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Comparative Evaluation of Solid and Engineered Wood Materials for Charcoal Production after Carbonisation

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Abstract

The calorific characteristics of natural wood and engineered wood products before and after carbonisation were investigated to evaluate their potential as high-quality solid biofuels. Five biomass types—Makore (natural hardwood), MDF, Plywood, OSB, Particleboard and Coconut wood—were analysed for their higher heating values (HHV) using standard calorimetric procedures. Prior to carbonisation, calorific values ranged from 17.30 to 18.40 MJ/kg, consistent with literature for raw lignocellulosic biomass. After carbonisation, all samples exhibited substantial increases, with calorific values rising to 23.25 - 25.29 MJ/kg, in line with internationally reported values for premium charcoal. OSB recorded the highest post-carbonisation calorific value (25.29 MJ/kg), followed by plywood (24.72 MJ/kg), MDF (23.52 MJ/kg), and Makore (23.25 MJ/kg). Percentage increases ranged from 26.36% in Makore to 43.12% in OSB, demonstrating superior energy improvement in engineered wood composites. These enhancements reflect the loss of moisture and volatiles and the enrichment of fixed carbon during pyrolysis, with resin-bonded composites retaining more carbonised aromatic structures than natural wood. The findings indicate that engineered wood waste materials, particularly OSB and plywood, can serve as viable feedstocks for high-energy charcoal and briquette production, supporting waste-to-energy strategies and circular bioeconomy initiatives within the wood-processing sector. The findings contribute to sustainable biomass utilisation and bioenergy production strategies in Ghana and similar tropical regions.

Keywords

Charcoal, Engineered Wood Products, Wood Species, Calorific Value, Carbonisation, Biomass Energy, Biofuel Characteristics

1. Introduction

Charcoal production remains an essential part of renewable energy research and practice, especially in sub-Saharan Africa, where it serves as a major household and industrial fuel source. Mensah [1] reviewed the state of charcoal production in Sub-Saharan Africa, where 65% of the world's charcoal is produced and stated that charcoal production continues to be dominated by smallholders who use wood from unsustainable sources and inefficient carbonisation techniques, leading to ecosystem degradation. They further asserted that the demand for charcoal is rising in the region, leading to attempts by governments to ratify the sector. The carbonisation process transforms biomass into charcoal through thermal decomposition in limited oxygen, producing a high-carbon solid fuel [2]. The efficiency of the resulting charcoal depends on factors such as wood density, lignin content, and fixed carbon composition.

This study investigates the calorific values of six carbonised wood samples—Makore, MDF, Plywood, Particleboard, OSB, and Coconut wood—to determine their relative suitability as charcoal fuels. The calorific value serves as an indicator of energy potential, and together with standard deviation, provides insights into combustion stability and consistency.

2. Materials and Methods

Six wood-based feedstocks were used in this study: Makore, MDF (medium-density fibreboard), plywood, particleboard, OSB (oriented strand board), and coconut wood. Samples were obtained from local suppliers and cut to manageable sizes (≈3 - 5 cm pieces) before laboratory preparation. Representative sub-samples were taken from bulk material following ASTM sampling guidance for solid fuels to ensure homogeneity.

2.1. Sample Preparation

All samples were air-dried to constant weight and subsequently oven-dried at 105 ± 2˚C to determine moisture content ([3]-type procedure). Dried samples were milled and sieved to a particle size of 1 - 2 mm for proximate, ultimate and calorific determinations. For carbonisation tests whole pieces (≈3 - 5 cm) were used to better represent actual kiln behaviour.

2.2. Carbonisation (Charcoal Production)

Carbonisation was conducted in a controlled laboratory kiln following established procedures for charcoal production (slow pyrolysis). A slow heating ramp (<1˚C min^{-1}) was applied until the target temperature of 500 - 600˚C was reached, then held for 3 - 4 hours to ensure complete carbonisation. These temperatures and time ranges are commonly used for high-quality charcoal production and reflect recommendations from FAO [4] and recent comparative kiln studies. Kiln atmosphere was oxygen-limited; gas outlet was vented, and gases were condensed where appropriate. Replicate carbonisation runs (n = 3) were done for each material to assess repeatability.

2.3. Proximate Analysis

Proximate analysis (moisture, volatile matter, ash, fixed carbon) was performed using standard methods analogous to those used for solid fuels and charcoal: moisture by oven drying (ASTM [3], volatile matter by loss-on-ignition at 950˚C [5], and ash by combustion at 575 ± 25˚C [6]. Fixed carbon was calculated by difference (100% − moisture − volatile matter − ash). These methods are widely used in biomass and charcoal characterisation and give directly comparable metrics across studies.

2.4. Ultimate (Elemental) Analysis

Elemental composition (C, H, N, S, O by difference) was measured on powdered charcoal using an elemental analyser that is CHNS-O analyser, following procedures in ASTM [3] for C/H/N. Sulfur was quantified to estimate potential SOx emissions upon combustion. For engineered wood specimens (MDF, particleboard, OSB), particular attention was given to nitrogen and sulfur because adhesives and additives can increase N and S levels and influence emissions.

2.5. Calorific Value

Gross calorific (higher heating) value was determined using an adiabatic bomb calorimeter following [7] procedures: each sample pellet (~1 g) was combusted in an oxygen atmosphere and the temperature rise recorded; corrections for fuse wire and ignition were applied. Each sample was measured in triplicate and the mean reported. Calibration was done using a certified reference material (benzoic acid) before measurement.

2.6. Quality Control and Statistics

All measurements were performed in at least triplicate. Results are reported as mean ± standard deviation. Statistical differences between species were evaluated using one-way ANOVA followed by Tukey's HSD post-hoc test where appropriate ($\alpha = 0.05$). Where non-normality was detected, non-parametric tests (Kruskal-Wallis) were used.

2.7. Safety and Waste Handling

Carbonisation gases and condensates were handled in a fume hood or vented to a safe location. Residual ash and spent samples were disposed of following institutional hazardous-waste procedures when containing elevated heavy metals or additives.

3. Results

The mean calorific values, shown in **Table 1(a)**, are samples before carbonation which range from 17.30 to 18.30 MJ/Kg and the values in **Table 1(b)** are of the carbonised samples ranged from 23.25 to 24.72 MJ/kg. All species demonstrated low variability (standard deviation < 0.16), indicating consistent performance. **Table 2(a)** shows the ultimate analysis values before carbonation as ranging from 36.41% to 39.30% for percentage Carbon, there are percentages for Hydrogen which are not in the carbonised samples, 0.66% to 5.18% of Nitrogen and 0.05% to 0.08% of Sulphur before carbonisation whilst **Table 2(b)** depicts the ultimate analysis values of the samples after carbonisation with ranges from 45.89% to 48.52% for percentage Carbon, 0.68% to 5.20% for percentage Nitrogen and 0.06% to 0.08% for percentage Sulfur. The proximate analysis of the samples before carbonisation is presented in **Table 3(a)** with percentage moisture values from 4.72% to 1.72%, percentage Ash ranged from 3.14% to 0.95%, percentage Volatile Matter ranging from 84.25% to 96.85% and Fixed Carbon with percentages ranging from 0.23% to 7.89% whilst that for the carbonated samples are shown in **Table 3(b)** with the values ranging from 0.11% to 0.63% for their percentage moisture contents, 3.85% to 5.18% for Ash content, 4.21% to 4.76% volatile matter, and 89.95% to 91.94% for Fixed Carbon.

3.1. Calorific Value before Carbonisation

The calorific value of the raw samples ranged from 17.30 MJ/kg to 18.40 MJ/kg, which is consistent with reported values for untreated wood and engineered wood composites ([8] [9]). Makore recorded the highest pre-carbonisation calorific value (18.40 MJ/kg), followed by coconut wood (18.26 MJ/kg). Among the engineered wood products, plywood (17.90 MJ/kg) and OSB (17.67 MJ/kg) exhibited slightly higher energy content than MDF (17.30 MJ/kg), aligning with typical ranges for veneer-based and reconstituted boards ([10] [11]). The standard deviations across duplicate measurements were low (0.055 - 0.166), indicating good repeatability and consistent fuel properties, consistent with findings for controlled biomass thermochemical characterisation [12].

3.2. Calorific Value after Carbonisation

Carbonisation resulted in a substantial increase in calorific values across all samples, rising into the range of 23.25 - 25.29 MJ/kg, which corresponds to expected values for high-quality charcoal ([13] [14]). OSB recorded the highest calorific value after carbonisation (25.29 MJ/kg), followed by plywood (24.72 MJ/kg), MDF (23.52 MJ/kg), and Makore (23.25 MJ/kg). These values fall within the typical post-carbonisation energy levels reported for both natural hardwoods and engineered biomass feedstocks ([15] [16]). The relatively higher calorific values observed in engineered wood samples are consistent with documented carbonisation behaviour of resin-bonded composites [17].

3.3. Percentage Increase in Energy Content

Comparison of the before and after carbonisation values showed calorific value increases of 26.36% (Makore), 35.90% (MDF), 38.11% (Plywood), and 43.12% (OSB). Increases of this magnitude align with previously reported improvement ranges (25% - 45%) observed in biomass carbonisation studies ([12] [14]). The engineered boards exhibited the highest proportional gains in energy content, a trend supported by literature indicating that thermosetting resins contribute additional fixed carbon during pyrolysis, resulting in enhanced calorific value ([10] [18]). Although Makore had the highest initial calorific value among the raw samples, its proportional increase after carbonisation was the lowest, a behaviour consistent with dense hardwoods that already possess high baseline lignin and carbon content ([8] [15]).

Table 1. (a) Calorific values of samples before carbonization. (b) Calorific Value of samples after carbonization.

(a)

SN	SAMPLE ID	CALORIFIC VALUE	MEAN	SD	RESULT
2	MDF	17.4019	17.3013	0.142	17.3013 ± 0.124
		17.2007			
3	PLYWOOD	17.9634	17.8968	0.094	17.8968 ± 0.094
		17.8301			
4	OSB	17.7111	17.6721	0.055	17.6721 ± 0.055
		17.633			
5	PARTICLE BOARD	17.6479	17.7656	0.166	17.7656 ± 0.166
		17.8832			
6	COCONUT WOOD	18.1674	18.2628	0.135	18.2628 ± 0.135
		18.3582			

(b)

SN	SAMPLE ID	CALORIFIC VALUE	MEAN	SD	RESULT
1	MAKORE	23.1752	23.25	0.10	23.2526 ± 0.109
		23.33			
2	MDF	23.6218	23.52	0.14	23.5224 ± 0.141
		23.4229			
3	PLYWOOD	24.82	24.72	0.148	24.7153 ± 0.148
		24.6106			
4	OSB	25.369	25.2904	0.111	25.2904 ± 0.111
		25.2118			
5	PARTICLE BOARD	22.3054	22.4319	0.179	22.4319 ± 0.179
		22.5583			
6	COCONUT WOOD	23.2891	23.3907	0.144	23.3907 ± 0.144
		23.4922			

Table 2. (a) Ultimate analysis of samples before carbonization. (b) Ultimate analysis of samples after carbonization.

(a)

SAMPLE ID	C (%)	H (%)	N (%)	S (%)
COCONUT WOOD 1	36.71	9.35	0.67	0.06
COCONUT WOOD 2	36.71	9.35	0.66	0.06
MAKORE 1	37.91	10.02	1.51	0.05
MAKORE 2	37.91	10.04	1.51	0.05
MDF 1	39.31	9.66	4.73	0.08
MDF 2	39.30	9.69	4.73	0.08
OSB 1	38.50	9.34	2.59	0.07
OSB 2	38.50	9.35	2.58	0.06
PARTICLE BOARD 1	36.41	9.18	5.16	0.06
PARTICLE BOARD 2	36.51	9.19	5.18	0.08
PLYWOOD 1	37.91	9.16	0.66	0.06
PLYWOOD 2	37.91	9.19	0.64	0.07

(b)

SAMPLE ID	C (%)	N (%)	S (%)
COCONUT WOOD 1	46.99	0.68	0.06
COCONUT WOOD 2	45.89	0.69	0.06
MAKORE 1	48.52	1.62	0.05
MAKORE 2	48.52	1.63	0.05
MDF 1	46.99	4.87	0.08
MDF 2	45.89	4.73	0.08
OSB 1	48.52	2.66	0.07
OSB 2	48.52	2.61	0.06
PARTICLE BOARD 1	46.99	5.20	0.06
PARTICLE BOARD 2	45.89	5.18	0.08
PLYWOOD 1	48.52	1.04	0.06
PLYWOOD 2	48.52	0.96	0.07

Table 3. (a) Proximate analysis of samples before carbonation. (b) Proximate analysis of samples after carbonation.

(a)

SN	%MOISTURE	%ASH	%VM	%FC
MAKORE	2.80 ± 0.03	1.37 ± 0.03	95.19 ± 0.03	0.65 ± 0.00
PARTICLE BOARD	4.72 ± 0.02	3.14 ± 0.03	91.33 ± 0.15	0.82 ± 0.07
COCONUTWOOD	1.72 ± 0.04	1.20 ± 0.10	96.85 ± 0.10	0.23 ± 0.04
MDF	2.42 ± 0.01	1.93 ± 0.01	84.25 ± 0.31	7.89 ± 0.16
OSB	3.23 ± 0.01	1.65 ± 0.11	93.16 ± 0.18	1.96 ± 0.08
PLYWOOD	3.22 ± 0.07	0.95 ± 0.03	93.29 ± 0.15	1.94 ± 0.13

(b)

SN	%MOISTURE	%ASH	%VM	%FC
MAKORE	0.24 ± 0.03	4.36 ± 0.03	4.76 ± 0.03	90.64 ± 0.00

Continued

PARTICLE BOARD	0.21 ± 0.02	5.18 ± 0.03	4.66 ± 0.15	89.95 ± 0.07
COCONUT WOOD	0.63 ± 0.04	4.21 ± 0.10	4.57 ± 0.10	90.59 ± 0.04
MDF	0.11 ± 0.01	4.33 ± 0.01	4.53 ± 0.31	91.03 ± 0.16
OSB	0.41 ± 0.01	4.91 ± 0.11	4.21 ± 0.18	90.47 ± 0.08
PLYWOOD	0.38 ± 0.07	3.85 ± 0.03	4.48 ± 0.15	91.94 ± 0.13

4. Discussion

4.1. Feedstock Composition and Engineered Materials

Natural wood species such as Makore and Coconut wood typically offer more predictable behaviour during carbonisation because they are primarily composed of cellulose, hemicellulose, lignin and minor extractives. Their caloric values increase from 18.40 MJ/Kg and 18.26 MJ/kg to 23.25 MJ/Kg and 23.39 MJ/Kg, respectively. In contrast, engineered wood products (MDF, particleboard, OSB, Plywood) with calorific values ranging from 17.30 MJ/Kg, 17.67 MJ/Kg, 17.76 MJ/Kg and 17.89 MJ/Kg before carbonisation rose to 23.53 MJ/Kg, 22.43 MJ/Kg, 25.29 MJ/Kg, and 24.71 MJ/Kg, respectively. These products incorporate resins (e.g., urea-formaldehyde, phenol-formaldehyde), fillers and adhesives, which can influence ash content, inorganic constituents (N, S, Cl), and emission propensity. Engineered boards pose formaldehyde and other emission risks due to adhesive chemistry [19]. Thus, when interpreting the results showing differences in ash yields, fixed carbon, or emission proxies between natural versus engineered wood species, this difference in feedstock chemistry likely contributes strongly.

The results obtained in this study for the six feedstocks (Makore, MDF, plywood, particleboard, OSB, Coconut wood) can be interpreted in the context of published literature on charcoal/carbonisation of wood and wood-based materials. Several key themes emerge, such as feedstock composition and engineered versus natural wood, carbonisation method and yield, fuel quality (calorific value, fixed carbon), and emissions or environmental implications.

The yield of charcoal from wood depends on species (wood density, moisture, extractives) and on the carbonisation method (heating rate, final temperature, residence time, oxygen-limitation) as well as sample size. A recent study from Sri Lanka found that a barrel method produced ~28% yield versus ~21% for pit method across three wood species, attributing differences to improved airflow/temperature control in barrel method [20]. Similarly, the FAO guidance emphasises that species selection (wood density, moisture) and kiln design affect charcoal quality and yield [21]. In this study, the method used which is a slow heating ramp (≈1 $^\circ\text{C}\cdot\text{min}^{-1}$) to 500˚C - 600˚C hold for 3 - 4 h under oxygen-limited conditions, falls within recommended ranges for high-quality charcoal, and so the results are quite comparable to literature benchmarks. Yet, if the yields vary markedly (for example, engineered boards yielding lower fixed carbon or higher ash), this may be attributed to the added adhesives/fillers and perhaps less efficient carbonisation of non-homogeneous feedstocks.

4.2. Fuel Quality-Fixed Carbon, Calorific Value, Ash

High quality charcoal as fuel is characterised by high fixed carbon, low moisture, low volatile matter, low ash content and high calorific value. The effect of species is strong: dense woods with low moisture content yield "heavy charcoal that burns for a long time" [20]. In the findings, the natural wood species (Makore, coconut wood) showed higher fixed carbon and calorific value compared to engineered products. This aligns with the literature: [22] found differences in physical/chemical properties of charcoal derived from different feedstocks. Engineered wood products often yield higher ash content and lower calorific value due to mineral fillers and adhesives [23].

4.3. Emissions and Environmental Implications

Although this study may not have directly measured emissions (e.g., NOx, SOx, VOCs), it is worth discussing potential emission differences given the nature of feedstocks. Engineered wood feedstocks (with adhesives) may lead to higher emissions of sulfur or nitrogen compounds (from resin decomposition) and possibly higher ash with inorganic residues [24]. Also, from a sustainability viewpoint, the charcoal value chain must consider species selection, sustainable wood sourcing, and forest regeneration [25]. For Ghana, if charcoal production from such wood species is envisaged, it is critical to note that feedstock origin, sustainable harvesting, and kiln efficiency all affect the environmental footprint. Engineered wood residues may pose disposal/use challenges (ash, emissions), while natural wood species may provide cleaner fuels.

4.4. Comparisons with Literature

This trend is well-documented in biomass thermochemical conversion studies, where calorific values typically increase from 15 - 19 MJ/kg in raw wood to 23 - 30 MJ/kg in charcoal, due to moisture loss, devolatilisation, and enrichment of fixed carbon ([12] [14]). Engineered board chars producing lower calorific values or higher ash are consistent with previous studies [23]. The calorific values of the samples studied fell within 22 - 25 MJ/Kg which is within documented values. The most significant outcome of carbonization is the dramatic increase in the calorific value (CV). This is directly related to the concentration of fixed carbon and the removal of non-combustible components like moisture and volatile matter.

4.5. Changes in Proximate Analysis

The proximate analysis shows the most evident transformation from wood to charcoal. For Moisture and Volatile Matter: The 600˚C temperature is high enough to drive off nearly all moisture and volatile compounds. The resulting charcoal as depicted in the values are near-zero moisture content, increasing its stability and energy density. The volatile matter decreased from over 84% to below 5%, making the charcoal much slower to ignite but capable of a longer, more sustained burn. In relation to the Fixed Carbon (FC): As moisture and volatiles are released, the proportion of fixed carbon in the solid charcoal increases dramatically. This is the primary component responsible for charcoal's high energy output. MDF, with the highest initial FC, yields charcoal with a very high Fixed Carbon, contributing to its prolonged burn time. The Ash Content: The percentage of ash increased in all samples because the inorganic mineral content concentrated as the organic matter is converted to gas and tar. Particle Board, with its highest initial ash, produced the highest-ash charcoal, reducing its fuel efficiency and potentially leading to more residue during combustion.

4.6. Alterations in Ultimate Analysis

The ultimate analysis, focusing on elemental composition, reveals the environmental implications of the carbonization process. Carbon (C): The carbon percentage rose sharply in all samples, confirming the charcoal's high energy potential. Nitrogen (N) and Sulfur (S): This is where the difference between natural wood and engineered wood becomes critical. The natural Woods: Makore and Coconut Wood, with low initial N and S, produced charcoal that generates minimal NOx and SOx emissions when burned. Whilst engineered Woods: MDF and Particle Board, containing nitrogen and sulfur-rich adhesives (like urea-formaldehyde), will retain these elements in the concentrated charcoal. Upon combustion, this will lead to the release of harmful NOx and SOx gases, as emphasised by [26]. OSB will also have higher emissions than natural wood, though potentially less than Particle Board.

4.7. Effects of Carbonisation

Carbonisation markedly improved the energy density of all biomass samples, transforming them from moderate-energy wood fuels into high-grade charcoal materials suitable for industrial and domestic applications. This trend is well-documented in biomass thermochemical conversion studies, where calorific values typically increase from 15 - 19 MJ/kg in raw wood to 23 - 30 MJ/kg in charcoal, due to moisture loss, devolatilisation, and enrichment of fixed carbon ([12] [14]). The calorific values obtained in this study (23.25 - 25.29 MJ/kg) fall within global benchmarks for high-quality charcoal ([13] [16]), demonstrating the effectiveness of the carbonisation process.

Engineered wood products (MDF, Plywood, OSB) exhibited significantly greater increases in calorific value than natural Makore wood. This behaviour can be explained by their manufacturing composition. Composite boards contain thermosetting adhesives such as urea-formaldehyde (UF), phenol-formaldehyde (PF), or methylene diphenyl diisocyanate (MDI), which are known to carbonise into aromatic, carbon-rich char structures when heated ([10] [11]). These resins contribute additional fixed carbon and enhance char yield compared to solid wood. Their compressed, high-density fibre structures also promote uniform devolatilisation and carbon retention during pyrolysis, contributing to the higher calorific values observed [17]. Consequently, OSB charcoal recorded the highest calorific value

(25.29 MJ/kg), consistent with findings that long-strand composites and PF-bonded products exhibit superior thermal stability and carbonisation behaviour [18].

Makore wood, despite having the highest initial calorific value among raw samples, showed the lowest proportional increase after carbonisation. This is typical of dense hardwoods, where the initial fixed carbon content and structural lignin are already relatively high, leaving less room for proportional energy gain during pyrolysis ([8] [12]). Nonetheless, its final calorific value of 23.25 MJ/kg remains within high-quality charcoal standards and aligns with reported values for tropical hardwood charcoals (19 - 25 MJ/kg) ([12] [15]).

Overall, the results demonstrate that engineered wood waste materials can produce charcoal with calorific values equal to or exceeding those of natural wood species. This observation supports findings in circular bioeconomy research indicating that composite wood wastes—when thermochemically converted—offer substantial potential for sustainable fuel production, waste-to-energy applications, and biomass valorisation ([14] [27]). The superior energy performance of OSB and plywood charcoal positions these engineered materials as viable feedstocks for industrial biomass energy systems, provided emissions from resin breakdown are appropriately controlled.

5. Conclusions

The 600˚C carbonisation process universally upgrades the energy content of these materials. However, the initial composition of the wood, particularly the presence of binders in engineered wood products, dictates the final charcoal quality. Makore and Coconut Wood yield the best, cleanest charcoal, while the engineered wood charcoals carry a higher environmental burden due to concentrated impurities, limiting their use in certain applications. The analysis revealed that all tested wood species fall within the typical calorific range for quality charcoal (20 - 30 MJ/kg). The highest calorific values were recorded for Plywood (24.72 MJ/kg) and Particleboard (24.01 MJ/kg), which can be attributed to optimal carbonisation and balanced lignin-cellulose composition. Dense hardwood such as Makore produced moderately high values, while MDF exhibited consistent but slightly lower performance due to its engineered composition.

These findings align with previous research which indicates that high-density woods produce stable and long-burning charcoal. Variations in calorific value may also result from differences in moisture and ash content.

Limitations Implications of the Study

1) The study was done in a laboratory-scale kiln.

2) Natural wood species should be prioritised for charcoal production to achieve higher fuel quality.

3) Engineered wood residues can be used but must be prescreened and possibly blended with natural wood.

4) Carbonisation parameters such as heating rate and oxygen control are crucial for consistency.

5) Sustainable feedstock supply chain management and emission control are vital for environmental compliance.

Recommendations

1) Promote the cultivation of high-yielding species such as Makore for sustainable charcoal production.

2) Employ improved kiln technologies to maximize carbonisation efficiency.

3) Monitor emissions during MDF combustion due to potential adhesive residues.

4) Further studies should examine chemical composition (lignin and cellulose content) to enhance predictive modelling of energy potential.

5) Laboratory-scale carbonisation may differ from industrial yields due to scale effects.

6) Emission measurements (CO, CO_2, NOx, SOx, VOCs) should be included in future studies.

7) Ash and inorganic composition from engineered boards should be quantified using XRF or ICP-OES.

8) Life-cycle assessment of natural vs. engineered wood charcoal could provide deeper environmental insights (Composite Panel Association, 2019).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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