

VALORISATION OF INVASIVE WOODY WEEDS FOR SUSTAINABLE CHARCOAL PRODUCTION: SPECIES-SPECIFIC PATHWAYS AND APPLICATION POTENTIALS

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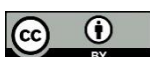
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ABSTRACT

This study explores the sustainable valorisation and charcoal production potentials of three invasive weed species (IWS): *Crotalaria spectabilis* (CTS), *Hibiscus trionum* (HBT), and *Sesbania herbacea* (SSH) through carbonisation. IWS severely hamper agricultural productivity by outcompeting crops, destroying soil structure and increasing costs of weed control in Nigeria. Carbonisation presents a cost-effective, technologically efficient, and sustainable approach for the valorisation of each IWS into charcoal. Each sample was carbonised and analysed for morphological, mass-based, and energy-related properties after heating at 600 °C for 30 min under a limited oxidising environment using a muffle furnace. The resulting charcoals showed unique characteristics related to their anatomical morphologies and thermal behaviour. The mass yields (MY) ranged from 34.62 % $\pm$ 1.30 % to 42.93 % $\pm$ 2.63 %, bulk density (BD) from 131.50 kg/m³ $\pm$ 0.02 kg/m³ to 203.50 kg/m³ $\pm$ 0.01 kg/m³ and higher heating values (HHV) from 25.18 to 25.96 MJ/kg. Further analysis revealed that the specific morphology of IWS is critical for the mass and energy properties of their resulting charcoals' functionality, which supports policy strategies for IWS carbonisation into value-added products. Overall, the study shows that carbonisation of CTS, HBT, and SSH in charcoal is a practical approach to addressing their environmental impacts. Therefore, future studies could explore hybrid fuel formulations and applications of such charcoals in non-energy and functional materials applications.

Keywords: valorisation, carbonisation, *Crotalaria spectabilis*, *Hibiscus trionum*, *Sesbania herbacea*, invasive plants, weed management

INTRODUCTION

The quest for sustainable growth and development has increased global attention to environmentally friendly alternatives to fossil fuels [1]. For countries facing increasing energy demands and environmental degradation, biomass energy has emerged as a crucial aspect of the transition to renewable energy sources [2]. Similarly, the United Nations (UN) Sustainable Development Goal (SDG) number 7 calls for the transition to affordable, sustainable, reliable, and modern energy worldwide by 2030 [3]. This shift will also curb and/or mitigate the twin challenges of global warming and climate change that currently plague growth and development, particularly in developing countries facing energy poverty [4]. Accordingly, the Paris Agreement calls on nations to work to reduce and mitigate greenhouse gas (GHG) emissions by 43 % by 2030, and to achieve net-zero emissions by mid-century in order to limit the global temperatures increase to 1.5 °C above pre-industrial levels [5]. This requires a transition from fossil fuels, such as oil and coal, to renewable energy sources, such as biomass [6].

For developing countries, the recent attention has focused on biomass energy. The valorisation of non-traditional biomass has gained particular importance due to the growing increase in the production of such waste from the agroforestry sector [7]. Significantly, invasive weed species (IWS) are potential candidates for valorisation into affordable and clean energy due to their woody and lignocellulosic nature [8]. IWS are abundant and underutilised and present minor competition to food crops, making them suitable raw materials for conversion into bioenergy and biofuels [9]. These plants have the potential for rapid growth, tolerance to harsh conditions, and the ability to survive in degraded lands [10].

Currently, IWS pose significant socioeconomic and environmental problems worldwide. These plants are known to reproduce aggressively, crowding out native

species and damaging biodiversity, resulting in low land productivity [11]. Traditional strategies for weed control are considered expensive, laborious, and environmentally unsustainable [12]. However, features such as biomass yield, structural tolerance, and high growth rates of IWS present unique opportunities for bioresource conversion [13, 14]. Given this, the valorisation of IWS is a unique strategy for resource recovery, which could transform these ecological liabilities into value-added products and restore ecosystems.

One promising technology for the valorisation of IWS is carbonisation. The process is considered a technologically sound approach for the valorisation of biomass streams, such as IWS, into sustainable charcoal. Carbonisation is a form of pyrolysis that can convert various streams or feedstocks into carbon-rich products such as charcoal under mild conditions of temperature (400 - 700 °C), pressure (1 atm), and residence time (10 - 90 min) [15]. The process can facilitate the transformation of lignocellulosic materials through thermal degradation [16]. Mild process conditions, efficiency, and cost-effectiveness of carbonisation make it suitable for the valorisation of IWS into sustainable charcoals. Crop productivity, farmers' livelihoods, and food security of Nigeria are threatened every year by various IWS that aggressively outcompete cultivated crops, degrade soil health and increase management costs [17, 18]. Studies have reported several invasive and problematic weeds, such as *Lantana camara* [8], *Prosopis juliflora* [19], *Ageratum conyzoides* [20], and *Pontederia crassipes* [21].

In this study, the prospects and challenges for sustainable charcoal production of three selected invasive weed species were examined: *Crotalaria spectabilis* (CTS), *Hibiscus trionum* (HBT), and *Sesbania herbacea* (SSH), which are frequently found in agricultural lands across the country. Studies have shown that CTS, HBT, and SSH are extremely invasive weed species in agricultural lands in Nigeria [22 - 29]. CTS is particularly known to spread rapidly due to

high seed production and for its allelopathic properties that suppress crops and endanger livestock due to its toxicity [23, 27, 28]. Likewise, HBT is a problematic weed that thrives by producing large seeds that can grow even in disturbed soil, ensuring that it survives and outcompetes crops through aggressive growth [24 - 26]. SSH is known to colonise soils and lands with rapid biomass growth, outcompeting food crops. It can survive through seasons using its toxic seeds, which increases its pressure on ecosystems [22, 29]. Despite these challenges, these IWS are woody-stemmed and lignocellulosic in nature, which makes them suitable for valorisation through carbonisation.

Therefore, this study aims to examine the prospects and suitability of carbonisation for the valorisation of *Crotalaria spectabilis* (CTS), *Hibiscus trionum* (HBT), and *Sesbania herbacea* (SSH), which are frequently found on agricultural lands across the country. To the best of the authors' knowledge, this is the first study that explores carbonisation technology as an innovative and sustainable approach for the valorisation of woody stems of problematic, and underutilised invasive weed species, for sustainable charcoal production (SCP). It is anticipated that the findings will provide academics, farmers, and policymakers with empirical data and insights on weed control, management strategies, and valorisation technologies to address the threat of IWS in the country.

EXPERIMENTAL METHODOLOGY

Materials and preparation

This study examined the prospects and suitability of sustainable charcoal production from woody stems of invasive weed species (IWS) *Crotalaria spectabilis* (CTS), *Hibiscus trionum* (HBT), and *Sesbania herbacea* (SSH), commonly found on farms across Nigeria. Mature stems of IWS were harvested from local agricultural lands in Calabar city, Cross River State, Nigeria. Subsequently, the leaves and flowers of each IWS were cut or peeled

off and then sun-dried for three months to remove surface and inherent moisture before carbonisation and subsequent analysis. The dried stems were then sawn into cylindrical sections measuring 9.50 ± 0.865 cm in length, while the diameter of each was on average 1.8 ± 0.685 cm. The stems were then stored in hermetically sealed sample bags before conducting the carbonisation experiments.

Experimental process

Sustainable production of charcoal from the dried IWS stems was accomplished through carbonisation. The experimental approach involved heating ~10 g of the dried stems of *Crotalaria spectabilis* (CTS), *Hibiscus trionum* (HBT), and *Sesbania herbacea* (SSH) in a stainless-steel crucible at a temperature of 600 °C and a residence time of 30 min using a muffle furnace. After this time, the solid carbonised stems of IWS were separated and cooled down to room temperature. Then, the IWS charcoal stems were weighed using a weighing scale to determine the mass yield (MY, %), mass loss (ML, %), bulk density (BD, kg/m³), higher heating value (HHV, MJ/kg), energy density (ED, MJ/m³), and energy yield (EY, MJ) according to the following equations [30 - 33]:

$$\text{Mass yield (MY, \%)} = \frac{\text{Mass of charcoal}}{\text{Mass of raw biomass}} \times 100 \quad (1)$$

$$\text{Mass loss (ML, \%)} = 1 - \text{MY, \%} \quad (2)$$

$$\text{Bulk density (BD, kg/m}^3\text{)} = \frac{\text{mass of charcoal}}{\text{Volume occupied by charcoal}} \quad (3)$$

$$\text{Higher heating value (HHV, } \frac{\text{MJ}}{\text{kg}}\text{)} = 19.85 + 9.34 (\text{ML, \%}) \quad (4)$$

$$\text{Energy density (ED, MJ/m}^3\text{)} = \text{BD, kg/m}^3 \times \text{HHV, MJ/kg} \quad (5)$$

$$\text{Energy yield (EY, MJ)} = \text{MY, \%} \times \text{HHV, MJ/kg} \quad (6)$$

Mass yield (MY, %) is defined as the fraction of charcoal that is formed or remains after carbonisation of raw biomass. Mass loss (ML, %) is defined as the sum of volatile substances lost or released during the carbonisation process [31]. Bulk density (BD, kg/m³) is defined as the amount of charcoal that can

occupy a certain volume or space. This property is critical for assessing the transport, storage potential, and conversion efficiency of any solid fuel. The higher heating value (HHV, MJ/kg) is defined as the total energy packed in or released when a unit mass of any fuel (e.g., charcoal) is combusted [34]. Energy density (ED, MJ/m³) defines the energy in a given volume. The energy yield (EY, %) of any fuel is defined as the amount of energy stored in the charcoal compared to the feedstock. Overall, these parameters are considered useful indicators for evaluating the thermochemical effectiveness, as well as the economic feasibility of charcoal production from various biomass feedstocks [35].

RESULTS AND DISCUSSION

Morphological properties

The aim of this study is to examine and highlight the prospects and suitability of woody stems of invasive, and problematic weeds *Crotalaria spectabilis* (CTS), *Hibiscus trionum* (HBT), and *Sesbania herbacea* (SSH) for sustainable charcoal production. The results showed that carbonisation of the IWS at 600 °C for 30 min under partial oxidising conditions caused significant and specific changes in the morphology of each species, with each transformation being extremely influenced by the intrinsic anatomy of each plant, as shown in Figures 1 - 3.

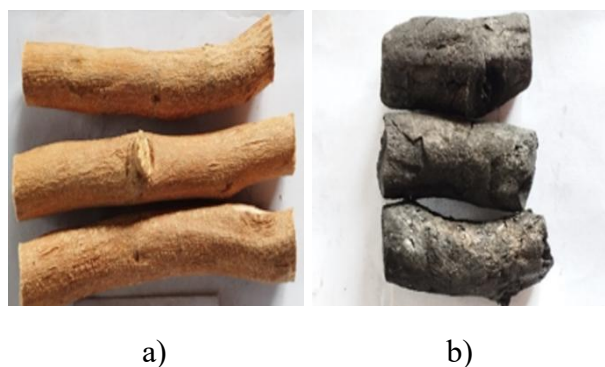


Figure 1. *Crotalaria spectabilis* (CTS): a) raw, b) carbonised

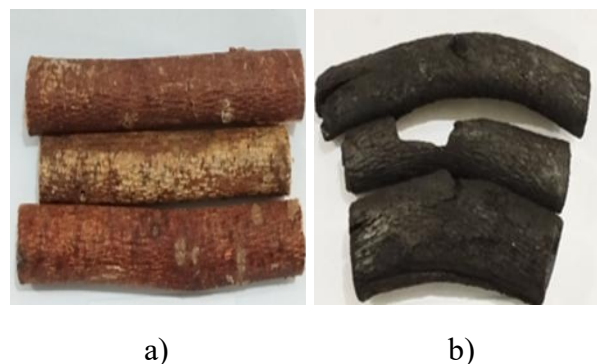


Figure 2. *Hibiscus trionum* (HBT): a) raw, b) carbonised

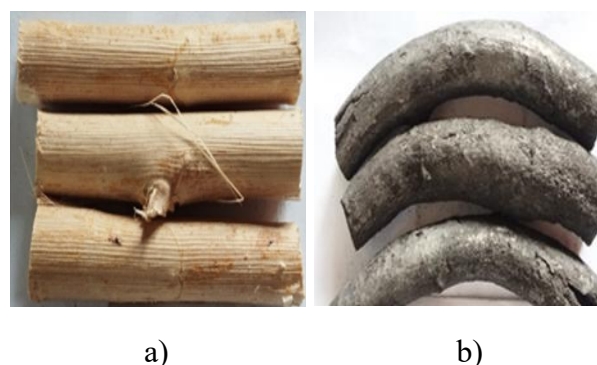


Figure 3. *Sesbania herbacea* (SSH): a) raw, b) carbonised

Figure 1(a) shows that the CTS, which initially appeared fibrous and cylindrical, transformed into a fragmented and angular mass of charcoal. The appearance is characterised by a glossy sheen and noticeable radial cracks as shown in Figure 1(b). It was also observed that charcoal from CTS resists symmetrical deformation, which may be due to the lignocellulosic content, resulting in volumetric shrinkage and longitudinal cracking [36]. Consequently, the charcoal has coarse macropores and structurally fragile fragments, which is typical of lignin-rich biomass [37].

Figure 2(a) shows the delicate, pith-filled, and herbaceous tissues of the HBT sample. After carbonisation, the sample was transformed into a friable charcoal with a distinctive microstructure as shown in Figure 2(b). As observed, the charcoal surface is characterised by the collapse of the pith cavity and degradation of cellulose [38]. Although the sample experienced substantial shrinkage, the structure of the raw sample was maintained,

probably due to the skeletal integrity of its micropores [39].

Figure 3(a) shows the succulent, parenchyma-dominant architecture of the SSH stems. However, after carbonisation, SSH underwent a striking transformation into a dense charcoal with a silvery gloss, with structures that are evident of conchoidal fracturing, but marginally noticeable porosity [37], as shown in Figure 3(b). It was also observed that thermal decomposition resulted in deep longitudinal ruptures, which may be responsible for the reorganisation of the carbon fragments into a combined pitted matrix [40].

Overall, the results showed that carbonisation of IWS is species-specific, and the impact is significantly influenced by anatomical differences, as observed in fracture conversions in CTS, preserved microporosity in HBT, and fissure-based links in SSH. It can be concluded that the structural behaviour of SSH is unconventional for herbaceous plants, while CTS reflects that of slowly pyrolysed hardwood. However, it is important to note that the findings on the morphological properties of the studied charcoals presented in this section are solely based on visual observations. Future studies will explore in-depth characterisation of their properties using analytical techniques.

Mass properties

In this section of the paper, the mass yield (MY), mass loss (ML), and bulk density (BD) of the charcoals of IWS *Crotalaria spectabilis* (CTS), *Hibiscus trionum* (HBT), and *Sesbania herbacea* (SSH) were examined. Table 1 shows the calculated mass-related properties MY, ML, and BD of IWS charcoals using equations 1 - 3.

Table 1. Mass-related properties of IWS charcoals

Charcoal property	Unit	<i>Crotalaria spectabilis</i> (CTS)	<i>Hibiscus trionum</i> (HBT)	<i>Sesbania herbacea</i> (SSH)
Mass yield	MY (%)	42.93±2.63	35.33±0.78	34.62±1.30
Mass loss	ML (%)	57.07±2.63	64.67±0.78	65.38±1.30
Bulk density	BD (kg/m ³)	132.50±0.08	131.50±0.02	203.50±0.01

The MY of the charcoals ranged from 34.62 % ± 1.30 % to 42.93 % ± 2.63 %, while the ML varied from 57.07 % ± 2.63 % to 65.38 % ± 1.30 % after carbonisation at the selected conditions. On the other hand, the BD for the charcoals ranged between 131.50 kg/m³ ± 0.02 kg/m³ and 203.50 kg/m³ ± 0.01 kg/m³. MY, ML, and BD showed that there were specific variations in the thermal resistance and structural behaviour after carbonisation of CTS, HBT, and SSH, as shown in Table 1. Further analysis showed that the highest MY (42.93 % ± 2.63%) was observed in CTS, reflecting its lignocellulosic and woody nature. As such, it is stable under thermal degradation conditions, probably through the cross-linking of aromatic groups [41]. The HBT and SSH charcoals showed lower MY values, with marginal differences between both samples, suggesting similar properties due to the volatilisation of holocellulose during carbonisation [42, 43].

Although charcoals have similar ML, the BD data present interesting findings. Notably, SSH has an outstanding BD (203.50 kg/m³ ± 0.01 kg/m³), which is over 50 % higher than for HBT (131.50 kg/m³ ± 0.02 kg/m³) and CTS (132.50 kg/m³ ± 0.08 kg/m³) and higher than values typically associated with herbaceous charcoal [41]. The values obtained for SSH are in the range of hardwoods (e.g., oak 210 kg/m³), pyrolysed under slow settings, suggesting that SSH stems experience viscous flow-based sintering [41]. During the process, melting and reconfiguration of the thin walls of the cell structures occurs, resulting in the formation of a solid carbon matrix with minimal porosity [44]. In contrast, HBT and CTS maintained their open porous structure,

which can be attributed to their lignin-based rigidity and finer stem structure [39].

The observed variations in the properties of IWS charcoals highlight the trade-offs critical to their behaviour during pyrolysis. High yields of CTS indicate devolatilization supported by fractures typical of lignin-rich biomasses. The extensive micropores and smooth stems of HBT could have enhanced the rapid release of volatiles, although at the expense of particle consolidation. However, fissures observed in SSH may have mediated escape pathways that enhanced densification despite the similar values observed for ML [45].

The combined matrices of SSH stored significantly more mass (~ 58 %) per cubic meter than HBT and CTS, which could offer significant logistic benefits during transportation or storage. Overall, the findings highlight the importance of the interplay between thermal response and anatomical structure, as well as how this influences the conversion of biomass into densified aggregates observed in SSH, fragmentation-dominated residues (CTS), and porosity-preserving shards in HBT.

Energy properties

In this section of the paper, the higher heating value (HHV), energy density (ED), and energy yield (EY) of the charcoals of IWS *Crotalaria spectabilis* (CTS), *Hibiscus trionum* (HBT), and *Sesbania herbacea* (SSH) were examined. Table 2 shows the energy-related properties of IWS charcoals calculated using equations 4 - 6. As observed, the energy-related values of IWS charcoals ranged from 25.18 MJ/kg to 25.96 MJ/kg for HHV, while ED ranged from 3336.34 MJ/m³ to 5282.10 MJ/m³, and EY is between 8.99 MJ and 10.81 MJ. The data revealed marginal variations in the HHV of the CTS, HBT, and SSH, suggesting that the carbon content in the charcoals was standardised by temperature-induced carbonisation. Nonetheless, the distribution patterns of energy-related properties show

significant deviation, which could be due to the specific structure and traits of each IWS.

Table 2. Energy-related properties of IWS charcoals

Charcoal property	Unit	<i>Crotalaria spectabilis</i> (CTS)	<i>Hibiscus trionum</i> (HBT)	<i>Sesbania herbacea</i> (SSH)
Heating value	HHV (MJ/kg)	25.18	25.89	25.96
Energy density	ED (MJ/m ³)	3336.34	3404.59	5282.10
Energy yield	EY (MJ)	10.81	9.15	8.99

The highest ED was observed for SSH (5282.10 MJ/m³), which is 1.58 times higher than for HBT (3404.59 MJ/m³) and CTS (3336.34 MJ/m³), which is largely related to BD. The results indicate that SSH is a remarkably effective fuel in terms of space optimisation, making it suitable for briquetting and applications in small reactor systems. In contrast, the highest EY was observed with CTS (10.81 MJ), surpassing SSH (8.99 MJ) by 20.20 %, indicating its high mass retention during carbonisation. Furthermore, CTS has a high efficiency of converting raw materials into energy, which is crucial for logistically and economically acceptable procurement of biomass. The EY and ED data for HBT were below average due to its low mass yield and moderate density.

The observed differences highlight two complementary pathways for energy optimisation that are strongly influenced by morphological and anatomical responses to carbonisation. CTS samples maximise total energy recovery through structural resistance, while SSH is an example of concentration of volumetric energy through self-consolidation of fissure matrix. The ED of SSH is similar to coal, exceeding values typical of pelletized agroforestry fuels such as rice husks, solidifying its status as a high-performance and renewable biofuel.

The specific properties of each IWS could facilitate adapted strategies for valorisation into charcoal, which tackles global sustainability challenges. The high energy

density (5282 MJ/m³) and morphology of SSH are suitable for dispersed energy solutions. Moreover, its fissure-based matrix could reduce the costs of pelletisation, making it a transformative fuel for household cookstoves in energy-poor regions. It could also be useful as an efficient and dense industrial fuel with the potential to replace 20 - 30 % of coal in co-firing systems. Conversely, CTS charcoal has the highest energy yield (10.81 MJ), which is suitable for use in industrial bioenergy applications. This could ensure stable and consistent heat release, which is practical for energy-intensive processes such as metallurgy, cement production, and power applications [46, 47]. The microporous structure of HBT charcoal could be beneficial for circular economies through approaches such as application as a precursor for activated and porous carbons. Such carbons are widely used as adsorbents in the removal of heavy metals or toxic pollutants during water and wastewater treatment [48]. As observed, SSH charcoal has the highest HHV, which can be used for heating in households or industry. Similarly, it could be co-fired or co-combusted with low-grade coals, as its high HHV suggest synergistic potentials, which is suitable for energy recovery and utilisation applications [49]. Overall, it was found that the energy performance of biomass-derived charcoal is affected by densification, mass retention, and particle architecture, with structural consolidation influencing distribution per unit volume and energy storage.

CONCLUSION

The study examined the sustainable production of charcoal from three invasive, woody, and herbaceous weeds: *Crotalaria spectabilis* (CTS), *Hibiscus trionum* (HBT), and *Sesbania herbacea* (SSH). IWS represent an underutilised, problematic and environmentally challenging stream of biomass that could be used for fuel and energy recovery. However, their conversion into charcoal could alleviate such challenges by converting the weeds into a resource. The results showed that carbonisation under

selected conditions successfully transformed IWS into charcoal. Particularly, SSH was transformed from an ecological problem into a dense, high-energy charcoal, thereby emerging as a leading volumetric energy source. The findings position the valorisation of SSH, CTS, and HBT into charcoal as a dual-purpose solution to address energy poverty and control the spread of IWS through the generation of renewable resources. The findings also revealed that SSH achieved high ED through self-densification, which challenges traditional assumptions about biomass, while CTS preserved its structure during devolatilization, which increased its yield and efficiency. The microporosity of HBT, although less energy-rich, is suitable for applications in the circular economy. Overall, the study presents insights that could shape the valorisation of IWS biomass by transforming ecological burdens into various bioresources in the future.

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