	0.12 ± 0.01
15.	NtT1U(B)	0.22 ± 0.00	2.37 ± 0.01	2.19 ± 0.10	0.66 ± 0.00	0.40 ± 0.00	0.14 ± 0.00
16.	ItT1B(A)	0.15 ± 0.00	2.19 ± 0.00	1.80 ± 0.09	0.44 ± 0.00	0.26 ± 0.00	0.09 ± 0.00
17.	ItT1B(B)	0.21 ± 0.00	2.30 ± 0.01	1.94 ± 0.09	0.66 ± 0.00	0.26 ± 0.00	0.09 ± 0.01
18.	ItT1M(A)	0.15 ± 0.00	1.64 ± 0.00	1.75 ± 0.09	0.44 ± 0.00	0.26 ± 0.00	0.09 ± 0.00
19.	ItT1M(B)	0.19 ± 0.00	1.87 ± 0.01	1.88 ± 0.09	0.66 ± 0.00	0.26 ± 0.00	0.12 ± 0.00
20.	ItT1U(A)	0.12 ± 0.00	1.52 ± 0.01	1.87 ± 0.11	0.44 ± 0.00	0.26 ± 0.00	0.11 ± 0.00
21.	ItT1U(B)	0.16 ± 0.00	1.89 ± 0.01	2.04 ± 0.10	0.44 ± 0.00	0.26 ± 0.00	0.13 ± 0.01
22.	ItT2B	0.23 ± 0.00	2.07 ± 0.01	2.24 ± .10	0.66 ± 0.00	0.26 ± 0.00	0.13 ± 0.01
23.	ItT2M	0.21 ± 0.00	2.46 ± 0.00	2.30 ± .07	0.66 ± 0.00	0.26 ± 0.00	0.13 ± 0.01
24.	ItT2U	0.23 ± 0.00	2.74 ± 0.02	2.26 ± 0.08	0.66 ± 0.00	0.40 ± 0.00	0.15 ± 0.01

the total potassium content of the biochar produced [37]. According to Yu et al. [43], pyrolysis temperature below 500 °C resulted to accumulate large quantities of available K. But several studies reported that the pyrolysis temperature increased the total potassium content in biochar [36, 44]. Due to the high-vaporization temperature of potassium, the potassium concentration increases with increasing temperature [39, 45].

3.1.9 Effect of independent variable on total sodium content

Tender coconut husk biochar contains total sodium in the range of 1.25 to 2.30% (Table 3). The total sodium content of coconut shell biochar was 1.68% as reported by Shenbagavalli and Mahimairaja [46]. Prakongkep et al.[47] reported that the total sodium concentration of coconut fiber biochars was high (> 1.5%) and this sodium was highly water soluble. If the pyrolysis temperature is less than 600 °C sodium present in the biomass are easily separated out due to their low thermal stability. Above 600 °C sodium enters gaseous phase and hence the inorganic sodium begins to decrease [48]. The volatalization process is maximum between temperature 600 °C and 700 °C. As the pyrolysis temperature rises from 500 °C to 900 °C the overall percent of water soluble sodium decreases to a great extend [48].

3.1.10 Effect of independent variable on total calcium content

The total calcium content of TCH biochar produced ranges from 0.44 to 0.66%. The calcium content in different coconut waste biochar was ranging from 0.04 to 1.0% [47]. In general the calcium content of biochar of various feed stock increased with increasing pyrolysis temperature [36, 49]. According to Prakongkep et al. [47], even though the total calcium present in most of the biochar is high, its solubility in water is low as it mainly exists as calcium carbonate, and hence, its plant availability is very low. As the pyrolysis temperature increases, the soluble calcium content in the biochar decreases, whereas the insoluble calcium content increases [48]. According to Naeem et al. [36], the total concentration of calcium increased with increased volatilization losses of C, H, O, and N.

3.1.11 Effect of independent variable on total magnesium content

The concentration of total magnesium in the TCH biochar was in the range of 0.26 to 0.40%. In coconut shell biochar, the total magnesium content was about 0.58% [46]. Total magnesium content of coconut fiber biochar was found 0.05%, and coconut shell was 0.08% [47]. The total magnesium content increased with increasing pyrolysis temperature, and the total magnesium content is maximum at a pyrolysis temperature of 500 °C [36]. The percent content of extractable magnesium decreases with the pyrolysis temperature beyond 500 °C [48]. In general, the pyrolysis temperature increases the available magnesium content in biochar, but in temperature > 800 °C, it reduces the availability. It is also reported that pyrolysis temperature < 300 °C or > 800 °C leads to the production of biochar with low available nutrients [37].

3.1.12 Effect of independent variable on total sulfur content

Total sulfur content in the tender coconut biochar was in the range of 0.07 to 0.14%. The total sulfur content of coconut husk ranges between 0.16 and 0.17% and not showed much variation as the pyrolysis temperature increases [50]. Wang et al. [51] reported that relatively lower pyrolysis temperature (< 500 °C) keeps total biochar sulfur content intact, and as the temperature increases, gaseous sulfur losses occur. There were no significant changes in sulfur content of biochar as the pyrolysis temperature varies, but the temperature determines the sulfur forms in the biochar [37]. In biochar, sulfur is mainly present as dibenzothiophene and dibenzyldisulfide which are bound to biochar-borne carbon [52]. These organic sulfur forms are converted into gasses and will lose as the pyrolysis temperature increases [53]. Even above 800 °C, some sulfur remains in a recalcitrant form bound to K, Ca, Mg, and Si [54].

3.2 Effect of independent variable on total micronutrients content

Among the micronutrient content of TCH biochar, total iron content ranges from 298.65 to 4121 ppm, the total manganese values vary between 28.08 and 244.67 ppm, total zinc values range from 22.03 to 80.57 ppm, total copper ranges from 10.9 to 25. 28 ppm, and total boron varies from 37 to 76.08 ppm (Table 4). According to Chang et al. (2015), biochar contains good amount of iron, copper, zinc, manganese, and cobalt which can be used as potential source of these elements to plant. Gondim et al. [35] reported that the green coconut husk biochar contains 347 ppm total iron, 13 ppm total Mn, 15 ppm total Zn, and 5 ppm total copper. The total

Table 4 Micronutrients content of TCH-based biochar

SL No	Treatments	Total Fe (ppm)	Total Mn (ppm)	Total Zn (ppm)	Total Cu (ppm)	Total B (ppm)
1.	MT1B	1487.75 ± 15.66	55.05 ± 6.68	32.32 ± 2.65	13.60 ± 1.95	59.50 ± 1.75
2.	MT1M	592. 80 ± 9.93	58.07 ± 7.55	34.72 ± 3.38	24.33 ± 1.80	66.42 ± 4.96
3.	MT1U	646.98 ± 30.30	62.30 ± 2.01	35.30 ± 3.03	17.63 ± 3.35	67.33 ± 3.32
4.	MT2B	2571.97 ± 91.34	168.27 ± 5.72	76.47 ± 2.25	15.87 ± 1.64	69.00 ± 4.44
5.	MT2M	2785.77 ± 88.84	234.88 ± 5.50	75.65 ± 2.99	21.68 ± 2.03	69.92 ± 2.40
6.	MT2U	2001.23 ± 28.43	173.07 ± 6.25	57.70 ± 2.79	19.07 ± 1.00	76.08 ± 2.57
7.	MT3B	1745.22 ± 1.88	164.40 ± 7.58	47.43 ± 2.46	17.68 ± 0.32	74.00 ± 5.48
8.	MT3M	2094.35 ± 63.38	237.73 ± 7.78	66.33 ± 1.82	19.33 ± 3.70	65.58 ± 3.11
9.	MT3U	4121.00 ± 146.88	244.67 ± 12.05	80.57 ± 2.33	25.28 ± 0.49	72.50 ± 8.29
10.	NtT1B(A)	413.58 ± 7.93	29.58 ± 0.18	18.88 ± 1.98	11.13 ± 0.13	37.00 ± 0.50
11.	NtT1B(B)	602.73 ± 9.87	38.20 ± 0.25	22.03 ± 1.03	13.90 ± 1.05	45.75 ± 1.50
12.	NtT1M(A)	298.65 ± 4.10	28.08 ± 1.88	28.73 ± 0.03	11.70 ± 0.65	46.63 ± 1.63
13.	NtT1M(B)	624.95 ± 0.20	39.70 ± 0.65	30.98 ± 2.52	12.03 ± 0.53	50.25 ± 1.75
14.	NtT1U(A)	416.85 ± 14.10	52.60 ± 0.50	26.60 ± 1.30	13.65 ± 0.90	55.25 ± 0.50
15.	NtT1U(B)	688.68 ± 10.83	54.85 ± 0.35	28.78 ± 0.68	16.33 ± 0.27	55.50 ± 3.75
16.	ItT1B(A)	1734.10 ± 126.45	105.90 ± 6.80	31.43 ± 1.38	10.90 ± 0.45	45.00 ± 0.25
17.	ItT1B(B)	1239.53 ± 13.47	104.50 ± 9.55	23.50 ± 1.40	12.43 ± 0.08	46.88 ± 3.88
18.	ItT1M(A)	1870.35 ± 10.35	68.75 ± 0.30	36.70 ± 0.70	11.40 ± 0.35	44.25 ± 1.75
19.	ItT1M(B)	1287.00 ± 2.95	68.13 ± 3.28	26.48 ± 1.42	16.63 ± 0.17	44.63 ± 2.63
20.	ItT1U(A)	875.20 ± 0.70	50.50 ± 0.15	24.65 ± 1.40	13.50 ± 1.25	39.75 ± 4.00
21.	ItT1U(B)	620.85 ± 8.80	64.45 ± 0.40	26.75 ± 1.40	15.93 ± 0.37	47.75 ± 0.50
22.	ItT2B	529.35 ± 6.70	36.23 ± 0.93	36.53 ± 7.58	11.50 ± 0.55	45.50 ± 0.25
23.	ItT2M	704.68 ± 189.83	37.63 ± 0.82	33.48 ± 1.98	15.50 ± 0.05	53.50 ± 2.25
24.	ItT2U	603.60 ± 11.60	55.50 ± 1.35	46.20 ± 1.65	16.43 ± 0.17	59.38 ± 0.63

Table 5 Yield of biochar obtained with varied operating conditions

Size of the combustion chamber	Type of fuel	Positioning of chamber	Amount of fuel (kg)	Initial sample weight (kg)	Final sample weight (kg)	Yield (%)
Large	Mature coconut husk	Normal	19.5	4.150	1.31	31.57
Medium	Mature coconut husk	Normal	22.45	1.45	0.43	29.65
Small	Mature coconut husk	Normal	29.55	0.71	0.24	33.80
Large	Tender coconut husk	Normal	25.19	4.1	1.55	37.80
Large	Tender coconut husk	Inverted	25.83	4.08	1.47	36.03
Medium	Tender coconut husk	Inverted	35.60	1.31	0.44	33.58

concentration of Fe, Zn, Mn, and Cu in the biochar increased with increasing pyrolysis temperature [55, 56]. The process of volatilization of the elements from the biomass during pyrolysis is due to the effect of their sublimation temperature [57]. Micronutrients especially Fe, Zn, Mn, and Cu in the plant biomass are volatilized at temperatures higher than 800 °C [58].

3.3 Optimization of process parameters

The highest yield (%) was observed for the small-sized pyrolysis chamber placed in upright position and using dried mature coconut husk as fuel (Table 5). It was followed by a setup of large-sized combustion chamber kept in upright position using tender coconut husk as fuel which recorded the second highest yield. The temperature distribution pattern is uniform in small-sized chamber compared to large-sized pyrolysis chamber. Considering the yield and physicochemical properties of biochar, the large-sized pyrolysis chamber and mature coconut husk were found to be appropriate. Also, the fuel consumption was minimal while using mature coconut husk as fuel due to its high-fibrous nature compared to TCH. The yield of biochar generally decreases with the increasing temperature due to higher rate of production of syngas [28, 59–61]. Sukartono et al. [62] reported that the coconut shell samples yield 65% biochar at the pyrolysis temperature of 190–280 °C for 8 h. Hence, pyrolysis temperature and the retaining period are the important factors that decide the yield of biochar [63].

4 Conclusion

In this study, biochar was produced from the tender coconut husks which are discarded after consumption of tender coconut water. The production was carried out with varying parameters such as the size of pyrolysis chamber (sample loading tank), type of fuel, and varying positioning of the pyrolysis chamber, and the results were analyzed. The yield of biochar with varying parameters was compared to identify a most suitable method and associated parameters for its production. The best experimental combination yielding the desirable results was MT1U (mature coconut husk as fuel, large-sized reactor, upper layer), wherein the sample from the upper layer of the large-sized reactor was using mature coconut husk as fuel. The physicochemical parameters observed for this combination are: yield (%) = 31.57%, moisture = 2.89 ± 0.16%, bulk density = 0.45 ± 0.001 g/cc, ash content = 8.68 ± 0.20%, pH = 10.51 ± 0.02, electric conductivity = 6.39 ± 0.03 mS/cm, and total nitrogen content = 0.77 ± 0.03%. The large-sized pyrolysis chamber seems to be a best fit for the production of biochar with the upright positioning and with suitable fuel which can be mature or TCH. The pyrolysis temperature was observed to exert a direct effect on certain quality parameters of the biochar. Biochar has multiple utilities as the product can be extensively used as a soil amendment, means of waste management, for treatment of wastewater, carbon sequestration, mitigation of climate changes, etc**.** The process of fermentation followed by pyrolysis of TCH needs to be studied further.

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Data availability All data are available upon request.

Declarations

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