

Article

Carbonisation of *Quercus* spp. Wood: Temperature, Yield and Energy Characteristics

Juan Carlos Contreras-Trejo ¹, Artemio Carrillo-Parra ² , Maginot Ngangyo-Heya ³ ,
José Guadalupe Rutiaga-Quñones ⁴ , Jorge Armando Chávez-Simental ² and José Rodolfo Goche-Télles ^{5,*}

¹ Programa Institucional de Doctorado en Ciencias Agropecuarias y Forestales (PIDCAF), Universidad Juárez del Estado de Durango (UJED), Durango 34100, Mexico; jcarlosct1994@hotmail.com

² Instituto de Silvicultura e Industria de la Madera (ISIMA), Universidad Juárez del Estado de Durango (UJED), Durango 34120, Mexico; acarrilloparra@ujed.mx (A.C.-P.); jorge.chavez@ujed.mx (J.A.C.-S.)

³ Facultad de Agronomía (FA), Universidad Autónoma de Nuevo León (UANL), Escobedo 66050, Mexico; nheyamaginat@yahoo.fr

⁴ Facultad de Ingeniería en Tecnología de la Madera (FITECMA), Universidad Michoacana de San Nicolás de Hidalgo (UMSNH), Morelia 58040, Mexico; jose.rutiaga@umich.mx

⁵ Facultad de Ciencias Forestales y Ambientales (FCFA), Universidad Juárez del Estado de Durango (UJED), Durango 34110, Mexico

* Correspondence: jgoche@ujed.mx

Abstract

Energy production is a global concern, encouraging the search for sustainable alternatives such as charcoal, a promising solid biofuel. This study evaluated the effects of temperature and carbonisation time on charcoal produced from *Quercus* wood. Carbonisation was carried out at 550 °C for 30 min, 700 °C for 30 min and under two progressive heating profiles: one starting at 550 °C for 30 min and increasing to 700 °C for a further 30 min, and another starting at 300 °C for 2 h and rising to 1000 °C for 10 min. Mass and volumetric yield, bulk density, proximate analysis, calorific value, energy yield and fuel ratio were determined. The results showed that carbonisation temperature affected charcoal properties. Mass and volumetric yields were highest at 550 °C (30.10% and 4.81 m³ t⁻¹) in *Q. convallata* and *Q. urbanii*. At higher temperatures, bulk density (0.56 g cm⁻³), fixed carbon (91.51%) and calorific value (32.82 MJ kg⁻¹) increased in *Q. urbanii*. Lower temperatures led to lower moisture levels (2.46%) and a higher energy yield (48.02%). Overall, temperatures above 700 °C improved energy properties, while those below 550 °C favoured higher yields. Species' characteristics also influenced charcoal quality. These findings offer valuable insights into optimising the carbonisation of *Quercus* species and supporting the development of more efficient, sustainable charcoal production methods.

Keywords: charcoal; *Quercus urbanii*; *Quercus convallata*; mass yield; volume yield; carbonisation temperature; energy yield; proximate analysis



Academic Editors: Marcos Alberto Coronado Ortega and José Ramón Ayala Bautista

Received: 18 June 2025

Revised: 15 July 2025

Accepted: 17 July 2025

Published: 19 July 2025

Citation: Contreras-Trejo, J.C.; Carrillo-Parra, A.; Ngangyo-Heya, M.; Rutiaga-Quñones, J.G.; Chávez-Simental, J.A.; Goche-Télles, J.R. Carbonisation of *Quercus* spp. Wood: Temperature, Yield and Energy Characteristics. *Processes* **2025**, *13*, 2302. <https://doi.org/10.3390/pr13072302>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The increase in world population combined with a growing energy demand (mainly fossil fuels) and the increase in CO₂ emissions represents one of the main threats to climate change [1,2]. In this context, the use of lignocellulosic biomass for energy production is gaining greater interest due to its properties as a renewable, ecological and easily accessible source [3,4]. Technical and economic limits of natural gas have highlighted solid biofuels like charcoal as a viable, low-impact alternative [5]. Depleting hydrocarbon reserves has further driven focus on the efficient carbonisation of woody biomass, requiring detailed

physical and chemical characterisation [6]. However, although the direct burning of biomass is the most commonly used method for harnessing its energy, it has several limitations that affect its efficiency, including a low calorific value, high moisture content in the feedstock, a high percentage of volatile compounds and variability in ash content—all of which reduce the effectiveness of the combustion process [7,8]. These disadvantages can be mitigated by pyrolysis, a process that transforms biomass into a high carbon biofuel.

The carbonisation of biomass is a pyrolytic process, with charcoal as the main product, which plays a crucial role in the metallurgical industry where it is used as an alternative to fossil coal, since charcoal can contribute to reducing the emissions generated by coke in metal reduction processes. In addition, biomass carbonisation also produces biogas and pyrolytic acid, which broadens the possibilities of using these by-products [9]. Apart from its use in iron and steel production, charcoal is also employed in the purification of toxic gases and the desulfurisation of industrial emissions [10,11]. Charcoal can be converted into activated carbon at temperatures close to 725 °C, yielding a highly porous material used in the purification of liquids and gases, the removal of colourants, the adsorption of impurities and industrial catalysis [12]. Complementarily, biochar—produced from organic waste—has shown strong potential in environmental applications such as soil remediation, water treatment and carbon sequestration, due to its low cost and high adsorption capacity [13]. Its ability to serve as a renewable carbon source makes charcoal an increasingly valued option for energy production, contributing to the reduction of dependence on fossil fuels and their associated pollutant emissions [14]. However, the quality and yield of charcoal are often highly dependent on specific parameters during its production, such as pyrolysis temperature, pressure, heating rate and residence time in the reaction zone [15]. Pyrolysis involves the thermal decomposition of organic materials in an oxygen-free environment, typically using inert gases such as nitrogen or helium to maintain controlled conditions [16].

In the carbonisation process, conditions can be adjusted to optimise the yield of the solid product. As a result, new applications are currently being explored for carbonised materials, which are generally produced at temperatures ranging from 300 °C to 600 °C [17]. High pyrolysis temperatures offer several benefits in charcoal production, including lower volatile matter content, increased density and higher fixed carbon levels, all of which contribute to a greater calorific value [18]. In addition, charcoal quality depends on factors such as high wood density, low ash content and a high lignin concentration. These characteristics, along with increased fixed carbon and reduced levels of volatiles and extractives, significantly influence both yield and overall quality [19].

A substantial body of research exists on low-temperature carbonisation; however, most studies concentrate on charcoal produced at temperatures below 1000 °C. In general, both wood characteristics and pyrolysis conditions significantly influence the quality of the resulting charcoal [7]. Dias-Junior et al. [20] reported that carbonisation temperatures of up to 950 °C in *Eucalyptus saligna* charcoal have reduced yield and volatile material content, while increasing its bulk density, fixed carbon content and mechanical strength, and its hygroscopic capacity also increases due to fissures and cracks generated at high temperatures. Usually, the highest mass loss occurs between 200 °C and 400 °C, while at typical carbonisation temperatures, between 500 °C and 800 °C, mass yields of about 30% can be obtained [21]. Studies at 600 °C, 700 °C and 800 °C for 2 h, 4 h and 6 h show an increase in fixed carbon from 63.01% to 81.58% and an increase in calorific value from 29,691.14 KJ kg^{−1} to 31,941.50 KJ kg^{−1} at 800 °C for 4 h [22].

The highest-quality charcoal, which can be used as an alternative to coke and coal, is produced from high-density material. First, it is heated to 200 °C for 120 h, and then it is refined at 1000 °C with a ramp rate of 50 °C min, resulting in a fixed carbon content of over 95% [18]. White charcoal produced at 1000 °C yields high percentages of fixed

carbon, volatile material and ash in bamboo samples (95.14%, 2.60% and 2.23%), coconut shell samples (96.65%, 2.44% and 0.91%) and coconut husk samples (95.61%, 2.02% and 2.37%) [23]. In general, a high pyrolysis temperature improves the combustion properties of charcoal, increasing its calorific value and reducing its volatile content. However, it also decreases the yield and requires more energy, so the pyrolysis temperature is crucial for designing and optimising commercial charcoal production processes [24]. Therefore, the objective of this research was to evaluate the impact of different temperatures and carbonisation times on the properties of charcoal produced from six oak species, assessing their effect on moisture content, volatile material, ash content, fixed carbon, calorific value, mass yield, volume yield and the bulk density of charcoal. The results will enable optimisation of the quality and performance of charcoal as a biofuel, contributing to its efficient and sustainable utilisation.

2. Material and Methods

2.1. Wood Origin and Characterisation

The *Quercus* spp. wood to be characterised was milled to a particle size of less than 1 millimetre according to UNE-EN 14780 standard (2012) [25]. Moisture content was determined according to UNE-EN 14774-3 (2010) [26]. Volatile material was calculated using UNE-EN 15148 (2010) [27]. Ash content was assessed according to UNE-EN 14775 (2010) [28]. Finally, the fixed carbon was calculated as the difference between the total dry mass and the sum of moisture content, volatile material and ash content.

The chemical composition of the wood was determined according to the Van Soest method of analysis, in which the wood was divided into neutral detergent fibre (NDF) and acid detergent fibre (ADF).

The basic density was calculated by dividing the dry mass by the green volume, considering the dimensions on the transverse, tangential and radial sides.

The determination of the higher calorific value (HHV) of *Quercus* biomass was calculated based on the proposal of Yin [29]. Table 1 shows the wood species codes and source, as well as the values of each analysis.

Table 1. Proximate analysis, compositional analysis and calorific value of wood.

Code	Species	Proximate Analysis (%)				Compositional Analysis (%)				Basic Density (g cm ⁻³)	Calorific Value (MJ kg ⁻¹)
		MC	VM	AC	FC	Cel	Hem	Lig	Ext	BD	HHV
Qs	<i>Q. sideroxylla</i>	5.46	76.89	1.10	16.55	62.28	17.64	13.24	5.74	0.63	18.82
Qj	<i>Q. jonesii</i>	5.81	77.43	0.92	15.83	57.66	18.27	13.44	9.71	0.66	18.74
Qu	<i>Q. urbanii</i>	5.39	77.21	0.79	16.62	58.54	17.97	12.46	10.24	0.70	18.89
Qd	<i>Q. durifolia</i>	5.02	77.33	1.02	16.62	63.61	17.72	14.94	2.71	0.63	18.92
Qc	<i>Q. convallata</i>	5.72	76.40	1.60	16.27	56.04	18.94	11.87	11.55	0.64	18.65
Qch	<i>Q. chihuahuensis</i>	6.29	75.59	1.95	16.17	58.41	18.66	12.80	8.18	0.70	18.47

MC; moisture content, VM; volatile matter, AC; ash content, FC; fixed carbon, Cel; cellulose, Hem; hemicellulose, Lig; lignin, Ext; extractives, BD; basic density, HHV; higher heating value.

2.2. Carbonisation Conditions

Charcoal was produced from 2 cm × 2 cm × 2 cm wooden cubes made from the transverse, tangential and radial sections. These cubes were placed in steel tubes with lids and were introduced into a 1400 FB1415M model muffle furnace (Thermolyne, Dubuque, IA, USA). Each wood sample of each species consisted of four cubes per treatment, for a total of 96 cubes (6 species, 4 cubes per species, 4 treatments), which were subjected to different time and temperature conditions inside the muffle. Once the carbonisation process

was completed, all the cubes exposed to each temperature were weighed and measured. Table 2 shows the different treatments used.

Table 2. Treatments used for charcoal production.

Treatment	Temperature	Time
T1	550 °C	30 min
T2	700 °C	30 min
T3	550 °C → 700 °C	30 min → 30 min
T4	300 °C → 1000 °C	2 h → 10 min

2.3. Charcoal Yields

The mass yield (%) is a measure that expresses the amount of useful product obtained in relation to the total material processed. The mass yield of charcoal production was calculated on a dry basis of wood and charcoal.

The volumetric yield ($\text{m}^3 \text{ t}^{-1}$) is a measure relating the volume of material processed to its weight in tonnes. The volumetric yield of the carbonised specimens was determined according to the volume of each specimen before and after treatment. Table 3 shows the yield formulas.

Table 3. Description of the formulas used for the calculation of charcoal yields.

Variable	Formula	Description
Mass yield	$MY = Dc / Dw$	MY = mass yield (%) Dc = dry mass of charcoal (g) Dw = dry mass of wood (g)
Volumetric yield	$VY = Vw / Mc$	VY = volumetric yield ($\text{m}^3 \text{ t}^{-1}$) Vw = volume of wood used (m^3) Mc = mass of charcoal produced (t)

2.4. Density of Charcoal

The bulk density of charcoal was determined from the mass of the carbonised specimen and the volume measured by the volumetric displacement of mercury in a graduated cylinder. The density was calculated using Formula (1):

$$CD = Cw / Vm \quad (1)$$

CD = charcoal density

Cw = mass of carbonised wood (g)

Vm = volume with mercury (mL)

2.5. Proximate Analysis

The carbonised material was conditioned according to the ASTM D 1762-84 standard [30]. First, it was ground using a porcelain mortar. Then, it was sieved on an AS 200 vibrating sieve at 100 RPM for 2 min, and the material with particles smaller than 1 mm was collected for analysis.

For each wood cube, the respective variable was determined according to the international standard ASTM D 1762-84 [30]. The moisture content of each cube was determined at 105 °C for 2 h. The volatile material was calculated at 950 °C for 11 min. The ash content was determined at 750 °C for 6 h. Finally, the fixed carbon was calculated as the difference between the total dry mass and the sum of moisture content, volatile material and ash content. Table 4 shows the corresponding formulas.

Table 4. Description of the formulas used for the calculation of the proximate analysis.

Variable	Formula	Description
Moisture content	$MC = [(A - B) / A] \times 100$	MC = moisture content (%) A = grams of air-dry sample used
Volatile matter	$VM = [(B - C) / B] \times 100$	B = grams of sample after drying at 105 °C VM = volatile matter (%)
Ash content	$AC = (D / B) \times 100$	C = grams of sample after drying at 950 °C AC = ash content (%)
Fixed carbon	$FC = 100 - MC - VM - AC$	D = grams of residue FC = fixed carbon (%)

2.6. Energy Properties of Charcoal

The higher calorific value or higher heating value (HHV) for each *Quercus* charcoal sample was calculated using the proposal of Cordero et al. [31].

The energy yield (%) was determined according to Canal et al. [32], who define it as the amount of biomass energy that is converted and conserved in the charcoal.

The fuel ratio is the proportion of fixed carbon to volatile material and is a distinctive value reflecting the characteristics of solid fuel. This value was determined according to Liu y Han [33]. Table 5 shows the formulas used to calculate the higher calorific value, energy efficiency and fuel ratio.

Table 5. Description of the formulas used to calculate the higher calorific value, energy efficiency and fuel ratio.

Variable	Formula	Description
Higher heating value	$HHV = 354.3FC + 170.8VM$	HHV = higher heating value (MJ kg ^{−1}) VM = Volatile matter from charcoal (%)
Energy yield	$EY = \frac{MY (\%) \times HHV_{charcoal}}{HHV_{wood}}$	FC = fixed carbon from charcoal (%) EY = energy yield (%)
Fuel ratio	$FR = FC_{charcoal} / VM_{charcoal}$	MY = mass yield (%) FR = fuel ratio

2.7. Statistical Analysis

Data normality was verified using the Shapiro–Wilk test. In cases where the data followed a normal distribution, an analysis of variance (ANOVA) was performed at a significance level of ($p > 0.05$), followed by a comparison of means using Tukey’s test when statistically significant differences were found between variables. For data that did not show normal distribution, the Kruskal–Wallis analysis was applied ($p < 0.05$). Data analysis was performed using R Studio software, version 4.3.2.

3. Results

3.1. Charcoal Yield

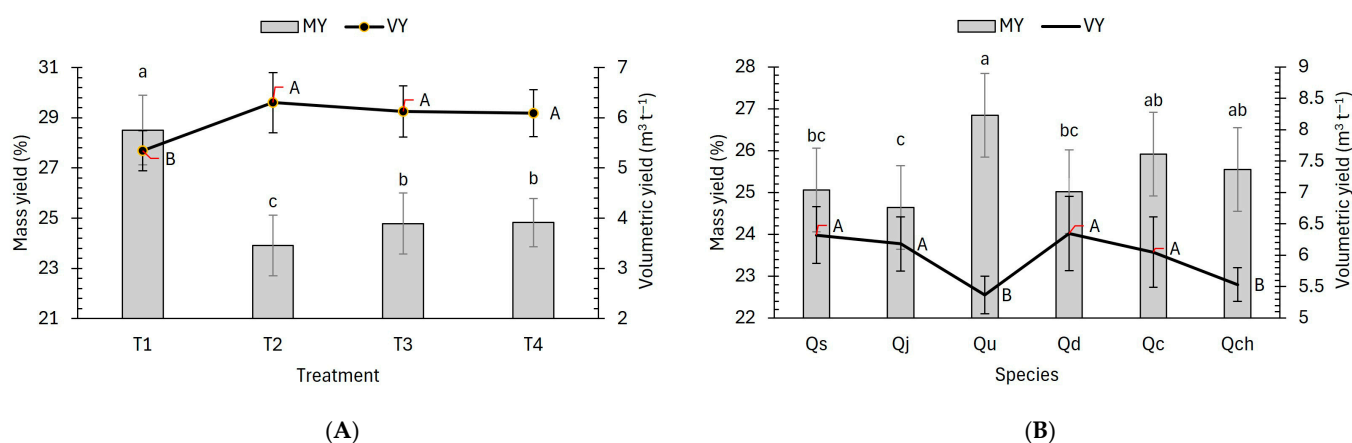
The mass and volumetric yields of charcoal from the six species with different temperature and time treatments showed significant statistical differences ($p \leq 0.05$) (Table 6).

Treatment T1 (550 °C for 30 min) produced the highest charcoal mass yield (28.50%), while treatment T2 (700 °C for 30 min) generated the lowest (24.82%). On the other hand, it was observed that the species that produced the highest charcoal mass yield were *Q. urbanii* and *Q. convallata* (26.84% and 25.91%, respectively), while *Q. jonesii* presented the lowest value (24.64%).

Table 6. Shapiro–Wilk and Kruskal–Wallis tests ($p \leq 0.05$) of charcoal mass yield and volumetric yield for different treatments, species and treatment–species interaction.

Mass Yield (MY)	Shapiro–Wilk Test		Kruskal–Wallis Test	
	Statistic	<i>p</i> -Value	Chi-Squared	<i>p</i> -Value
Treatments	0.917	1.58×10^{-4}	43.568	1.86×10^{-9}
Species			11.658	0.03
Treatment–species interaction			64.962	7.10×10^{-6}
Volumetric Yield (VY)				
Treatments	0.953	9.52×10^{-3}	24.587	1.88×10^{-5}
Species			25.77	9.88×10^{-5}
Treatment–species interaction			57.888	7.67×10^{-5}

Regarding the volumetric yield of charcoal, it was observed that the highest value occurred with treatments T2, T3 and T4 (700 °C for 30 min, 550 °C for 30 min and then 700 °C for 30 min, 300 °C for 2 h and then 1000 °C for 10 min) with values varying between $6.09 \text{ m}^3 \text{ t}^{-1}$ and $6.3 \text{ m}^3 \text{ t}^{-1}$, while the lowest value occurred with treatment T1 (550 °C for 30 min) with $5.34 \text{ m}^3 \text{ t}^{-1}$. On the other hand, *Q. durifolia*, *Q. sideroxylla*, *Q. jonesii* and *Q. convallata* had the highest values, which ranged from $6.05 \text{ m}^3 \text{ t}^{-1}$ to $6.34 \text{ m}^3 \text{ t}^{-1}$, while *Q. urbanii* had the lowest value ($5.36 \text{ m}^3 \text{ t}^{-1}$). Figure 1A shows the yields per treatment and Figure 1B shows the yields per species.

**Figure 1.** Mass yield—MY (%) and volumetric yield—VY ($\text{m}^3 \text{ t}^{-1}$). (A) Yield with treatments; (B) yield in species. Different lower-case letters indicate statistically significant differences in mass yield; different upper-case letters indicate statistically significant differences in volume yield ($p \leq 0.05$).

The treatment–species interaction for mass yield showed that *Q. convallata* and *Q. urbanii*, with treatment T1 (550 °C for 30 min), had the highest mass yield (30.10% and 29.22%). In contrast, *Q. durifolia* and *Q. jonesii*, with treatments T2 and T3 (700 °C for 30 min, 550 °C for 30 min and then 700 °C for 30 min), showed the lowest mass yields (22.66% and 23.22%, respectively) (Table 7).

Finally, when considering the treatment–species interaction for the T2 treatment (700 °C for 30 min), it was found that *Q. durifolia* and *Q. sideroxylla* showed the highest mass and volumetric yield (6.88% and $6.80 \text{ m}^3 \text{ t}^{-1}$, respectively). In contrast, *Q. urbanii* and *Q. convallata*, with treatment T1 (550 °C for 30 min), showed the lowest volumetric yield ($4.81 \text{ m}^3 \text{ t}^{-1}$ and $5.17 \text{ m}^3 \text{ t}^{-1}$, respectively) (Table 7).

Table 7. Mass yield (%) and volumetric yield ($\text{m}^3 \text{t}^{-1}$) of the treatment–species interaction. Values show means and standard deviations. Different lower-case letters indicate statistically significant differences ($p \leq 0.05$).

Code	Treatment	Mass Yield (%)	Volumetric Yield ($\text{m}^3 \text{t}^{-1}$)
Qs	T1	28.11 ± 1.34 ab	5.77 ± 0.22 def
Qj	T1	28.03 ± 0.64 ab	5.51 ± 0.24 fg
Qu	T1	29.22 ± 1.76 a	4.81 ± 0.59 g
Qd	T1	28.69 ± 0.68 ab	5.44 ± 0.12 fg
Qc	T1	30.10 ± 0.95 a	5.17 ± 0.18 g
Qch	T1	26.86 ± 0.47 bc	5.32 ± 0.19 fg
Qs	T2	23.69 ± 0.13 hi	6.80 ± 0.39 ab
Qj	T2	23.39 ± 0.50 hi	6.41 ± 0.17 abc
Qu	T2	25.90 ± 1.57 cde	5.56 ± 0.75 fg
Qd	T2	22.66 ± 0.11 i	6.88 ± 0.04 a
Qc	T2	23.57 ± 0.59 hi	6.43 ± 0.06 abc
Qch	T2	24.22 ± 0.42 fg	5.71 ± 0.11 def
Qs	T3	23.94 ± 0.35 gh	6.47 ± 0.25 abc
Qj	T3	23.22 ± 0.09 hi	6.37 ± 0.12 bc
Qu	T3	26.78 ± 0.91 bc	5.31 ± 0.20 fg
Qd	T3	24.49 ± 0.21 ef	6.58 ± 0.31 abc
Qc	T3	25.29 ± 0.32 cde	6.27 ± 0.23 cd
Qch	T3	24.97 ± 0.32 de	5.73 ± 0.34 ef
Qs	T4	24.48 ± 0.09 fg	6.23 ± 0.11 cde
Qj	T4	23.92 ± 0.35 gh	6.41 ± 0.12 abc
Qu	T4	25.47 ± 1.40 def	5.76 ± 0.51 def
Qd	T4	24.24 ± 0.46 fg	6.47 ± 0.18 abc
Qc	T4	24.67 ± 0.21 ef	6.31 ± 0.28 cd
Qch	T4	26.14 ± 0.43 cd	5.34 ± 0.04 fg

3.2. Density of Charcoal

Charcoal density among treatments and the treatment–species interaction showed significant statistical differences ($p \leq 0.05$). However, no differences were observed between species (Table 8).

Table 8. Shapiro–Wilk and Kruskal–Wallis tests ($p \leq 0.05$) used to evaluate statistical differences between treatments, species and treatment–species interaction for charcoal density.

Source of Variation	Shapiro–Wilk Test		Kruskal–Wallis Test	
	Statistic	<i>p</i> -Value	Chi-Squared	<i>p</i> -Value
Treatment	0.957	0.015	28.447	2.92×10^{-6}
Species			7.60	0.179
Treatment–species			56.269	1.29×10^{-4}

Treatments T3 and T4 (550 °C for 30 min and then 700 °C for 30 min, 300 °C for 2 h and then 1000 °C for 10 min) recorded the highest charcoal density (0.44 g cm^{-3} and 0.47 g cm^{-3} , respectively), while treatments T1 and T2 (550 °C for 30 min and 700 °C for 30 min) generated the lowest values (0.41 g cm^{-3} and 0.39 g cm^{-3} , respectively) (Figure 2).

The highest charcoal density (0.56 g cm^{-3}) was found in the *Q. chihuahuensis* interaction with the T4 treatment (300 °C for 2 h and then 1000 °C for 10 min); also, with the T3 treatment (550 °C for 30 min and then 700 °C for 30 min), a high density (0.49 g cm^{-3}) was obtained. On the other hand, *Q. urbanii* with the T2 treatment (700 °C for 30 min) and *Q. chihuahuensis* with the same treatment had the lowest density (0.34 g cm^{-3} and 0.36 g cm^{-3} , respectively) (Table 9).

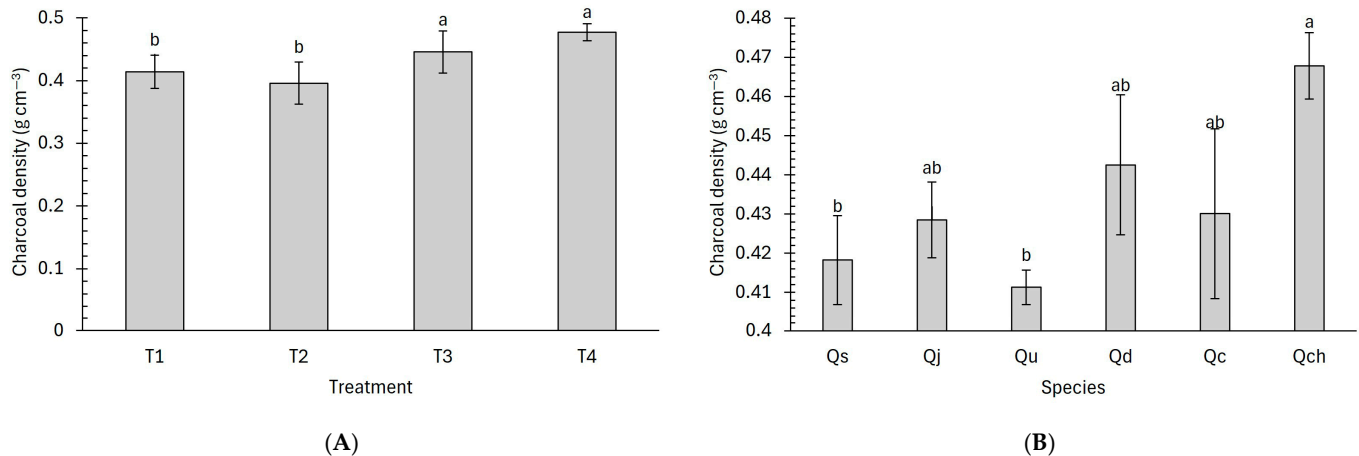


Figure 2. Charcoal density (g cm^{-3}). (A) Density across treatments; (B) density by species. Different lower-case letters indicate statistically significant differences ($p \leq 0.05$).

Table 9. Charcoal density (g cm^{-3}) of the treatment–species interaction. Values show means and standard deviations. Different lower-case letters indicate statistically significant differences ($p \leq 0.05$).

Code	Treatment	Charcoal Density (g cm^{-3})
Qs	T1	0.39 ± 0.02 ijkl
Qj	T1	0.39 ± 0.06 jkl
Qu	T1	0.40 ± 0.03 ijkl
Qd	T1	0.41 ± 0.02 fghi
Qc	T1	0.43 ± 0.01 defg
Qch	T1	0.44 ± 0.02 bcde
Qs	T2	0.40 ± 0.01 ijkl
Qj	T2	0.41 ± 0.03 fghi
Qu	T2	0.34 ± 0.08 l
Qd	T2	0.41 ± 0.02 ghij
Qc	T2	0.42 ± 0.06 efgh
Qch	T2	0.36 ± 0.03 kl
Qs	T3	0.43 ± 0.08 defg
Qj	T3	0.42 ± 0.01 efgh
Qu	T3	0.40 ± 0.01 ijkl
Qd	T3	0.46 ± 0.02 abcd
Qc	T3	0.45 ± 0.02 bcde
Qch	T3	0.49 ± 0.01 ab
Qs	T4	0.43 ± 0.04 cdef
Qj	T4	0.48 ± 0.03 abc
Qu	T4	0.48 ± 0.02 abc
Qd	T4	0.48 ± 0.01 abcd
Qc	T4	0.41 ± 0.02 ghij
Qch	T4	0.56 ± 0.02 a

This demonstrates that low temperature carbonisation over a long period and the high temperature refining processes favor density increase in the charcoal production process.

3.3. Proximate Analysis

The charcoal moisture content showed no significant differences among species; however, there were significant statistical differences ($p \leq 0.05$) among treatments and the treatment–species interaction (Table 10).

Table 10. Shapiro–Wilk, ANOVA and Kruskal–Wallis tests ($p \leq 0.05$) of moisture content, volatile material, ash content and fixed carbon of charcoal among treatments, species and treatment–species interactions.

Moisture Content (MC)	Shapiro–Wilk Test		Kruskal–Wallis Test		ANOVA Test	
	Statistic	<i>p</i> -Value	Chi-Squared	<i>p</i> -Value	<i>F</i> Value	<i>p</i> -Value
Treatments	0.968	0.07			58.457	2.2×10^{-16}
Species					1.48	0.205
Treatment–species					54.693	2.2×10^{-16}
Volatile matter (VM)						
Treatments	0.764	2.11×10^{-9}	51.85	3.22×10^{-11}		
Species					0.038	
Treatment–species					1.38×10^{-6}	
Ash content (AC)						
Treatments	0.824	8.23×10^{-8}	5.536	0.136		
Species					7.89×10^{-11}	
Treatment–species					3.14×10^{-6}	
Fixed carbon (FC)						
Treatments	0.864	1.52×10^{-6}	41.821	4.37×10^{-9}		
Species					6.13×10^{-4}	
Treatment–species					1.03×10^{-6}	

Treatments T1 and T4 (550 °C for 30 min, 300 °C for 2 h and then 1000 °C for 10 min) reached the highest moisture content (4.27% and 4.34%), while treatment T2 (700 °C for 30 min) had the lowest value (2.90%) (Figure 3). These results indicate that charcoal produced at both lower and higher temperatures tends to have a higher moisture content, while charcoal obtained at intermediate temperatures tends to have a lower moisture content.

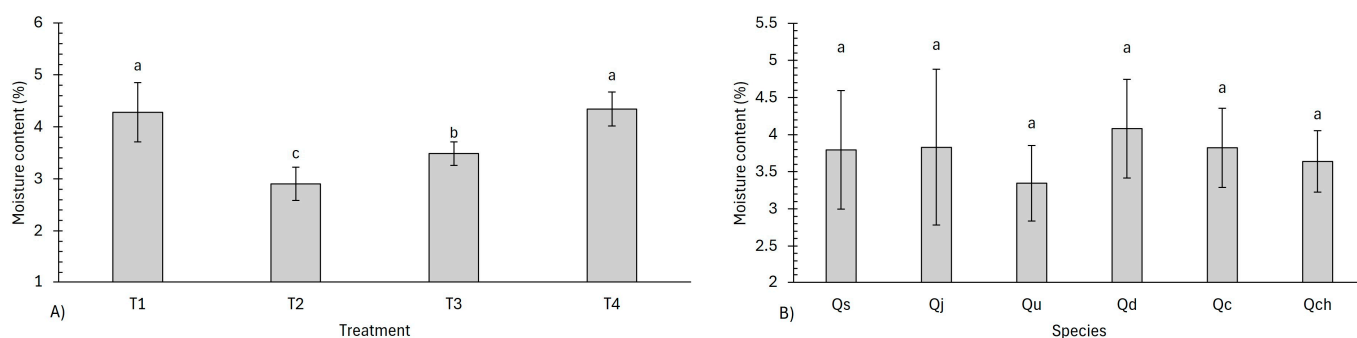


Figure 3. Moisture content of charcoal (%). (A) Moisture content with treatments; (B) moisture content by species. Different lower-case letters indicate statistically significant differences ($p \leq 0.05$).

The treatment–species interaction with regard to moisture content showed that charcoal from *Q. jonesii* and *Q. durifolia* with treatment T1 (550 °C for 300 min) had high moisture contents (4.82% and 4.80%, respectively), while *Q. urbanii* and *Q. jonesii* with treatment T2 (700 °C for 30 min) showed the lowest moisture contents values (2.63% and 2.46%, respectively) (Table 11). Carbonisation for treatment T4 (300 °C for 2 h and then 1000 °C for 10 min) produced the highest moisture contents.

The volatile material content of charcoal showed a non-normal distribution of the data, and significant statistical differences ($p \leq 0.05$) were observed between species, treatments and the treatment–species interaction (Table 10).

Table 11. Moisture content (MC), volatile material (VM), ash content (AC) and fixed carbon (FC) of the charcoal treatment–species interaction. Values show means and standard deviations. Different lowercase letters indicate statistically significant differences ($p \leq 0.05$).

Code	Treatment	Proximate Analysis (%)			
		MC	VM	AC	FC
Qs	T1	4.61 ± 0.20 ab	20.48 ± 0.20 bc	2.02 ± 0.05 kl	72.86 ± 0.16 mn
Qj	T1	4.82 ± 0.38 a	18.61 ± 0.31 cd	2.15 ± 0.10 jk	74.40 ± 0.50 lm
Qu	T1	3.66 ± 0.24 def	12.18 ± 0.25 ef	2.39 ± 0.30 hi	81.75 ± 0.22 jk
Qd	T1	4.80 ± 0.09 a	21.17 ± 0.39 ab	2.16 ± 0.08 jk	71.85 ± 0.33 no
Qc	T1	4.26 ± 0.05 bc	22.30 ± 0.25 a	4.80 ± 0.09 cd	68.62 ± 0.22 o
Qch	T1	3.50 ± 0.09 defg	14.13 ± 0.15 de	5.62 ± 0.21 bc	76.73 ± 0.08 kl
Qs	T2	2.78 ± 0.01 hij	6.75 ± 0.18 h	2.58 ± 0.06 fg	87.88 ± 0.19 e
Qj	T2	2.46 ± 0.18 j	5.71 ± 0.12 mn	2.36 ± 0.39 hij	89.45 ± 0.44 cd
Qu	T2	2.63 ± 0.22 ij	5.05 ± 0.19 p	2.58 ± 0.09 fg	89.72 ± 0.11 c
Qd	T2	3.19 ± 0.01 fgh	7.43 ± 0.07 fg	2.74 ± 0.16 ef	86.62 ± 0.26 f
Qc	T2	3.11 ± 0.03 ghi	6.82 ± 0.20 gh	6.57 ± 0.43 ab	83.48 ± 0.37 hi
Qch	T2	3.23 ± 0.10 fgh	6.81 ± 0.45 hi	7.24 ± 0.26 a	82.70 ± 0.31 ij
Qs	T3	3.35 ± 0.06 defg	6.65 ± 0.13 hi	2.43 ± 0.03 gh	87.56 ± 0.18 e
Qj	T3	3.31 ± 0.06 defg	5.86 ± 0.32 lm	1.54 ± 0.46 l	89.27 ± 0.26 d
Qu	T3	3.27 ± 0.25 efgh	5.12 ± 0.46 op	2.23 ± 0.15 ijk	89.35 ± 0.30 d
Qd	T3	3.79 ± 0.10 cde	6.35 ± 0.03 jk	2.76 ± 0.31 ef	87.08 ± 0.20 f
Qc	T3	3.57 ± 0.13 defg	6.52 ± 0.01 ij	5.28 ± 0.45 bc	84.61 ± 0.37 g
Qch	T3	3.58 ± 0.12 defg	5.20 ± 0.26 op	6.18 ± 0.11 ab	85.02 ± 0.22 g
Qs	T4	4.43 ± 0.15 ab	2.80 ± 0.31 q	2.36 ± 0.03 hij	90.39 ± 0.43 b
Qj	T4	4.71 ± 0.17 ab	2.64 ± 0.11 q	1.70 ± 0.08 l	90.93 ± 0.22 ab
Qu	T4	3.80 ± 0.08 cd	2.32 ± 0.39 q	2.34 ± 0.08 hij	91.51 ± 0.42 a
Qd	T4	4.53 ± 0.11 ab	5.32 ± 0.21 o	3.03 ± 0.20 de	87.10 ± 0.40 f
Qc	T4	4.33 ± 0.10 ab	6.24 ± 0.12 kl	4.22 ± 0.66 cd	85.19 ± 0.70 g
Qch	T4	4.23 ± 0.27 bc	5.44 ± 0.25 no	6.59 ± 0.42 ab	83.71 ± 0.27 h

The volatile material content was higher (18.14%) for treatment T1 (550 °C for 30 min), while for treatment T4 (300 °C for 2 h and then 1000 °C 10 min), it did not exceed 4.13%. The species with the highest content of volatile material was *Q. convallata* (10.47%), while *Q. urbanii* had the lowest percentage (6.17%) (Figure 4). These results indicate that high-temperature carbonisation as a refining method is effective in reducing the volatile material content.

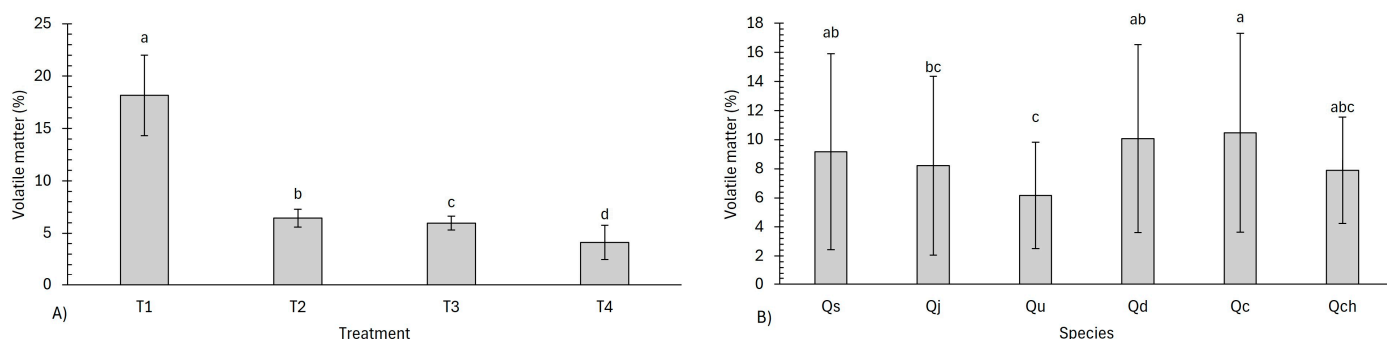


Figure 4. Volatile material content of charcoal (%). (A) Volatile material content with treatments; (B) volatile material content by species. Different lower-case letters indicate statistically significant differences ($p \leq 0.05$).

The treatment–species interaction found that the volatile material obtained with treatment T1 (550 °C for 30 min) with *Q. convallata*, *Q. durifolia* and *Q. sideroxyla* was high, with values ranging from 20.48% to 22.30%, compared to the other interactions. As for the

lowest volatile material content, it was found with *Q. sideroxyla*, *Q. jonesii* and *Q. urbanii* with treatment T4 (300 °C for 2 h and then 1000 °C for 10 min), with values of 2.80%, 2.64% and 2.32%, respectively (Table 11). These results demonstrate the effect of applying temperatures above 1000 °C as a charcoal-refining process.

The ash content of charcoal showed no significant differences among treatments; however, among species and between treatment–species interactions, there were statistically significant differences ($p \leq 0.05$) (Table 10).

The species with the highest ash content was *Q. chihuahuensis* (6.41%), while *Q. jonesii* had the lowest percentage (1.94%) (Figure 5).

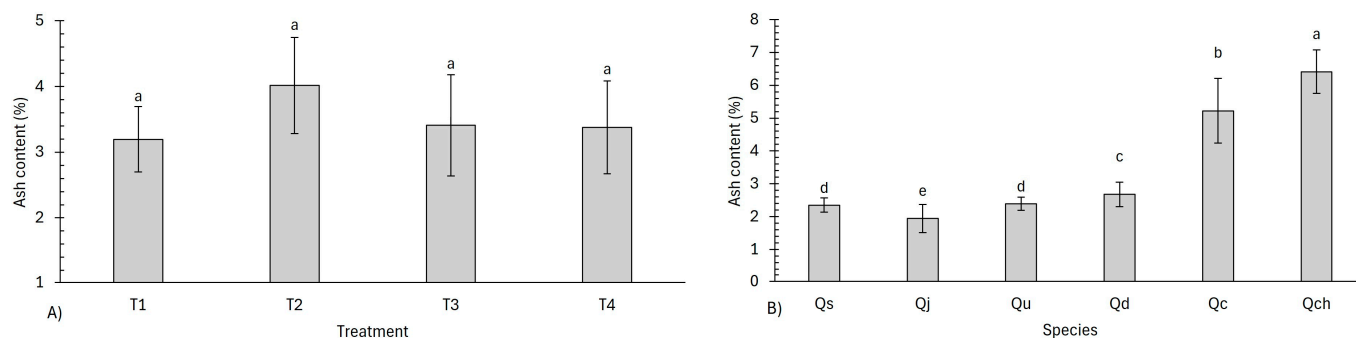


Figure 5. Charcoal ash content (%). (A) Ash content across treatments; (B) ash content by species. Different lowercase letters indicate statistically significant differences ($p \leq 0.05$).

In the treatment–species interaction of ash content, *Q. jonesii* charcoal with the T3 treatment (550 °C for 30 min and then 700 °C for 30 min), as well as with the T4 treatment (300 °C for 2 h and then 1000 °C for 10 min), showed the lowest values compared to the other species (1.54% and 1.70%, respectively). On the other hand, *Q. chihuahuensis* with the T4 treatment (300 °C for 2 h and then 1000 °C for 10 min), as well as with the T2 treatment (700 °C for 30 min), showed the highest ash values (6.59% and 7.24%, respectively) (Table 11).

The fixed carbon content of charcoal showed significant differences among treatments, species and treatment–species interactions ($p \leq 0.05$) (Table 10).

The fixed carbon content was higher at elevated carbonisation temperatures, reaching 88.14% with treatment T4 (300 °C for 2 h and then 1000 °C for 10 min). The lowest percentage (74.37%) was observed with treatment T1 (550 °C for 30 min). Regarding the species, *Q. jonesii* and *Q. urbanii* presented a fixed carbon content of 86.01% and 88.08%, respectively, while *Q. convallata* and *Q. chihuahuensis* reached 80.48% and 82.04%, respectively (Figure 6).

For the treatment–species interaction of fixed carbon content, it was observed that at the low temperatures of treatment T1 (550 °C for 30 min), charcoal from *Q. convallata* and *Q. durifolia* presented the lowest values of fixed carbon (68.62% and 71.85%, respectively). On the other hand, at the high temperatures of treatment T4 (300 °C for 2 h and then 1000 °C for 10 min), the *Q. sideroxyla*, *Q. jonesii* and *Q. urbanii* species showed the highest percentages of fixed carbon (90.39%, 90.93% and 91.51%, respectively) (Table 11).

3.4. Energy Properties of Charcoal

The calorific value and energy yield of charcoal from the six species with different temperature and time treatments showed significant statistical differences ($p \leq 0.05$) (Table 12).

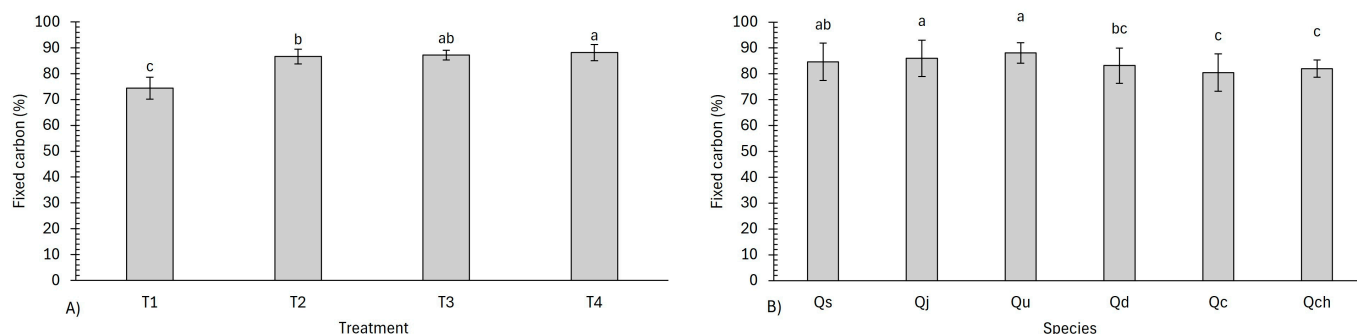


Figure 6. Fixed carbon content of charcoal (%). (A) Fixed carbon content across treatments; (B) fixed carbon content by species. Different lowercase letters indicate statistically significant differences ($p \leq 0.05$).

Table 12. Shapiro–Wilk, Kruskal–Wallis and ANOVA ($p \leq 0.05$) tests of the calorific value and energy yield of charcoal between treatments, species and treatment–species interaction.

Charcoal Calorific Value (CCV)	Shapiro–Wilk Test		Kruskal–Wallis Test		ANOVA Test	
	Statistic	<i>p</i> -Value	Chi-Squared	<i>p</i> -Value	F Value	<i>p</i> -Value
Treatments	0.906	5.41×10^{-5}	34.213	1.78×10^{-7}		
Species			28.589	2.78×10^{-5}		
Treatment–species			69.83	1.29×10^{-6}		
Energy yield (EY)						
Treatments	0.953	0.009	30.778	9.46×10^{-7}		
Species			19.791	0.001		
Treatment–species			62.079	1.90×10^{-5}		
Fuel ratio (FR)						
Treatments	0.838	2.17×10^{-7}	50.445	6.42×10^{-11}		
Species			13.063	0.022		
Treatment–species			69.714	1.34×10^{-6}		

Treatments T2, T3 and T4 (700 °C for 30 min, 550 °C for 30 min and then 700 °C for 30 min, 300 °C for 2 h and then 1000 °C for 10 min) produced the highest calorific value of charcoal (31.79 MJ kg^{−1}, 31.89 MJ kg^{−1} and 31.93 MJ kg^{−1}, respectively), while treatment T1 (550 °C for 30 min) generated the lowest (29.45 MJ kg^{−1}). *Q. urbanii* showed the highest calorific value (32.26 MJ kg^{−1}), while *Q. convallata* and *Q. chihuahuensis* presented the lowest (30.30 MJ kg^{−1} and 30.41 MJ kg^{−1}, respectively).

The treatment–species interaction for calorific value showed that charcoal from *Q. jonesii* and *Q. urbanii* with treatments T2 and T4 (700 °C for 30 min, 300 °C for 2 h and then 1000 °C for 10 min) had a high calorific value (32.66 MJ kg^{−1} and 32.82 MJ kg^{−1}, respectively), while *Q. convallata* and *Q. durifolia* with treatment T1 (550 °C for 30 min) showed the lowest values (28.12 MJ kg^{−1} and 29.07 MJ kg^{−1}, respectively) (Table 13).

Regarding charcoal energy yield, the highest value was presented with treatment T1 (550 °C for 30 min) (44.75%), while the lowest value occurred with treatment T2 (700 °C for 30 min) (40.54%), with *Q. urbanii* presenting the highest energy yield (45.79%), and the other species presenting the lowest yield ($\geq 42.05\%$) (Figure 7).

The treatment–species interaction found that the energy yield obtained with treatment T1 (550 °C for 30 min) with *Q. urbanii* and with treatment T3 (550 °C for 30 min and then 700 °C for 30 min) with the same species was high (48.02% and 46.12%, respectively), while the lowest energy yield was presented with *Q. durifolia* and *Q. convallata* with the T2 treatment (700 °C for 30 min), with values of 38.27% and 38.84%, respectively (Table 13).

Table 13. Calorific value, energy yield and fuel ratio for the charcoal treatment–species interaction. Values show means and standard deviations. Different lowercase letters indicate statistically significant differences ($p \leq 0.05$).

Code	Treatment	Higher Heating Value (MJ kg ⁻¹)	Energy Yield (%)	Fuel Ratio
Qs	T1	29.31 ± 0.06 lm	43.79 ± 2.05 bcde	3.55 ± 0.03 mn
Qj	T1	29.54 ± 0.13 kl	44.18 ± 0.92 abc	3.99 ± 0.09 lm
Qu	T1	31.04 ± 0.11 i	48.02 ± 2.93 a	6.71 ± 0.12 jk
Qd	T1	29.07 ± 0.06 mn	44.08 ± 0.98 abcd	3.39 ± 0.07 no
Qc	T1	28.12 ± 0.05 n	45.38 ± 1.41 abc	3.07 ± 0.04 o
Qch	T1	29.60 ± 0.02 kl	43.03 ± 0.73 cdef	5.42 ± 0.06 kl
Qs	T2	32.29 ± 0.04 e	40.64 ± 0.27 ijk	13.01 ± 0.39 h
Qj	T2	32.66 ± 0.17 b	40.78 ± 0.94 hij	15.64 ± 0.27 e
Qu	T2	32.65 ± 0.04 b	44.76 ± 2.75 abcd	17.76 ± 0.66 b
Qd	T2	31.96 ± 0.07 fg	38.27 ± 0.19 k	11.65 ± 0.30 ij
Qc	T2	30.74 ± 0.14 j	38.84 ± 1.07 k	12.24 ± 0.37 i
Qch	T2	30.46 ± 0.04 jk	39.94 ± 0.70 jk	12.16 ± 0.83 i
Qs	T3	32.15 ± 0.04 ef	40.91 ± 0.55 hij	13.17 ± 0.29 gh
Qj	T3	32.63 ± 0.12 bc	40.44 ± 0.20 ijk	15.25 ± 0.86 e
Qu	T3	32.53 ± 0.03 cd	46.12 ± 1.71 ab	17.51 ± 1.59 bc
Qd	T3	31.93 ± 0.07 fg	41.33 ± 0.34 ghi	13.69 ± 0.06 f
Qc	T3	31.09 ± 0.13 i	42.15 ± 0.62 efg	12.96 ± 0.07 h
Qch	T3	31.01 ± 0.06 i	41.92 ± 0.64 fg	16.36 ± 0.82 cde
Qs	T4	32.50 ± 0.09 d	42.28 ± 0.24 defg	32.52 ± 4.05 a
Qj	T4	32.66 ± 0.66 b	41.70 ± 0.81 gh	34.49 ± 1.59 a
Qu	T4	32.82 ± 0.09 a	44.25 ± 2.43 bcde	40.10 ± 6.65 a
Qd	T4	31.77 ± 0.11 fg	40.70 ± 0.88 hij	16.37 ± 0.73 cd
Qc	T4	31.25 ± 0.22 hi	41.33 ± 0.16 ghi	13.63 ± 0.38 fg
Qch	T4	30.59 ± 0.08 j	43.28 ± 0.84 cdef	15.39 ± 0.72 e

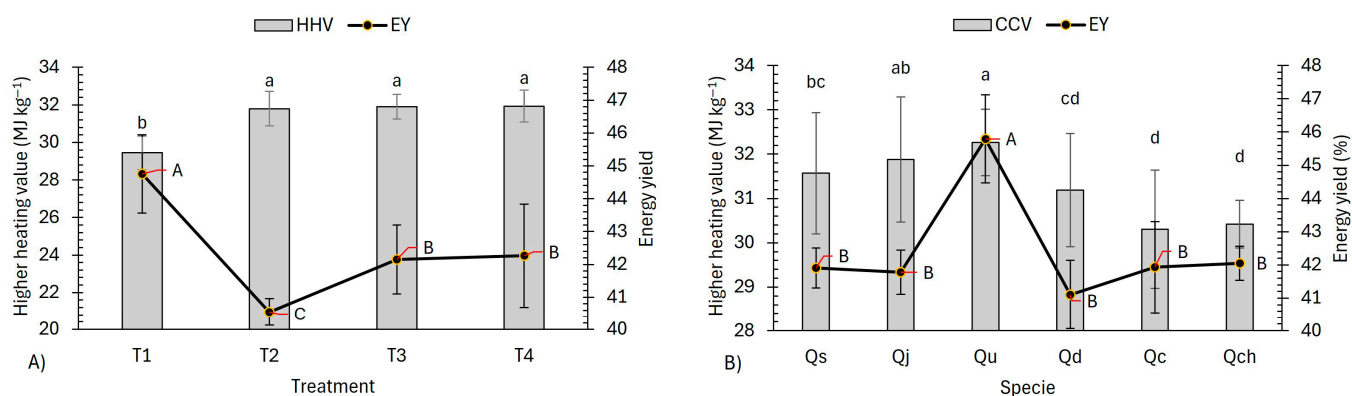


Figure 7. Calorific value (MJ kg⁻¹) and energy yield (%). (A) Calorific value and energy yield between treatments; (B) calorific value and energy yield between species. Different lowercase letters indicate statistically significant differences in calorific value; different uppercase letters indicate statistically significant differences in energy yield ($p \leq 0.05$).

The charcoal–fuel ratio showed significant differences between treatments, species and treatment–species interactions ($p \leq 0.05$) (Table 12).

The T4 treatment (300 °C for 2 h and then 1000 °C for 10 min) generated the highest fuel ratio (25.41), and T1 treatment (550 °C for 30 min) generated the lowest value (4.36), where the species with the highest fuel ratio were *Q. urbanii* (20.52) and *Q. jonesii* (14.34), and the species with the lowest fuel ratio were *Q. convallata* (10.48) and *Q. durifolia* (11.27) (Figure 8).

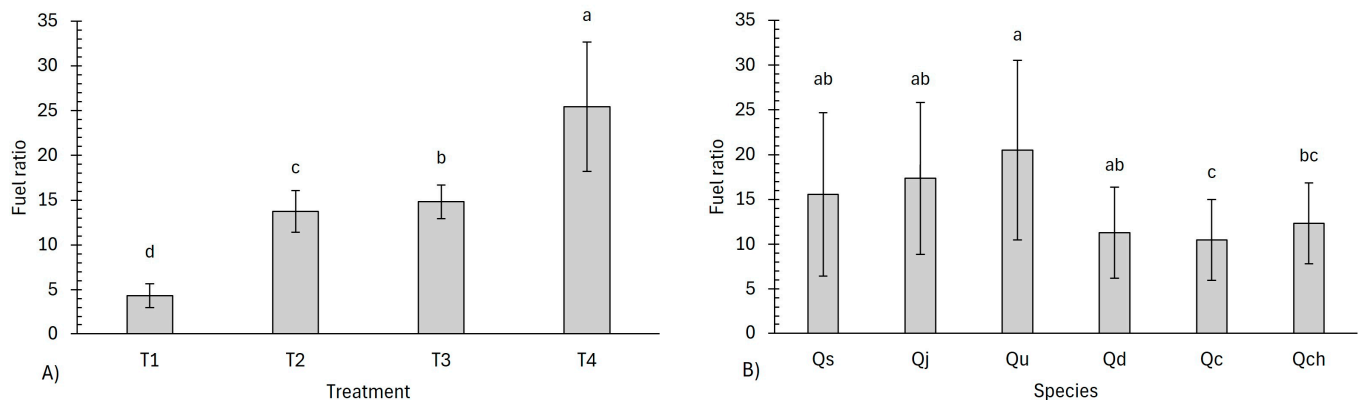


Figure 8. Fuel ratio of charcoal. (A) Fuel ratio across treatments; (B) fuel ratio across species. Different lowercase letters indicate statistically significant differences ($p \leq 0.05$).

The treatment–species interaction with the fuel ratio showed that *Q. urbanii* and *Q. jonesii* charcoal with the T4 treatment (300 °C for 2 h and then 1000 °C for 10 min) presented a high value (40.10 and 34.49, respectively), while *Q. convallata* and *Q. durifolia* with the T1 treatment (550 °C for 30 min) showed the lowest values (3.07 and 3.39, respectively) (Table 13).

4. Discussion

4.1. Charcoal Yield

The mass yield of charcoal decreased with increasing temperature, when the process was kept constant, as with treatments T1 and T2 (550 °C for 30 min, 700 °C for 30 min), with a yield difference of 16.21%. However, when there were temperature changes during the process, as with treatments T3 and T4 (550 °C for 30 min and then 700 °C for 30 min, 300 °C for 2 h then 1000 °C for 10 min), the yield was similar despite using different high temperatures, and the highest temperatures did not have the lowest values. Charvet et al. [34] observed a charcoal yield of less than 35% at 450 °C with very similar trends in oak, cork oak and Eucalyptus wood. At a high carbonisation temperature, the mass yield was low, which is in agreement with Ronsse et al. [35] who found charcoal yields of 23% and 22.7% at 750 °C for 10 min and 1 h, respectively, like the results obtained in this research with *Q. jonesii*. This effect has been attributed to the fact that high amounts of lignin in wood increase the mass yield of charcoal [36]. In pyrolysis studies at 900 °C with an increase of 2 °C min on eucalyptus charcoal, yields of 18.8% have been obtained [37]. It has been observed, in thermogravimetric analysis, that the yields obtained for *Abies* sp. and *Betula* sp. wood carbonised at 950 °C are 23.3% and 19.9%, respectively [38], similar to those values obtained for *Q. jonesii*, whose carbonisation yields were recorded in the T4 treatment (300 °C for 2 h and then 1000 °C for 10 min), suggesting a relationship between the species in terms of their behaviour during the carbonisation process. Often the volumetric yield is determined to know the amount of fuelwood required to produce one tonne of charcoal on an industrial scale. García-Quezada et al. [39] found volumetric yields of 5.07 m³ t^{−1}, 6.19 m³ t^{−1} and 5.12 m³ t^{−1} at maximum temperatures of 432 °C, 660 °C and 403 °C, respectively, in carbonised wood of *Q. magnoliifolia* and *Q. sideroxylla*. These data are like those in this study, which ranged from 4.81 m³ t^{−1} to 6.88 m³ t^{−1}. Also, Bustamante-García et al. [40] found high volumetric yields (5.4 m³ t^{−1}) for *Q. sideroxylla* charcoal produced at a final temperature of 975 °C.

4.2. Density of Charcoal

The charcoal density of the species showed a considerable increase when using treatments T3 and T4 (550 °C for 30 min and then 700 °C for 30 min, 300 °C for 2 h and then 1000 °C for 10 min), which is in agreement with that reported by Somerville and Jahan-shahi [41], who found high density (1030 kg m⁻³) in charcoal from compressed eucalyptus chips produced at temperatures of 700 °C, reporting that the increase in density is likely due to the restructuring of the graphitic structure at high temperatures. Lima et al. [42] observed variations in the charcoal of *Tapirira guianensis* and *Licania* sp., ranging between 0.24 g cm⁻³ and 0.65 g cm⁻³, which are comparable to the values reported in this study. Abreu Neto et al. [43] found a density of 0.44 g cm⁻³ at a final temperature of 750 °C, which is slightly higher than the value obtained in this study using the T2 treatment (700 °C for 30 min) (0.39 g cm⁻³). This may be due to the species used to produce charcoal. Trugilho and da Silva [44], for their part, observed a decrease in charcoal density with increasing pyrolysis temperature (300–700 °C) and concluded that carbonised materials have a minimum density at 660 °C, above which the density increases, for example at 900 °C. White charcoal is an example of this, characterised by its high density, and produced at temperatures between 240 °C and 1000 °C over long periods of time [18]. Miki et al. [45] found densities of up to 1 g cm⁻³ in *Quercus phillyreoides* charcoal when carbonisation temperatures above 800 °C were used, demonstrating much higher density values than those obtained in this research. However, Kwon et al. [46] found that white charcoal produced in a modified thermotherapy furnace had a density of 0.47 g cm⁻³, which is identical to the value obtained in the T4 treatment (300 °C for 2 h and then 1000 °C for 10 min) in this study. Furthermore, Kim and Hanna [47] determined that *Quercus variabilis* charcoal has a density of 0.51 g cm⁻³ at 1000 °C. Charcoal density is considered a very important parameter in the industry. Couto et al. [48] found that charcoal exhibits greater density and stiffness at higher carbonisation temperatures (>550 °C) due to the rearrangement of carbon chains. This is beneficial in the steel industry as it improves the mechanical strength and durability of charcoal.

4.3. Proximate Analysis

The moisture content of the charcoal was high (>4%) when treatments T1 and T4 were used (550 °C for 30 min, 300 °C for 2 h and then 1000 °C for 10 min). Conversely, very low moisture contents (1.76% and 2.72%) were obtained for *Eucalyptus benthamii* when the carbonisation temperature was set at 600 °C [49], which is consistent with the moisture content of charcoal obtained with treatment T2 (700 °C for 30 min). Kwon et al. [50] reported moisture contents of 3.47%, 4.00% and 6.00% in carbonised *Quercus variabilis* sapwood when temperatures of 600 °C, 800 °C and 1000 °C were used, respectively. This indicates that at lower carbonisation temperatures, charcoal retains a higher moisture content because the temperature is insufficient to effectively release the moisture. At intermediate temperatures, moisture content decreases as more water is driven off. However, at higher temperatures, the total volume of micropores and specific surface area increases, which can enhance the moisture absorption capacity of charcoal [51]. Similar work by Dias Junior et al. [20] found that charcoal produced at >750 °C had high moisture absorption due to its porosity. Additionally, the structural reorganisation of charcoal at very high temperatures may also contribute to increased moisture retention. This explains the relatively high moisture content observed in the charcoal from the T1 and T4 treatments (550 °C for 30 min, 300 °C for 2 h and then 1000 °C for 10 min) in this study. In terms of user preference, coal is generally desired to have a low moisture content, since moisture reduces the average pyrolysis temperature and weakens the carbon deposition effect, ultimately decreasing the fixed carbon content [52].

The volatile content of charcoal was higher at low temperatures with treatment T1 (550 °C for 30 min), while at high temperatures with treatment T4 (300 °C for 2 h and then 1000 °C for 10 min), the values were lower. Zanutto et al. [53] studied charcoal produced from *Eucalyptus paniculata*, *E. urophylla*, *Pinus oocarpa* and *Corymbia citriodora* wood at 450 °C, reporting volatile values of 22.46%, 23.41%, 27.77% and 20.71%, respectively. Patlán et al. [54] found a value of 15% in *Quercus* sp. charcoal produced at 500 °C and observed that fixed carbon increases as a function of temperature, while volatile material decreases with increasing temperature. This is consistent with the results obtained in this study. Briseño-Urbe et al. [55] reported a value of 3.2% at 1050 °C in *Eucalyptus camaldulensis* charcoal and highlighted that low levels of volatile material favour cleaner combustion by reducing smoke emissions and tar production. Generally, high levels of volatile material suggest a heterogeneous carbonisation process at low temperatures, preventing the volatilisation of tars that would be released during combustion. As volatile material increases, so do mass yield, calorific value, compressive strength, cohesion and friability [40,56]. However, values above 7% do not meet the quality requirements of the German standard DIN 51749 [57].

The ash content of species carbonised at different temperatures ranged from 1.54% to 7.24%. De la cruz-Montelongo et al. [58] reported ash values of 3.7–8.3% for charcoal from *Prosopis* sp., *Ebenopsis* sp. and *Quercus* sp. Ruiz-Aquino et al. [59] found that charcoal made from high-density wood had an ash content ranging from 1.06% to 4.98%. These data coincide with those obtained in this study. Furthermore, the results show that most of the charcoal produced complies with the permitted values in the German standard DIN 51749 [57] (<6%) and the European standard EN 1860-2 [60] (<8%). Variations in ash content between species may be due to differences in their elemental composition and the temperatures used, given that each species has a different chemical constitution [61]. Generally, ash content varies between species and results from the combustion of materials. It is composed of elements such as calcium, magnesium, potassium, silicon, iron, phosphorus, aluminum and sulphur, which can cause problems such as scorching, fouling, sintering and fusibility at high temperatures [62–64]. Budianto et al. [12] consider ash content to be a very important parameter and found that optimal values range between 6.8% and 10%.

The fixed carbon content decreased at low temperatures when treatment T1 (550 °C for 30 min) was used (68.62%) and increased at high temperatures when treatment T4 (300 °C for 2 h and then 1000 °C for 10 min) was used (91.51%). Ruiz-Aquino et al. [59] found that increasing the temperature decreases the volatile material and thus increases the amount of fixed carbon. Wang et al. [65] studied charcoal produced at 950 °C and found fixed carbon values in *Quercus rubra* L. and *Liquidambar styraciflua* samples of 94.73% and 89.76%, respectively. Odeyun et al. [66] reported values of 78.07% for *Endospermum chinense* charcoal at 400 °C with a heating rate of 5 °C/min, which are very similar to the values obtained in this study. Generally, the amount of fixed carbon in charcoal from most species at various temperatures complies with international standards: NBN M11-001 [67] (75%), DIN 51749 [57] (78%) and EN 1860-2 [60] (75%). According to Chen et al. [68], fixed carbon is important because it improves the efficiency of thermal processes; its high oxidation temperature favors a longer process duration, thus increasing the effectiveness and performance of the heat treatment.

4.4. Energy Properties

The calorific value at high temperatures with treatment T4 (300 °C for 2 h and then 1000 °C for 10 min) was significantly higher, reaching a maximum value of 32.82 MJ kg^{−1}. These values are consistent with those reported by Oke et al. [69], who found calorific values for ten species ranging between 32.82 MJ kg^{−1} and 39.41 MJ kg^{−1}. Ngangyo-Heya et al. [70] found calorific values between 29 MJ kg^{−1} and 35.0 MJ kg^{−1} in charcoal made

from branches, which are an important source of energy. Mencarelli et al. [71] for their part, analysed the energy properties of 24 bags of charcoal, finding values that ranged between 27.9 MJ kg^{-1} and 32.3 MJ kg^{-1} . Generally, the calorific value relates to the quality of the charcoal and is therefore affected by the quantity of water, volatile substances and ash [72]. According to Dias Junior et al. [73] prolonging the carbonisation process increases the fixed carbon and calorific value; however, the ash content reduces the calorific value of the charcoal as it does not participate in the combustion.

The energy yield values of charcoal ranged from 38.27% to 48.02%. The lowest values were found with treatment T2 (700 °C for 30 min), while the highest values were found with treatment T1 (550 °C for 30 min). García-Quezada et al. [74] reported energy yields of 54.5%, 43.91% and 38.65% in different kiln firings. Meanwhile, Canal et al. [32] reported obtaining an energy yield of 51.83% using charcoal from *Eucalyptus* sp., which coincides with the values obtained in this study. Ge et al. [75] however, determined that energy yield decreases with increasing treatment time, indicating that a shorter treatment period generates a higher energy content, which was not demonstrated in this research.

Contrary to the case with treatment T1 (550 °C for 30 min), the fuel ratio of charcoal was highest with treatment T4 (300 °C for 2 h and then 1000 °C for 10 min), with values ranging from 3.07 to 40.10. Ge et al. [75] found fuel ratio values ≥ 26.47 and noted that higher ratios result in lower emissions of volatile pollutants such as CO and NO_x during combustion. Hu et al. [24] found maximum fuel ratio values of 18.01 at 800 °C, highlighting that coal releases fewer volatile pollutants at high temperatures. These previous findings are consistent with the results of this study. Liu and Han [33] state that although the fuel ratio improves combustion efficiency and reduces pollutant emissions, energy efficiency decreases with increasing temperature due to the reduction in coal mass yield.

5. Conclusions

- Carbonisation temperature significantly affects charcoal yield; lower temperatures (T1, 550 °C for 30 min) maximise mass yield, but at the expense of energy properties, while higher temperatures (T4, 300 °C for 2 h and then 1000 °C for 10 min) produce denser charcoal with better calorific value but a lower mass yield;
- *Q. urbanii* and *Q. convallata* showed the highest mass yields, making them more efficient for charcoal production;
- High density does not always relate to superior energetic properties, as seen in *Q. chihuahuensis* under T4 treatment;
- Volatile matter, moisture and ash content are sensitive to carbonisation conditions; higher temperatures reduce volatile matter, improving energy efficiency;
- For high energy efficiency and calorific value, high-temperature treatments like T4 are recommended, especially for species like *Q. urbanii*;
- For applications prioritising mass yield, *Q. urbanii* and *Q. convallata* at lower temperatures (T1) are preferable as they optimise yield without greatly reducing density.

Author Contributions: Conceptualisation, J.C.C.-T., J.R.G.-T. and A.C.-P.; methodology, J.C.C.-T., J.R.G.-T. and A.C.-P.; software, J.C.C.-T., J.R.G.-T. and A.C.-P.; validation, M.N.-H., J.G.R.-Q. and J.A.C.-S.; formal analysis, J.C.C.-T., J.R.G.-T., A.C.-P., J.C.C.-T. and J.R.G.-T.; resources, A.C.-P., M.N.-H. and J.A.C.-S.; data curation, A.C.-P.; writing—original draft preparation, J.C.C.-T.; writing—review and editing, J.R.G.-T., A.C.-P., M.N.-H., J.G.R.-Q. and J.A.C.-S.; visualisation, J.R.G.-T. and A.C.-P.; supervision, J.R.G.-T. and A.C.-P.; project administration, J.R.G.-T. and A.C.-P.; funding acquisition, A.C.-P., M.N.-H., J.G.R.-Q., J.R.G.-T. and J.A.C.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank the CONAHCYT National Laboratory for Solid Biofuels (BIO-ENER). (BIOENER) (SupportLNC-2023-40).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Khan, I.; Hou, F.; Le, H.P. The Impact of Natural Resources, Energy Consumption, and Population Growth on Environmental Quality: Fresh Evidence from the United States of America. *Sci. Total Environ.* **2021**, *754*, 142222. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Rehman, E.; Rehman, S. Modeling the Nexus between Carbon Emissions, Urbanization, Population Growth, Energy Consumption, and Economic Development in Asia: Evidence from Grey Relational Analysis. *Energy Rep.* **2022**, *8*, 5430–5442. [\[CrossRef\]](#)
3. Tshikovhi, A.; Motaung, T.E. Technologies and Innovations for Biomass Energy Production. *Sustainability* **2023**, *15*, 12121. [\[CrossRef\]](#)
4. Kant Bhatia, S.; Palai, A.K.; Kumar, A.; Kant Bhatia, R.; Kumar Patel, A.; Kumar Thakur, V.; Yang, Y.H. Trends in Renewable Energy Production Employing Biomass-Based Biochar. *Bioresour. Technol.* **2021**, *340*, 125644. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Belousov, A.; Lushpeev, V.; Sokolov, A.; Sultanbekov, R.; Tyan, Y.; Ovchinnikov, E.; Shvets, A.; Bushuev, V.; Islamov, S. Experimental Research of the Possibility of Applying the Hartmann–Sprenger Effect to Regulate the Pressure of Natural Gas in Non-Stationary Conditions. *Processes* **2025**, *13*, 1189. [\[CrossRef\]](#)
6. Bondarenko, A.V.; Islamov, S.R.; Ignatyev, K.V.; Mardashov, D.V. Laboratory Studies of Polymer Compositions for Well-Kill under Increased Fracturing. *Perm. J. Pet. Min. Eng.* **2020**, *20*, 37–48. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Dhyani, V.; Bhaskar, T. A Comprehensive Review on the Pyrolysis of Lignocellulosic Biomass. *Renew. Energy* **2018**, *129*, 695–716. [\[CrossRef\]](#)
8. Mi, B.; Liu, Z.; Hu, W.; Wei, P.; Jiang, Z.; Fei, B. Investigating Pyrolysis and Combustion Characteristics of Torrefied Bamboo, Torrefied Wood and Their Blends. *Bioresour. Technol.* **2016**, *209*, 50–55. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Mousa, E.; Wang, C.; Riesbeck, J.; Larsson, M. Biomass Applications in Iron and Steel Industry: An Overview of Challenges and Opportunities. *Renew. Sustain. Energy Rev.* **2016**, *65*, 1247–1266. [\[CrossRef\]](#)
10. Akubueyi, F.C.; Odokuma, L.O. Biogas Production from Domestic Waste and Its Purification with Charcoal. *Pac. J. Sci. Technol.* **2013**, *14*, 63–69.
11. Shah, S.S.; Ahmad, I.; Ahmad, W.; Ishaq, M.; Khan, H. Deep Desulphurization Study of Liquid Fuels Using Acid Treated Activated Charcoal as Adsorbent. *Energy Fuels* **2017**, *31*, 7867–7873. [\[CrossRef\]](#)
12. Budianto, A.; Kusdarini, E.; Effendi, S.S.W.; Aziz, M. The Production of Activated Carbon from Indonesian Mangrove Charcoal. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *462*, 012006. [\[CrossRef\]](#)
13. Wang, J.; Wang, S. Preparation, Modification and Environmental Application of Biochar: A Review. *J. Clean Prod.* **2019**, *227*, 1002–1022. [\[CrossRef\]](#)
14. Dufourny, A.; Van De Steene, L.; Humbert, G.; Guibal, D.; Martin, L.; Blin, J. Influence of Pyrolysis Conditions and the Nature of the Wood on the Quality of Charcoal as a Reducing Agent. *J. Anal. Appl. Pyrolysis* **2019**, *137*, 1–13. [\[CrossRef\]](#)
15. Khaeso, K.; Sukhuna, B.; Katekaew, S.; Junsiri, C.; Monatrakul, W.; Srichat, A.; Senawong, K.; Lagoon, K. Sustainable Conversion of Agricultural Waste into Solid Fuel (Charcoal) via Gasification and Pyrolysis Treatment. *Energy Convers. Manag. X* **2024**, *24*. [\[CrossRef\]](#)
16. Trejo-Zamudio, D.; García-Trejo, F.; Antonio-Gutiérrez, C. Conversión de Residuos a Biocombustibles. *Ciencia* **2019**, *70*, 64–71.
17. Ronsse, F.; Nachenius, R.W.; Prins, W. Carbonization of Biomass. In *Recent Advances in Thermochemical Conversion of Biomass*; Elsevier Inc.: Amsterdam, The Netherlands, 2015; pp. 293–324. ISBN 9780444632906.
18. Chia, C.H.; Joseph, S.D.; Rawal, A.; Linser, R.; Hook, J.M.; Munroe, P. Microstructural Characterization of White Charcoal. *J. Anal. Appl. Pyrolysis* **2014**, *109*, 215–221. [\[CrossRef\]](#)
19. Pereira, B.L.C.; Oliveira, A.C.; Carvalho, A.M.M.L.; de Carneiro, A.C.O.; Santos, L.C.; Vital, B.R. Quality of Wood and Charcoal from Eucalyptus Clones for Ironmaster Use. *Int. J. For. Res.* **2012**, *2012*, 523025. [\[CrossRef\]](#)
20. Dias-Junior, A.F.; Esteves, R.P.; da Silva, Á.M.; Sousa-Júnior, A.D.; Oliveira, M.P.; Brito, J.O.; Napoli, A.; Braga, B.M. Investigating the Pyrolysis Temperature to Define the Use of Charcoal. *Eur. J. Wood Wood Prod.* **2020**, *78*, 193–204. [\[CrossRef\]](#)
21. Weber, K.; Quicker, P. Properties of Biochar. *Fuel* **2018**, *217*, 240–261. [\[CrossRef\]](#)

22. Kurniawan, E.W.; Amirta, R.; Budiarto, E.; Arung, E.T. Mixing of Acacia Bark and Palm Shells to Increase Caloric Value of Palm Shells White Charcoal Briquette. *AIP Conf. Proc.* **2017**, *1854*, 020021. [\[CrossRef\]](#)
23. Pijarn, N.; Intaraprasert, J.; Ophap, S.; Uma, T.; Deekarnkol, S.; Bowornkietkaew, W. Microstructural Characterization of White Charcoal for Rapid Reduction of Chemical Oxygen Demand and Automatically Adjust PH to Neutral in Wastewater Treatment. *J. Mater. Res. Technol.* **2021**, *13*, 336–345. [\[CrossRef\]](#)
24. Hu, W.; Feng, Z.; Yang, J.; Gao, Q.; Ni, L.; Hou, Y.; He, Y.; Liu, Z. Combustion Behaviors of Molded Bamboo Charcoal: Influence of Pyrolysis Temperatures. *Energy* **2021**, *226*, 120253. [\[CrossRef\]](#)
25. UNE-EN 14780; Biocombustibles Sólidos. Preparación de Muestras. AENOR: Madrid, España, 2012.
26. UNE-EN 14774-3; Biocombustibles Sólidos. Métodos para la Determinación del Contenido de Humedad. Método de Secado en Estufa. Parte 3: Humedad en la Muestra de Análisis General. AENOR: Madrid, España, 2010.
27. UNE-EN 15148; Biocombustibles Sólidos. Determinación del Contenido de Materias Volátiles. AENOR: Madrid, Spain, 2010.
28. UNE-EN 14775; Biocombustibles Sólidos. Método para la Determinación del Contenido en Cenizas. AENOR: Madrid, España, 2010.
29. Yin, C.-Y. Prediction of Higher Heating Values of Biomass from proximate and Ultimate Analyses. *Fuel* **2011**, *90*, 1128–1132. [\[CrossRef\]](#)
30. ASTM D1762-84; Standard Test Method for Chemical Analysis of Wood Charcoal. ASTM International: West Conshohocken, PA, USA, 2021.
31. Cordero, T.; Marquez, F.; Rodriguez-Mirasol, J.; Rodriguez, J.J. Predicting Heating Values of Lignocellulosics and Carbonaceous Materials from Proximate Analysis. *Fuel* **2001**, *80*, 1567–1571. [\[CrossRef\]](#)
32. Canal, W.D.; Carvalho, A.M.M.; Figueiró, C.G.; de Cássia Oliveira Carneiro, A.; de Freitas Fialho, L.; Donato, D.B. Impact of Wood Moisture in Charcoal Production and Quality. *Floresta Ambiente* **2020**, *27*, e20170999. [\[CrossRef\]](#)
33. Liu, Z.; Han, G. Production of Solid Fuel Biochar from Waste Biomass by Low Temperature Pyrolysis. *Fuel* **2015**, *158*, 159–165. [\[CrossRef\]](#)
34. Charvet, F.; Silva, F.; Ruivo, L.; Tarelho, L.; Matos, A.; da Silva, J.F.; Neves, D. Pyrolysis Characteristics of Undervalued Wood Varieties in the Portuguese Charcoal Sector. *Energies* **2021**, *14*, 2537. [\[CrossRef\]](#)
35. Ronsse, F.; van Heck, S.; Dickinson, D.; Prins, W. Production and Characterization of Slow Pyrolysis Biochar: Influence of Feedstock Type and Pyrolysis Conditions. *GCB Bioenergy* **2013**, *5*, 104–115. [\[CrossRef\]](#)
36. Massuque, J.; De Assis, M.R.; Loureiro, B.A.; Matavel, C.E.; Trugilho, P.F. Influence of Lignin on Wood Carbonization and Charcoal Properties of Miombo Woodland Native Species. *Eur. J. Wood Wood Prod.* **2021**, *79*, 527–535. [\[CrossRef\]](#)
37. Elyounssi, K.; Collard, F.X.; Mateke, J.A.N.; Blin, J. Improvement of Charcoal Yield by Two-Step Pyrolysis on Eucalyptus Wood: A Thermogravimetric Study. *Fuel* **2012**, *96*, 161–167. [\[CrossRef\]](#)
38. Wang, L.; Skreiberg, Ø.; Van Wesenbeeck, S.; Grønli, M.; Antal, M.J. Experimental Study on Charcoal Production from Woody Biomass. *Energy Fuels* **2016**, *30*, 7994–8008. [\[CrossRef\]](#)
39. García-Quezada, J.; Musule-Lagunes, R.; Prieto-Ruiz, J.A.; Vega-Nieva, D.J.; Carrillo-Parra, A. Evaluation of Four Types of Kilns Used to Produce Charcoal from Several Tree Species in Mexico. *Energies* **2023**, *16*, 333. [\[CrossRef\]](#)
40. Bustamante-García, V.; Carrillo-Parra, A.; González-Rodríguez, H.; Ramírez-Lozano, R.G.; Corral-Rivas, J.J.; Garza-Ocañas, F. Evaluation of a Charcoal Production Process from Forest Residues of *Quercus Sideroxyla* Humb., & Bonpl. in a Brazilian Beehive Kiln. *Ind. Crops Prod.* **2013**, *42*, 169–174. [\[CrossRef\]](#)
41. Somerville, M.; Jahanshahi, S. The Effect of Temperature and Compression during Pyrolysis on the Density of Charcoal Made from Australian Eucalypt Wood. *Renew. Energy* **2015**, *80*, 471–478. [\[CrossRef\]](#)
42. Lima, M.D.R.; Massuque, J.; Bufalino, L.; Trugilho, P.F.; Ramalho, F.M.G.; de Protásio, T.P.; Hein, P.R.G. Clarifying the Carbonization Temperature Effects on the Production and Apparent Density of Charcoal Derived from Amazonia Wood Wastes. *J. Anal. Appl. Pyrolysis* **2022**, *166*. [\[CrossRef\]](#)
43. de Abreu Neto, R.; de Assis, A.A.; Ballarin, A.W.; Hein, P.R.G. Effect of Final Temperature on Charcoal Stiffness and Its Correlation with Wood Density and Hardness. *SN Appl. Sci.* **2020**, *2*, 1020. [\[CrossRef\]](#)
44. Trugilho, P.F.; da Silva, D.A. Influence of final carbonization temperature in the physical and chemical characteristics of the jatobá (*Himenea Courbaril* L.) charcoal. *Sci. Agrar.* **2001**, *2*, 45–53. [\[CrossRef\]](#)
45. Miki, M.; Kikuchi, T.; Nakamura, M.; Hatakeyama, K.; Takada, J. Electromagnetic Wave Absorption Characteristics of Bincho-Charcoal and Bamboo Charcoal. *Trans. Mater. Res. Soc. Jpn.* **2003**, *28*, 1053–1057.
46. Kwon, G.J.; Kim, A.R.; Lee, H.S.; Lee, S.H.; Hidayat, W.; Febrianto, F.; Kim, N.H. Characteristics of White Charcoal Produced from the Charcoal Kiln for Thermoherapy. *J. Korean Wood Sci. Technol.* **2018**, *46*, 527–540. [\[CrossRef\]](#)
47. Kim, N.H.; Hanna, R.B. Morphological Characteristics of *Quercus Variabilis* Charcoal Prepared at Different Temperatures. *Wood Sci. Technol.* **2006**, *40*, 392–401. [\[CrossRef\]](#)

48. Couto, A.M.; Trugilho, P.F.; Napoli, A.; Lima, J.T.; Da Silva, J.R.M.; Protásio, T.D.P. Quality of Charcoal from *Corymbia* and *Eucalyptus* Produced at Different Final Carbonization Temperatures. *Sci. For.* **2015**, *43*, 817–831. [\[CrossRef\]](#)
49. Missio, A.L.; Mattos, B.D.; Gatto, D.A.; De Lima, E.A. Thermal Analysis of Charcoal from Fast-Growing Eucalypt Wood: Influence of Raw Material Moisture Content. *J. Wood Chem. Technol.* **2014**, *34*, 191–201. [\[CrossRef\]](#)
50. Kwon, S.-M.; Kwon, G.-J.; Jang, J.-H.; Kim, N.-H. Characteristics of Charcoal in Different Carbonization Temperatures. *J. For. Environ. Sci.* **2012**, *28*, 263–267. [\[CrossRef\]](#)
51. Manabe, T.; Ohata, M.; Yoshizawa, S.; Nakajima, D.; Goto, S.; Uchida, K.; Yajima, H. Effect of Carbonization Temperature on the Physicochemical Structure of Wood Charcoal. *Trans. Mater. Res. Soc. Jpn.* **2007**, *32*, 1035–1038. [\[CrossRef\]](#)
52. Hu, E.; Zeng, X.; Ma, D.; Wang, F.; Yi, X.; Li, Y.; Fu, X. Effect of the Moisture Content in Coal on the Pyrolysis Behavior in an Indirectly Heated Fixed-Bed Reactor with Internals. *Energy Fuels* **2017**, *31*, 1347–1354. [\[CrossRef\]](#)
53. Zanoncio, A.J.V.; Carvalho, A.G.; Trugilho, P.F.; Monteiro, T.C. Extractive and Energetic Properties of Wood and Charcoal. *Rev. Árvore* **2014**, *38*, 369–374. [\[CrossRef\]](#)
54. Patlán, E.E.S.; Aquino, V.M.; Prado, C.O.; López, M.E.F.; Ortiz, A.O. Análisis de Calidad Del Carbón de Mezquite (*Prosopis* sp.), Encino (*Quercus* sp.) y Eucalipto (*Eucalyptus* sp.). *Braz. J. Anim. Environ. Res.* **2024**, *7*, e75544. [\[CrossRef\]](#)
55. Briseño-Urbe, K.C.; Carrillo-Parra, A.; Bustamante-García, V.; González-Rodríguez, H.; Foroughbakhk, R. Firewood Production, Yield and Quality of Charcoal from *Eucalyptus Camaldulensis* and *E. Microtheca* Planted in the Semiarid Land of Northeast Mexico. *Int. J. Green. Energy* **2015**, *12*, 961–969. [\[CrossRef\]](#)
56. Carrillo-Parra, A.; Foroughbakhkch-Pournavab, R.; Bustamante-García, V. Calidad del carbón de *Prosopis Laevigata* (Humb. & Bonpl. ex Willd.) M.C. Johnst. y *Ebenopsis Ebano* (Berland.) Barneby & J.W. Grimes elaborado en horno tipo fosa. *Rev. Mex. Cienc. For.* **2013**, *4*, 62–71.
57. DIN 51749; Grill Charcoal and Grill Charcoal Briquettes—Requirements, Tests. DIN: Berlin, Germany, 1989.
58. De la Cruz-Montelongo, C.; Herrera Gamboa, J.; Ortiz Sánchez, I.A.; Ríos Saucedo, J.C.; Rosales Serna, R.; Carrillo-Parra, A. Caracterización Energética Del Carbón Vegetal Producido En El Norte-Centro de México. *Madera Y Bosques* **2020**, *26*, e2621971. [\[CrossRef\]](#)
59. Ruiz-Aquino, F.; Ruiz-Ángel, S.; Santiago-García, W.; Fuente-Carrasco, M.E.; Sotomayor-Castellanos, J.R.; Carrillo-Parra, A. Energy Characteristics of Wood and Charcoal of Selected Tree Species in Mexico. *Wood Res.* **2019**, *1*, 71–82.
60. EN 1860-2; Appliances, Solid Fuels and Firelighters for Barbecueing—Part 2: Barbecue Charcoal and Barbecue Charcoal Briquettes. Requirements and Test Methods. CEN: Brussels, Belgium, 2005.
61. Contreras-Trejo, J.C.; Vega-Nieva, D.J.; Heya, M.N.; Prieto-Ruiz, J.A.; Nava-Berúmen, C.A.; Carrillo-Parra, A. Sintering and Fusibility Risks of Pellet Ash from Different Sources at Different Combustion Temperatures. *Energies* **2022**, *15*, 5026. [\[CrossRef\]](#)
62. Kleinhans, U.; Wieland, C.; Frandsen, F.J.; Spliethoff, H. Ash Formation and Deposition in Coal and Biomass Fired Combustion Systems: Progress and Challenges in the Field of Ash Particle Sticking and Rebound Behavior. *Prog. Energy Combust. Sci.* **2018**, *68*, 65–168. [\[CrossRef\]](#)
63. Lachman, J.; Baláš, M.; Lisý, M.; Lisá, H.; Milčák, P.; Elbl, P. An Overview of Slagging and Fouling Indicators and Their Applicability to Biomass Fuels. *Fuel Process. Technol.* **2021**, *217*, 106804. [\[CrossRef\]](#)
64. Lu, Y.; Wang, Y.; Zhao, Y.; Wei, Z.; Li, Y.; Hao, W.; Zhang, Y. The Characteristics of Mineralogy, Morphology and Sintering during Co-Combustion of Zhundong Coal and Oil Shale. *RSC Adv.* **2017**, *7*, 51036–51045. [\[CrossRef\]](#)
65. Wang, L.; Skreiberg, Ø.; Gronli, M.; Specht, G.P.; Antal, M.J. Is Elevated Pressure Required to Achieve a High Fixed-Carbon Yield of Charcoal from Biomass? Part 2: The Importance of Particle Size. *Energy Fuels* **2013**, *27*, 2146–2156. [\[CrossRef\]](#)
66. Oyedun, A.O.; Lam, K.L.; Hui, C.W. Charcoal Production via Multistage Pyrolysis. *Chin. J. Chem. Eng.* **2012**, *20*, 455–460. [\[CrossRef\]](#)
67. NBN-MII-001; Charcoal and Charcoal Briquettes for Domestic Use—Designation, Specifications, Tests. NBN: Brussels, Belgium, 1984.
68. Cheng, Z.; Yang, J.; Zhou, L.; Liu, Y.; Wang, Q. Characteristics of Charcoal Combustion and Its Effects on Iron-Ore Sintering Performance. *Appl. Energy* **2016**, *161*, 364–374. [\[CrossRef\]](#)
69. Oke, M.A.; Sonibare, J.A.; Odunlami, O.A.; Elehinfafe, F.B.; Onakpohor, A.; Akeredolu, A.F. Proximate Analysis of Some Common Charcoal in Southwestern Nigeria. *Results Eng.* **2022**, *15*, 100454. [\[CrossRef\]](#)
70. Ngangyo-Heya, M.; Pournavab, F.R.; Carrillo-Parra, A.; Serafin, C.U. Bioenergy Potential of Shrub from Native Species of Northeastern Mexico. *Int. J. Agric. Policy Res.* **2014**, *2*, 475–483. [\[CrossRef\]](#)
71. Mencarelli, A.; Cavalli, R.; Greco, R. Variability on the Energy Properties of Charcoal and Charcoal Briquettes for Barbecue. *Heliyon* **2022**, *8*, e10052. [\[CrossRef\]](#) [\[PubMed\]](#)
72. Seboka, Y. Bio-Carbon Opportunities in Eastern & Southern Africa. In *Charcoal Production: Opportunities and Barriers for Improving Efficiency and Sustainability*; United Nations Development Programme: New York, NY, USA, 2009; Volume 102.
73. Dias Júnior, A.F.; Andrade, C.R.; Lana, A.Q.; da Silva, Á.M.; Brito, J.O.; Milan, M. Tips on the Variability of BBQ Charcoal Characteristics to Assist Consumers in Product Choice. *Eur. J. Wood Wood Prod.* **2021**, *79*, 1017–1026. [\[CrossRef\]](#)

74. García-Quezada, J.; Musule-Lagunes, R.; Wehenkel, C.; Prieto-Ruíz, J.A.; Núñez-Retana, V.; Carrillo-Parra, A. Effect of Firewood Moisture Content on Quality, Yield, and Economic Gain during Charcoal Production in a Modified Half-Orange Kiln. *Fuels* **2023**, *5*, 1–16. [[CrossRef](#)]
75. Ge, S.; Foong, S.Y.; Ma, N.L.; Liew, R.K.; Wan Mahari, W.A.; Xia, C.; Yek, P.N.Y.; Peng, W.; Nam, W.L.; Lim, X.Y.; et al. Vacuum Pyrolysis Incorporating Microwave Heating and Base Mixture Modification: An Integrated Approach to Transform Biowaste into Eco-Friendly Bioenergy Products. *Renew. Sustain. Energy Rev.* **2020**, *127*, 109871. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.