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Effect of Initial Moisture Content of *Prosopis laevigata* Firewood on Charcoal Yield and Quality

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ABSTRACT

Charcoal yield and quality are influenced by both process parameters and raw material characteristics. In industrial settings, temperature, heating rate, and residence time are typically controlled. However, in rural and traditional production systems, raw material properties—particularly moisture content—become critical for improving efficiency. This study evaluated the effect of initial moisture content (MC) in *Prosopis laevigata* firewood on charcoal yield and quality. Firewood samples (20×20×20 mm) were conditioned to MC levels of 0%, 20%, 40%, and 60%, and subjected to pyrolysis under laboratory conditions at 450°C for 30 minutes. Firewood and charcoal characteristics were analyzed using one-way ANOVA, Pearson correlation, and linear regression ($p<0.05$). Results showed that the highest charcoal yield (28%) and density (0.28 g·cm^3) were obtained at 0% MC. Ash content decreased significantly with lower MC, reaching the lowest value (1.58%) at 0% MC. Strong correlations were found between firewood MC and basic density ($R^2=0.81$), charcoal yield ($R^2=0.87$), and energy efficiency ($R^2=0.65$). These findings suggest that reducing firewood moisture content is a simple and effective strategy to improve charcoal yield and quality in traditional production systems.

Keywords: biomass; pyrolysis; charcoal yield; moisture content; energy efficiency; *Prosopis laevigata*

INTRODUCTION

Charcoal has been produced and used globally for thousands of years. Today, its most common uses include domestic cooking, residential heating, and various industrial applications (Jahirul et al. 2012). Today, it remains a key resource for cooking, household heating, and various industrial processes (Antal and Grønli 2003, Dias Júnior et al. 2015, Hu and Gholizadeh 2019, Dias Junior et al. 2020, Oke et al. 2022).

More than one-third of the global population relies on firewood and charcoal as primary energy sources, particularly in regions where access to fossil fuels is limited (Dam 2017). The demand for charcoal has been increasing, driven by the rise of gourmet cooking and the lack of affordable alternative energy sources in developing countries. In 2023, global charcoal production was estimated at 61,228 million t, with Brazil (11.67%), Ethiopia (8.28%), Nigeria (8.15%), the Democratic Republic of the Congo (5%), India (4.70%), and China (3.98%) being the leading producers (FAO, 2024). However, inefficient charcoal production significantly contributes to deforestation and carbon emissions, highlighting the need to optimize production methods (Surup et al. 2020).

Charcoal production technologies range from traditional methods to industrial-scale processes (Mencarelli et al. 2023). Advanced techniques, such as batch-type kilns, Brazilian hives, metal kilns, and Adam retorts, provide some level of control over pressure, gas flow, temperature, and pyrolysis time, achieving efficiency rates of 35%–40% (Bustamante-García et al. 2013, Rodrigues and Braghini 2019, García-Quezada et al. 2021). However, in many rural areas of developing countries, traditional technologies like earth-mound kilns remain prevalent, often yielding less than 25% (Arias-Chalico 2018, Rodrigues and Braghini 2019).

Charcoal yield and quality are determined by multiple variables, including the composition of the raw material, heating rate, peak pyrolysis temperature, pressure, gas flow, and the presence of natural or synthetic catalysts (Antal and Grønli 2003, de Jesus et al. 2019). In small-scale charcoal production, temperature and moisture content (MC) are the most easily controlled parameters (Sangsuk et al. 2020). Therefore, optimizing production efficiency by regulating initial moisture content could be a key strategy to minimize biomass losses and improve product quality. However, one of the most critical factors affecting charcoal production efficiency and quality is the initial moisture content of the raw material. High moisture levels in firewood reduce process efficiency, increase charcoal friability, and lead to higher pollutant emissions (Sikarwar et al. 2017, Singh et al. 2017, Canal et al. 2020, da Silva et al. 2023). Some studies have determined the effect of moisture content on some quality aspects of charcoal, but without controlling production conditions. The missing gap is the lack of comparative data across species under standardized carbonization parameters. This study addresses this by evaluating moisture effects under controlled conditions, allowing clearer attribution of its impact on yield and quality.

This study aims to determine the effects of the initial moisture content of *Prosopis laevigata* firewood on the yield and quality of charcoal produced under controlled laboratory conditions. The findings of this research could contribute to the development of strategies to optimize charcoal production, particularly in traditional production settings where efficiency is low and environmental degradation is a growing concern.

MATERIALS AND METHODS

Tree Sampling

Three mature *Prosopis laevigata* trees were randomly selected from the Ejido La Reforma in Linares, Nuevo León, Mexico. Logs approximately 1 meter long were harvested from each tree, leaving a 0.3-meter stump. Each log was sawn, and 40 firewood samples with dimensions of 20×20×20 mm were obtained per log.

Samples Conditioning

Ten samples were selected from each log. Five samples were used to determine the initial MC using the gravimetric method, while the remaining five were subjected to carbonization. The heating process was manually controlled, with temperature increments of 50°C every 30 minutes, corresponding to a heating rate of 1.67°C·min^{-1}, until reaching a final temperature of 450°C, which was maintained for 30 minutes (Meneiros et al. 2012, Briseño-Uribe et al. 2015, Fialho et al. 2022, Gomes et al. 2024, Teixeira et al. 2024). The charcoal produced under these conditions served as the control treatment (CT).

In contrast, the remaining samples (30 per log) were conditioned in an electric chamber (SHC28) at 20°C and exposed to different relative humidities (RH) to progressively reach moisture contents of 20, 40, and 60. To obtain 0% MC, the samples were oven-dried at 103±5°C until a constant weight was achieved. Once the samples stabilized at each RH level, ten were selected: five for experimental moisture content determination and five for charcoal production.

Firewood Characterization

Green, dry, and basic density of firewood were determined with Equations (1) and (2), respectively:

$$FW_{d(g,d)}=\frac{m_{(g,d)}}{v_{(g,d)}} \tag{1}$$

$$FW_{bd}=\frac{m_d}{v_g} \tag{2}$$

where $FW_{d(g,d)}$ is the firewood density at green or oven dry condition (g·cm^{-3}), FW_{bd} is the firewood basic density (g·cm^{-3}), $m_{(g,d)}$ is the firewood mass at green or oven dry condition (g) and $v_{(g,d)}$ is the firewood volume at green or oven dry condition (cm^3), these were determined by Archimedes' principle (Borrego-Núñez et al. 2025), in this case the samples were immerses in mercury contained in a graduated cylinder, the displacement of the mercury was the volume of the firewood sample.

Charcoal Yield and Proximate Analysis

Charcoal yields (ychar) (%) from samples of each moisture content were determined from the relationship between weight at the beginning and the end of the process, according to Somerville and Jahanshahi (Somerville and Jahanshahi 2015). The charcoal volume was also determined using Archimedes' principle.

Proximate analysis, including moisture content (MC; %), volatile material (VM; %), ash (ASH; %), and fixed carbon (FC; %) , was determined according to the international standard ASTM D-1762-84 (2021) with Equations (3), (4), (5), and (6), respectively:

$$MC=\left(\frac{A-B}{A}\right)\cdot 100 \tag{3}$$

$$VM=\left(\frac{B-C}{B}\right)\cdot 100 \tag{4}$$

$$ASH=\left(\frac{D}{B}\right)\cdot 100 \tag{5}$$

$$FC=100-MC-VM-ASH \tag{6}$$

where A is the grams of air-dry sample used, B is the grams of sample after increasing the temperature to 105°C, C is the grams of sample after increasing the temperature to 950°C, and D is the mass of residues (g).

Higher Heating Value

The higher heating value (HHV; KJ·kg^{-1}) was determined according to Equation (7) using the method developed by Cordero et al. (2001):

$$HHV = 354.3FC + 170.8VM \tag{7}$$

Gravimetric Yield, Energy Efficacy of Carbonization and Energetic Density

These characteristics were calculated using Equations (8), (9), and (10) , respectively (Matali et al. 2016):

$$GY=\left(\frac{m_{ch}}{m_f}\right)\cdot 100 \tag{8}$$

$$EY=GY\cdot\frac{HHV_{ch}}{HHV_f} \tag{9}$$

$$EY=FW_{bd}\cdot HHV_f \tag{10}$$

where GY is the gravimetric yield (%), m_{ch} is the dry mass of charcoal (g), m_f is the dry mass of firewood (g), EY is the energy yield (%), HHV_{ch} is the charcoal higher heating value ($KJ\cdot kg^{-1}$), HHV_f is the firewood higher heating value ($KJ\cdot kg^{-1}$) and ED is the energetic density ($KJ\cdot m^{-3}$).

Energy efficiency (EE; $KJ\cdot kg^{-1}$) was determined by the relationship between net heating value and mass of wet firewood using Equation (11) (Shah et al. 1992):

$$EE=\frac{ED\cdot V_g}{M_g} \tag{11}$$

where ED is the energetic density ($KJ\cdot m^{-3}$), V_g is the green volume without bark (m^3) of the tree, and M_g is the green mass (kg).

Statistical Analysis

Means and standard errors were calculated for firewood and charcoal properties at each MC level. One-way ANOVA was used for a completely randomised design with 15 replicates. Moisture content was the independent variable, while yield and charcoal quality parameters were the dependent variables Steel and Torrie (1960). Percentage data were transformed using the arcsine square root method before analysis. Tukey's HSD test ($p<0.05$) was used for pairwise comparisons. Pearson correlation and linear regression were used to assess relationships between moisture content and other variables. All statistical analyses were performed using R software, version 3.2.2.

RESULTS AND DISCUSSION

Firewood Properties

The average MC measured immediately after logging of *Prosopis laevigata* trees was 64%, which is lower than the 100% reported by Carrillo-Parra et al. (2013). Green, oven-dry, and basic densities of the firewood under different laboratory relative humidity conditions are presented in Table 1. The three density types respond differently to moisture because each one incorporates specific moisture conditions in its calculation. Green density increased markedly with moisture content (0.67–1.03 $g\cdot cm^{-3}$), as expected, since it includes both solids and water while the firewood volume remains relatively stable. This resulted in statistically significant differences among treatments. In contrast, oven-dry density showed only minor variation (0.65–0.67 $g\cdot cm^{-3}$) because it depends solely on dry mass and final dry volume, both of which tend to remain constant within a species; therefore, most treatments did not differ statistically. Basic density (0.63–0.66 $g\cdot cm^{-3}$) exhibited a similar pattern, as the small volumetric changes associated with moisture-induced swelling were insufficient to alter the relationship between oven-dry mass and green volume.

Basic density values at 0, 20, 40, and 60% MC were lower than the 0.79 $g\cdot cm^{-3}$ reported by Carrillo-Parra et al. (2011). This difference may be attributed to variations in tree age, season of sampling, site conditions, or sampling methodology.

Overall, green density showed statistically significant differences among moisture levels, whereas oven-dry and basic densities did not. This behavior reflects the nature of each density calculation: green density incorporates both solids and moisture, making it highly sensitive to water content, while oven-dry and basic densities rely on dry mass and relatively stable volumes, resulting in non-significant differences across moisture levels.

Different letters in Green density represent statistically significant difference among firewood MC by Tukey test ($p\leq 0.05$).

Charcoal Density and Mass Yield

The charcoal density showed statistical differences ($p<0.05$) at different firewood MC (Figure 1a), the highest charcoal density value (0.28 $g\cdot cm^{-3}$) was produced from firewood at 0% MC, followed by values of 0.26 $g\cdot cm^{-3}$ produced at 40 and 60% MC, the lowest charcoal density (0.25 $g\cdot cm^{-3}$) was at 20% MC.

The charcoal yield showed statistical differences ($p<0.001$) between different firewood moisture content (Figure 1b). The highest charcoal yield (28%) was obtained at the lowest firewood samples at MC 0%, while the lowest

Table 1. Mean and standard error of green, oven dry and basic density of *Prosopis laevigata* firewood from an experimental plantation, conditioned at different moisture content.

Moisture Content (%)	Green density ($g\cdot cm^{-3}$)		Oven dry density ($g\cdot cm^{-3}$)		Basic density ($g\cdot cm^{-3}$)	
	Mean	Std. error	Mean	Std. error	Mean	Std. error
0	0.67 (d)	0.01	0.66	0.01	0.66	0.01
20	0.73 (c)	0.01	0.67	0.01	0.63	0.01
40	0.89 (b)	0.02	0.65	0.04	0.64	0.01
60	1.03 (a)	0.01	0.66	0.01	0.63	0.01

yield (18%) was at 60%. Baghel et al. (2022) reported a yield of 63.40, 44.5, 36.65 and 30.50% for temperatures of 300, 400, 500 and 600°C in *Prosopis juliflora* species, this difference is related to the use of inert gas in carbonization, on the other hand, Chandrasekaran et al. (2021) obtained a yield of 36.18% at 400°C with a moisture content of less than 12%, while Nigatu et al. (2012) obtained a higher yield with *Prosopis juliflora* (33.1%) at a firewood moisture content of 21.2%. Missio et al. (2014) reported a similar relationship between yields and moisture content on charcoal of *Eucalyptus benthamii* firewood produced at high pressure. Yields of 36.34%, 34.79%, and 30.30% were obtained at moisture content of 0%, 30%, and 50%, respectively. On the other hand, Darmstadt et al. (2000) reported no differences in yield, regarding moisture content, on *Acer saccharum* bark particles pyrolyzed under vacuum conditions. The reduction of charcoal yield after increasing the moisture content of the raw material is attributed to extending the period of devolatilization produced by steam. High levels of moisture content also contribute to reducing the heating rate and to standardizing and delaying the process, the lower charcoal yield at higher moisture contents is due to the longer steam-driven degradation during pyrolysis and the extra firewood consumed to generate the heat needed to remove water, leaving less material available for charcoal formation (de Diego et al. 2003, Missio et al. 2014, Di Blasi et al. 2016).

Proximate Analysis

Results of proximate analysis of charcoal produced from different moisture content of firewood samples showed that only ash content was statistically different (p<0.001) (Figure 2). The highest and lowest values (3.43% and 1.68%) were obtained from firewood at 60% and 0% MC, respectively. Contrary to these findings, Missio et al. (2014) described a non-linear relationship between

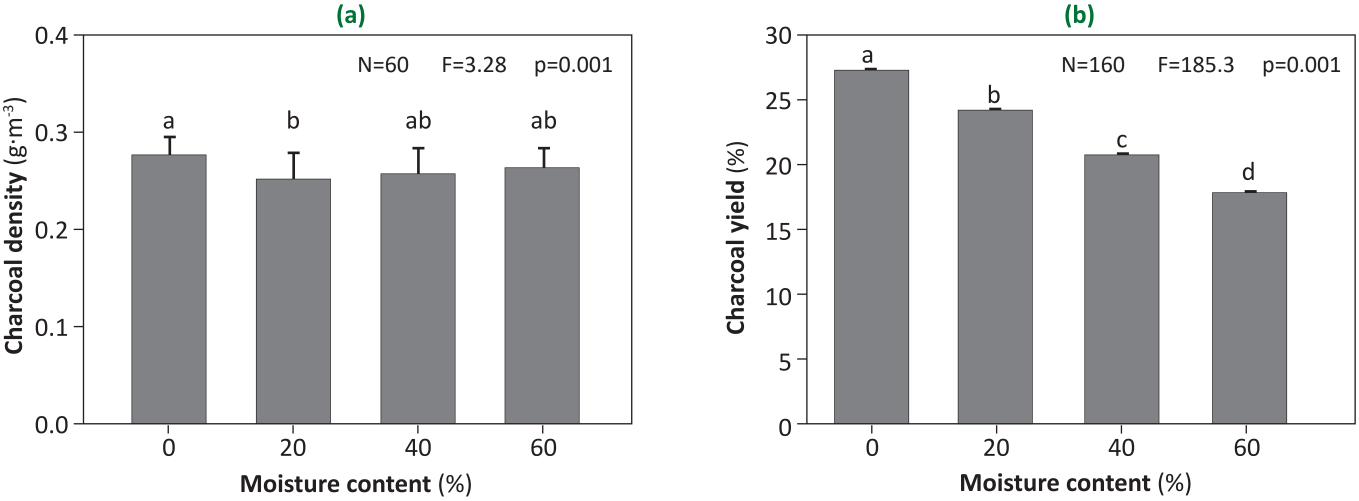

Figure 1. Mean and standard error of charcoal density and yield produced from firewood at four initial moisture contents: **(a)** Charcoal density (g·cm^{-3}); **(b)** Charcoal yield (%).

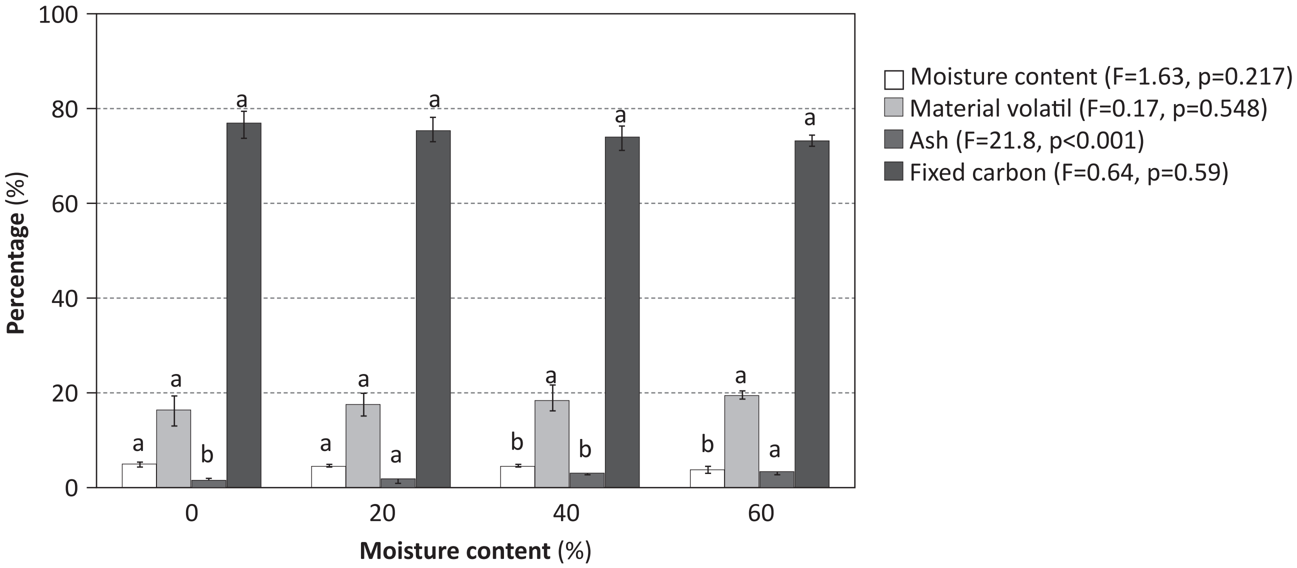

Figure 2. Proximate analysis of charcoal produced from firewood at four initial moisture contents, n=60, line bars represent the standard error.

reductions of moisture content of raw material, from 50%, 30%, and 0%, to the percentage reduction of ashes; the difference in the patterns is attributed to residence times. In this research, the residence time may not be enough to leach the firewood, reducing the amount of demineralization by water. Regarding charcoal quality, high ash content is a negative characteristic (Sangsuk et al. 2020). According to Antal and Grønli (2003), good charcoal quality should present ash values between 0.5 and 5%. Charcoal moisture content was the lowest at 60% and highest at 0%. There were no statistically significant differences in charcoal moisture content, nor were there any significant differences in volatile material nor in fixed carbon (Figure 2). Similar results were reported by Antal and Grønli (2003). However, Shah et al. (1992) found differences in fixed carbon at different moisture contents of the firewood used for charcoal production in a pilot kiln.

Higher Heating Values, Energetic Density, and Energy Efficiency of Carbonisation

Higher heating values of charcoal showed no statistical differences at different values of firewood moisture content

Table 2. Correlation analysis between moisture content with respect to yields and characteristics of charcoal.

Variable	Equation	R2	F	P
FWd*	FWd = 0.666+0.00565(MC)	0.8130	257.6	<0.0001**
CHd	CHd = 0.265+ 0.000105(MC)	-0.0053	0.68	0.412
CHy (m/m)	CHy(m/m) = 27.465 - 0.148(MC)	0.8680	389.2	<0.0001
CHy (v/m)	CHy(v/m) = 5.401 - 0.0009(MC)	-0.0130	0.231	0.633
CHMC	CHMC = 4.961 - 0.017(MC)	0.0330	2.99	0.089
CHVM	CHVM = 16.398 - 0.057(MC)	0.0056	1.33	0.253
CHAsh	CHAsh = 1.701 - 0.027(MC)	0.4510	50.28	<0.0001
CHFC	CHFC = 76.856 - 0.063(MC)	0.0094	1.563	0.216
CHHHV	CHHHV = 30031 -12.347(MC)	0.0107	1.638	0.206
CHED	CHED = 7964 -6.533(MC)	0.0211	2.274	0.137
CHEE	CHEE = 5503.2 - 33.742(MC)	0.6450	108.1	<0.0001

FWd= Firewood basic density, CHd= Charcoal density, CHy= Charcoal yield (mass/mass), CHy (v/m) = Charcoal yield (volume/mass), CHMC= Charcoal moisture content, CHVM = Charcoal volatile material, CHAsh = Charcoal ash, CHFC= Charcoal fixed carbon, CHHHV = Charcoal higher heating values, CHED = Charcoal energy density, CHEE = Charcoal energy efficacy. **Values of p<0.001 are bold.

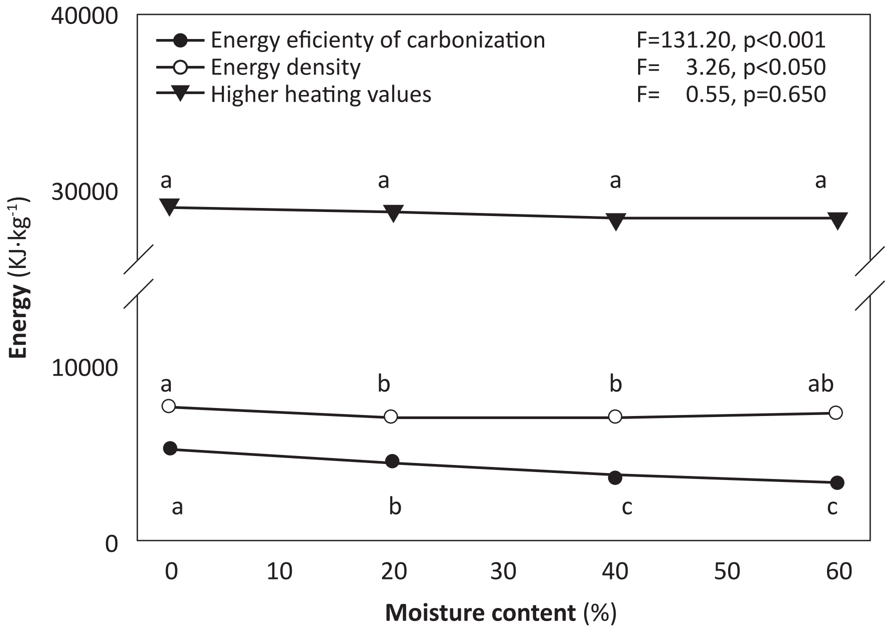

Figure 3. Higher heating values, energy density and energy efficiency of carbonization from firewood at four initial moisture contents, n=60.

(Figure 3). However, the values obtained (29,354 KJ·kg^{-1} – 30,079 KJ·kg^{-1}) are within the requirements of international standards. Energy density, which involves calculating the higher heating values and the moisture content (Equation 10) of firewood, was statistically different ($p<0.05$) for different moisture contents. The highest energy density value (8,294) was obtained from firewood at 0% MC, and the lowest (7,739) from firewood at 60% MC (Figure 3). Energy efficiency of carbonisation also showed statistical differences between moisture contents of the firewood; the values decreased when increasing moisture content and showed a similar pattern to that reported by Demirbas (2016).

Relationship Between Firewood Moisture Content, Charcoal Yield, and Charcoal Characteristics

High determination coefficient values (0.81, 0.86, 0.41, 0.64) were found between the moisture content of firewood and firewood density of charcoal yields (%), charcoal ash content, and energy efficiency of carbonization, as shown in Table 2. Figure 4 presents the relationship among variables. According to Adamu et al. (2018) and Baqir et al. (2019), wood moisture content affects combustion efficiency because part of the energy from wet wood is expended on evaporating its internal water. Consequently, increasing firewood moisture content reduces energy output, prolongs thermochemical conversion time, and leads to higher emissions, lower yields, and greater friability (Dias Júnior et al. 2015, Assis et al. 2016, Özyuğuran and Yaman 2017).

The reduction in charcoal energy associated with firewood with higher moisture content is reflected in the negative correlations observed (Figure 4). Since the moisture content of charcoal is typically kept below 10%, this promotes efficient energy release during combustion without significant energy losses due to water evaporation. Although some authors, such as Canal et al. (2020), reported no significant differences in volatile matter, fixed carbon, ash content, bulk density, or gross calorific value of charcoal. However, they note that pyrolysis removes part of the firewood as volatile compounds from hemicelluloses and extractives, increasing the concentration of fixed carbon and ash. This behavior is also evident in these results (Figure 4, Table 2).

It has been observed that the ideal moisture content for a carbonization process is between 0 and 20%. In the industry, it is difficult to reach 0% moisture, but it is possible to reach 20% and thus achieve a correct production of charcoal.

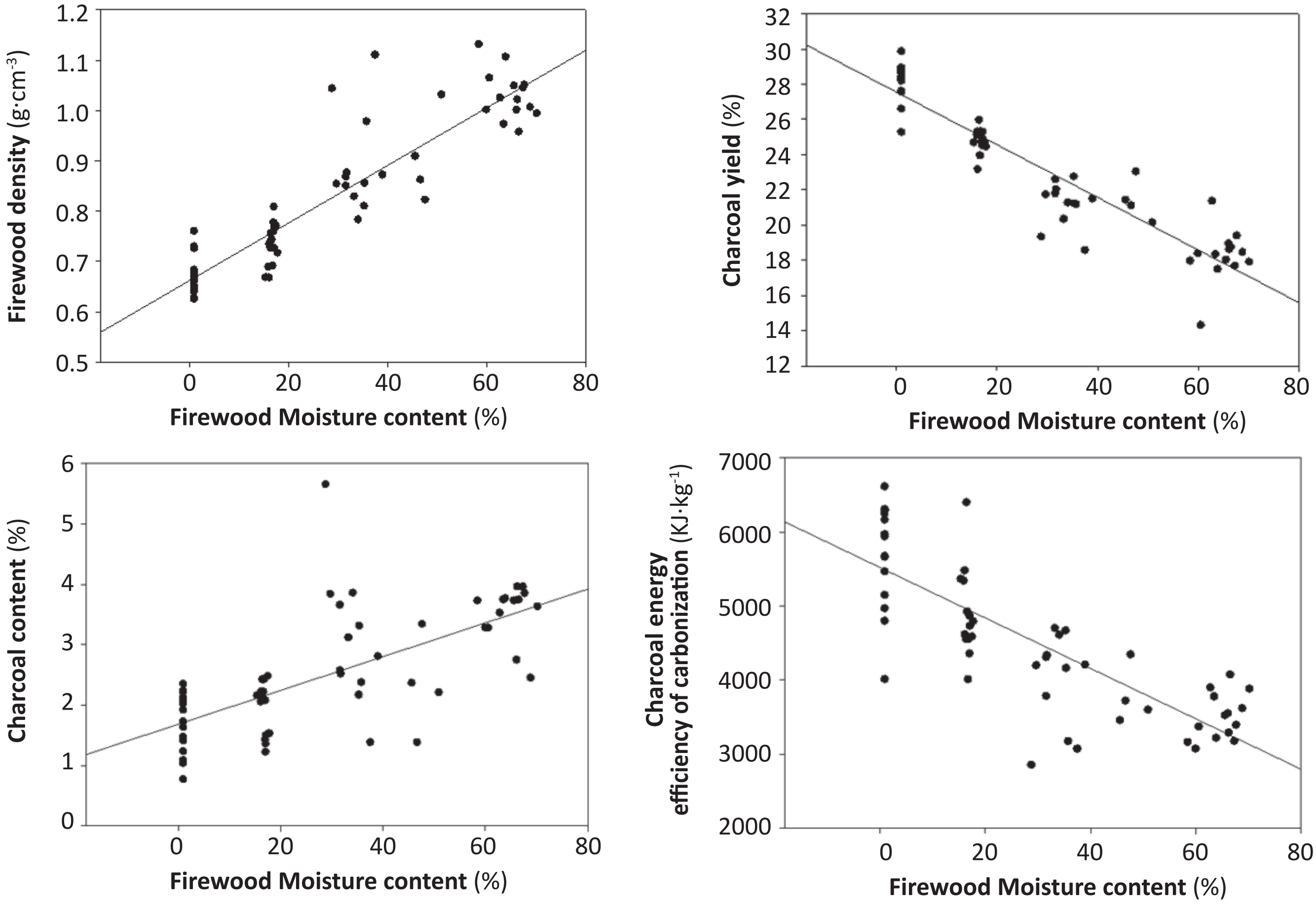

Figure 4. Regressions between moisture content of firewood with respect to: **(a)** firewood density (g·cm^{-3}); **(b)** charcoal yields (%); **(c)** charcoal ash content (%) and **(d)** charcoal energy efficiency of carbonization (KJ·kg^{-1}).

CONCLUSION

The yield, quality, and some other quality parameters of *Prosopis laevigata* charcoal increased when it was produced with firewood at low moisture content. The most important charcoal parameter for the producers is yield, and it was observed that by seasoning the firewood up to 20% and 0% of MC, the yields were higher than 25%.

The strong linear correlations between firewood moisture content and variables such as yield, ash content, and energy efficiency suggest that moisture control is not only a key driver of quality but also a practical, quantifiable lever for optimization. The predictive models generated in this research provide a valuable reference for improving traditional and semi-industrial charcoal practices, especially in rural or resource-limited settings.

Since moisture content is a very easily modifiable characteristic of the firewood used in the traditional charcoal production process, producers in normal environmental conditions should pay attention to reducing the firewood moisture content as low as possible, in order to increase the yield and quality of charcoal.

Author Contributions

Conceptualization: AC-P and JG-Q; Methodology: AC-P; Software: AC-P and JG-Q; Validation: AC-P and JG-Q; Formal analysis: AC-P; Resources: AC-P; Data curation: AC-P and JG-Q; Writing-original draft preparation: AC-P; Writing-review and editing: JG-Q and AC-P; Visualization: AC-P and JG-Q; Supervision: AC-P and JG-Q; Project administration: AC-P; Funding acquisition: AC-P. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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