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Quantification and Determinants of Carbonization Yield in the Rural Zone of Lubumbashi, DR Congo: Implications for Sustainable Charcoal Production

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Abstract: Although charcoal production is a source of income, it is often associated with deforestation due to the felling of trees in rural areas. In this study, we quantified the yield of carbonization in the rural area of Lubumbashi, Democratic Republic of the Congo (DR Congo), and identified its determinants. By analyzing 20 kilns of professional producers in different villages, we found that these charcoal producers build large kilns, which contained an average of 46.9 ± 21.5 m^3 of wood from 19 species of Miombo woodland trees, with a predominance of *Julbernardia paniculata* (Benth.) Troupin, alongside *Brachystegia microphylla* Harms and *B. spiciformis* Benth. The average carbonization yield was 10.2%, varying from village to village due to parameters such as kiln size, quantity of wood used, kiln coverage time, wind exposure, substrate type, and tree species. It was noted that the moisture content and dimensions of the wood did not significantly correlate with the quantity of charcoal harvested per kiln. Yield improvement should, therefore, take these parameters into account to enable charcoal producers to increase their income while adopting sustainable production practices.

Keywords: pyrolysis; deforestation; charcoal; Miombo woodland; environment

1. Introduction

Forests are crucially important to human well-being, as emphasized by Ref. [1]. They offer a multitude of essential products, from food resources to traditional medicine ingredients and building materials, thus making a significant contribution to our daily lives [2]. In monetary terms, forests play a key role in the national economies of developing countries as sources of income through the timber industry and recreational areas [3,4]. Beyond their economic impact, forests maintain the ecological balance by storing large quantities of atmospheric carbon in their vegetation and soils [5]. Their sociocultural role of protecting the flora and fauna makes the value of forests inestimable [6], and so their protection represents a crucial challenge given the benefits they provide [7].

Tropical and subtropical rainforests, in particular, which make up 43% of the world's forest cover, are under considerable pressure. Between 2005 and 2013, nearly 5.5 million hectares of these forests was lost annually to the expansion of cash crops, grazing, and even tree planting [8]. Central Africa is home to the continent's largest forests—notably, the Congo Basin, the world's second largest tropical forest massif after Amazonia, and accounting for nearly 62% of the forest in the DR Congo, with a total surface area estimated at over 166 million hectares [9]. The population density near cities encourages the fragmentation of these forests by human activities, with the DR Congo, in particular, recording a deforestation rate of 0.4% between 2001 and 2019 [10].

The forest that characterizes the rural area of Lubumbashi is the Miombo [11], a woodland in southern Katanga [12]. However, it faces cover losses due to agricultural activities, charcoal production, urban sprawl, and mining activities [13]. Mining and charcoal production are emerging as the main drivers of deforestation in this region, and the increased demand for charcoal has led to an intensive exploitation of forest resources, accentuating the deforestation and contributing to the ecological degradation of the surrounding rural areas [14]. Rapid urbanization has led to an increase in energy consumption, mainly fueled by the widespread use of charcoal for cooking and heating, creating direct pressure on local forests [15]. Charcoal producers in the rural areas adjacent to the city, depending on charcoal sales for their economic needs, are thus trapped in a vicious circle, where urban development intensifies the pressure on forest resources [16].

Although the charcoal industry in Lubumbashi generates an estimated added value of USD 50 million, only 59% of this value is allocated to the charcoal producers [15]. In addition, the traditional kiln method used is rudimentary and results in a low carbonization yield—often less than 10% [17]. In the DR Congo, this yield varies from region to region, estimated at 28.1% in Plateau Batéké and 12.8% in Yangambi [18], with an estimate of around ±10% in Lubumbashi [19]. Control of the carbonization process and other factors, such as wood diameter, moisture content, air supply, and carbonization temperature, are essential for improving this yield [20].

The moisture content of the wood influences the carbonization time, the quality of the charcoal produced, and the energy efficiency of the production process [21]. Controlling the carbonization process is crucial to increasing the charcoal yield and quality [22]. It is also imperative to reduce heterogeneity inside the kiln by controlling the carbonization temperature to increase production [23]. Maintaining a consistent temperature level (above 290 °C) inside the kiln is crucial to achieving satisfactory yields. However, excessive increases in temperature can lead to decreased yields [24]. The chemical composition (cellulose, hemicelluloses, lignin, extracts, and ash content) of the wood used plays a significant role in the energy potential of the charcoal, particularly the influence of the lignin content on its calorific value [25].

Quantifying the carbonization yield involves evaluating the conversion of wood into charcoal, which is expressed as a percentage of the initial weight of the carbonized wood [26,27]. Various methods have been used for this assessment, each providing specific data on the carbonization process. These approaches are closely affected by the moisture content [26] and include directly weighing the wood before and after carbonization, taking measurements of the volume of the charcoal kiln, chemically analyzing the wood samples before and after carbonization to determine the yield by assessing changes in the chemical composition, and measuring the gases produced during carbonization, such as carbon dioxide (CO_2) and carbon monoxide (CO) [28]. In situ monitoring of the kilns is also of crucial importance, enabling the identification of inefficiencies and sources of losses, and facilitating real-time adjustments to improve carbonization yield. This approach contributes to optimizing the process, reducing raw material losses, and enhancing the sustainability of charcoal production [29,30].

The aim of this study was to assess the carbonization activity in the rural area of Lubumbashi, DR Congo. The objectives were to quantify the yield of the charcoal production and identify the determinants influencing this process and their implications for sustainable charcoal production. We postulated that the carbonization yield was influenced by various factors, such as kiln size, wood dimensions, and moisture content, the type of soil on which the kiln was built, the orientation of the kiln in relation to the prevailing wind, and the tree species used [20,31,32].

2. Materials and Methods

2.1. Study Area

This study was carried out in the rural area of Lubumbashi in the south-east of the DR Congo (as illustrated in Figure 1). The region has a CW climate type, based on the Köppen classification [33], characterized by high humidity, with an average annual precipitation of 1230 mm [34,35]. The average temperature is 20 °C, with the cooler months being in June and July and the warmer months in October and November [34,36]. The area is situated on latosols, which can be divided into red earth, red-ochre earth, and yellow earth based on their iron oxide content [12]. The major environmental challenges perceived by the local communities include deforestation and loss of soil fertility [37]. In addition to charcoal production, the Miombo forest is essential to the local population, who depend on its resources for food, subsistence agriculture, fishing, and caterpillar, mushroom, and honey harvesting [35].

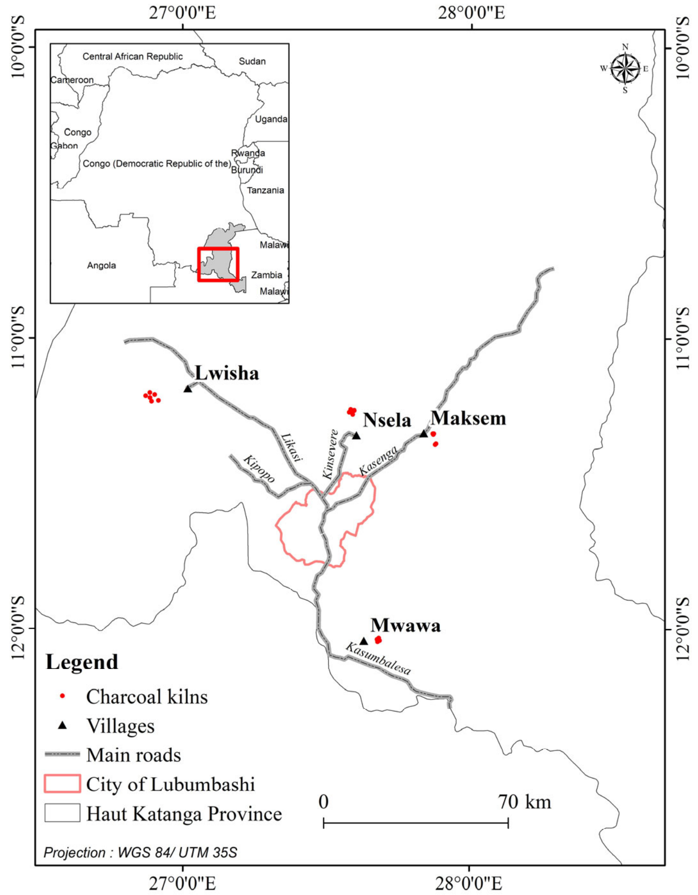

Figure 1. Location of the city of Lubumbashi in the DR Congo and the surrounding area where charcoal is produced (dark triangles—villages; red dots—kilns).

2.2. Methods

2.2.1. Village Selection and Sampling

The four villages selected for this study—Luisha, Maksem, Sela, and Mwawa—are located within a radius of 80 km around the city of Lubumbashi. Among the 15 villages studied during the exploratory surveys conducted from 7 July to 7 August 2020, these four villages were selected due to their significant charcoal production, evidenced by the abundant presence of bags of charcoal and the frequent activity of transporters and vendors. Their respective geographical positions to the north-east, north-west, and south of Lubumbashi also motivated this selection, ensuring a comprehensive representation of the area.

In this study, we monitored 20 kilns used by professional charcoal producers, resulting from the 258 households in the four villages. Therefore, these professional charcoal producers were distinguished by their substantial production of bags of charcoal per kiln, with a minimum of 40 bags, compared with reports from previous studies [16,38]. The charcoal producers were continually active, being engaged in charcoal production throughout the entire year. The size of our sample was determined using the Bernoulli formula [39,40], as described in Equation (1).

$$n = \frac{1.64^2 \times N}{1.64^2 + I^2 \times N - 1} \quad (1)$$

where n = total number of households to be surveyed; N = total number of households in the selected villages; 1.64 = critical coefficient at a 90% confidence level; and I = acceptable margin of error set at 10%.

2.2.2. Data Collection

The data collection took place from 4 January to 28 September 2022, with a carbonization monitoring sheet used to track the 20 kilns built by the participants, which were distributed as follows: six in Luisha, five in Maksem, four in Mwawa, and five in Sela.

In the chosen villages, the wood used was mainly *Brachystegia microphylla*, *B. spiciformis*, and *Julbernardia paniculata*, which mostly belong to the Fabaceae family [19,41]. The wood carbonization process began with preparation of the wood, which involved cutting it into appropriately sized pieces. Then, the prepared wood was loaded into the kiln or carbonization chamber, and the kiln was covered with soil and grass packed tightly enough to ensure controlled conditions. The wood was gradually heated using fire to high temperatures, ranging up to more than 450 °C. Finally, the kiln was opened to allow for the collection of the produced charcoal (Figure 2).

Figure 2. Illustration showing the major stages of carbonization and data collection during monitoring of the kilns in the rural area of Lubumbashi, DR Congo. (**A**) Arranging the wood after tree felling. (**B**) Covering the pile with soil. (**C**) Harvesting the charcoal after carbonization. (**D**) Conditioning the harvested charcoal.

Information on the carbonization practices was collected at each stage, from the moment of tree felling to the harvesting of the charcoal. Appointments with the charcoal producers were scheduled based on different stages in the process, taking into account the variability of the village locations relative to the city of Lubumbashi.

Each kiln was described in detail. The wood moisture content was measured using a moisture meter (Yioyag model, China), the wood diameter was recorded with a tape measure (made in China), and the dimensions of the kilns (length, width, and height) were taken to enable the estimation of the volume of the wood in cubic meters. The categorization of the wood into small, medium, and large diameters was carried out through observation.

For each tree species used, the vernacular name was gathered from the charcoal producers, and the scientific name was identified later using the reports by Refs. [35,42,43]. The number of days required for the charcoal producer to cover their kiln, the quality of the insulation (i.e., the layer of earth covering the stacked wood), the orientation of the kiln in relation to the prevailing wind, and the substrate on which the kiln was constructed were also recorded to allow us to assess the variables influencing the carbonization yield efficiency. These were critical elements in the carbonization process because an appropriate covering time affects the efficiency of the carbonization and the quality of the charcoal. The orientation of the charcoal kiln influences air circulation, while the nature of the substrate can affect stability and interaction with the environment, also playing a crucial role in the carbonization yield.

2.2.3. Data Analysis

The yields from the kilns were calculated in order to assess the level of efficiency of the carbonization practices among the charcoal producers using the formula proposed by Ref. [26], which involved calculating the ratio between the mass of the charcoal produced and the mass of the wood used to produce the charcoal, expressed as a percentage in Equation (2).

$$MY_a = \frac{M_{ca}}{M_{aw}}100 \tag{2}$$

where MY_a = mass yield of carbonization of anhydrous wood (%); M_{ca} = mass of anhydrous charcoal (kg); and M_{aw} = mass of anhydrous wood (kg).

Starting with Equation (2), and recognizing that it is challenging to find wood with anhydrous mass in the field, we rewrote the equation as follows, taking into account the moisture content of the wood used.

$$C_y = \frac{M_c}{M_w}100 \tag{3}$$

C_y = carbonization yield (%); M_c = mass of charcoal; and M_w = mass of wood used with its moisture content (kg).

In addition to the yield calculation, a characterization of the yields was carried out by studying the properties of the kilns, following the approach outlined in Ref. [44]. Descriptive statistics were employed to comprehensively produce both qualitative and quantitative data. The four villages, sharing the common characteristic of being high-intensity charcoal producers, were subjected to comparisons and were considered repetitions in order to generalize the results for the study area. To determine whether the species composition of the trees in the kilns significantly varied among the villages, a chi-squared test was applied. An analysis of variance was used to assess differences in the amount of wood used per kiln among the villages, providing insights into potential variations in wood utilization and the quantity of harvested charcoal [45,46]. To identify the factors influencing the carbonization yield, a first step involved the use of a correlation matrix, focusing on quantitative variables, such as kiln size, wood diameter, wood moisture content, as well as the time taken for carbonization to occur and the amount of time the kiln was covered for [47–49]. Next, for the qualitative variables influencing carbonization yield, a multiple correspondence analysis (MCA) was performed, considering the tree species used, the carbonization season, the substrate on which the kiln was built (soil with or without concretions), and the orientation relative to the wind [50]. The statistical analyses were conducted using SPSS version 21 software, with the significance threshold set at $p < 0.05$.

3. Results

3.1. Characteristics of Kilns Built by Charcoal Producers in the Rural Area of Lubumbashi

3.1.1. Kilns Dimensions, Diameter, and Wood Moisture Content

The kilns had an average length of 7.2 ± 2.5 m, width of 3.6 ± 0.7 m, and height of 1.8 ± 0.2 m. Regarding the wood in the kilns, the overall means for all studied types indicated a diameter of 72.2 ± 7.0 cm and a moisture content of 26.3% ± 12.6% (Table 1).

Table 1. Kiln dimensions, wood diameter, and moisture content in the kilns.

Village	Length (m)	Width (m)	Height (m)	Diameter (cm)	Moisture Content (%)
	Mean ± St. Dev.	**Mean ± St. Dev.**	**Mean ± St. Dev.**	**Mean ± St. Dev.**	**Mean ± St. Dev.**
Luisha (n = 6)	7.8 ± 1.9	3.8 ± 0.7	1.7 ± 0.1	74.9 ± 5.5	26.2 ± 10.8
Maksem (n = 5)	4.9 ± 1.3	3.0 ± 0.6	1.8 ± 0.3	74.2 ± 6.8	18.5± 9.2
Mwawa (n = 4)	8.8 ± 4.1	3.8 ± 0.5	1.9 ± 0.1	68.4 ± 7.6	40.1 ± 11.2
Sela (n = 5)	7.4 ± 1.2	3.9 ± 0.6	1.7 ± 0.3	69.8 ± 8.4	23.2 ± 12.4
Mean ± St. Dev.	7.2 ± 2.5	3.6 ± 0.7	1.8 ± 0.2	72.2 ± 7.0	26.3 ± 12.6

n—sample size; St. Dev.—standard deviation.

3.1.2. Wood Species Used in Charcoal Production

A total of 19 charcoal-producing tree species were recorded. The chi-squared test did not reveal any significant differences among the species used ($p > 0.05$), although three species were notable. These were *Julbernardia paniculata*, which was found in 15 of the 20 kilns examined, and *Brachystegia microphylla* and *B. spiciformis*, identified in nine of the kilns. Furthermore, fruit trees from the Miombo woodland, such as *Uapaca nitida* (observed in three kilns), *Anisophyllea boehmii* (present in one kiln), and *Parinari curatellifolia* (identified in five kilns), were also used in charcoal production (Table 2).

Table 2. Tree species used by the professional charcoal producers in the rural area of Lubumbashi.

N°	Vernacular Name	Scientific Name (Family)	Villages: Luisha	Maksem	Mwawa	Sela	Total
			***n* (%)**	***n* (%)**	***n* (%)**	***n* (%)**	***n***
1	Mutondo	*Julbernardia paniculata* (Benth.) Troupin (Fabaceae)	6 (25.8)	3 (14)	4 (57.5)	2 (10.8)	15
2	Kaputu	*Brachystegia spiciformis* Benth (Fabaceae)	3 (29.2)	2 (10)	-	4 (25)	9
3	Musamba	*Brachystegia microphylla* Harms (Fabaceae)	-	1(10)	4 (30)	4 (19)	9
4	Kakula	*Pterocarpus tinctorius* Welw (Fabaceae)	4 (1.3)	2 (5)	-	2 (3.6)	8
5	Mutobo	*Isoberlinia angolensis* (Welw. ex Benth.) (Caesalpiniaceae)	4 (5.4)	2 (7)	-	-	6
6	Museshi	*Marquesia macroura* Gilg (Dipterocapaceae)	4 (17.1)	1 (8)	-	1 (11)	6
7	Mubanga	*Pterocarpus angolensis* DC (Fabaceae)	2 (5.8)	3 (5.8)	-	3 (16)	8
8	Mupundu *	*Parinari curatellifolia* Planch. ex Benth. (Chrysobalanaceae)	-	2 (12)	2 (6.3)	1 (1)	5
9	Masuku *	*Uapaca nitida* f. sokolobe P.A. Duvign. (Euphorbiaceae)	-	1 (2)	-	2 (10)	3
10	Ndale	*Bobgunnia madagascariensis* (Desv.) (Fabaceae)	1 (1.3)	1 (2)	-	-	2
11	Kayimbi	*Erythrophleum africanum* Benth. (Fabaceae)	-	-	1 (3.7)	1 (2)	2
12	Fungo *	*Anisophyllea boehmii* Engl. (Fabaceae)	1 (1.3)	-	-	-	1
13	Kasabwe	*Milletia biquaertii* Wight & Arn. (Fabaceae)	1 (0.8)	-	-	-	1

Table 2. *Cont.*

N°	Vernacular Name	Scientific Name (Family)	Villages				Total
			Luisha	Maksem	Mwawa	Sela	
			n (%)	*n* (%)	*n* (%)	*n* (%)	*n*
14	Sandwé	*Jullbernardia globiflora* (Benth.) Troupin. (Fabaceae)	-	2 (14)	-	-	2
15	Mulama	*Combretum zeyheri* (Combretaceae)	-	1 (2)	-	-	1
16	Kipunga Ngombé	*Acacia amythethophylla* (Fabaceae)	-	1 (8)	-	-	1
17	Munyangwé	*Ochna schweinfurthiana* F.Hoffm (Ochnaceae)	-	-	1 (2.5)	-	1
18	Kimpampa	*Monotes katangensiss* De Wild. (Dipterocarpaceae)	-	-	-	1 (0.6)	1
19	Mwenge	*Diplorhynchus condylocarpon* rg.) Pichon. (Apocynaceae)	-	-	-	1 (1)	1
	p = 0.066						

n—number of kilns; %—proportion in the kiln; and *—fruit tree.

3.2. Carbonization Yield

We found that the kilns contained an average of 46.9 ± 21.5 m^3 of wood, equivalent to 33,808.5 ± 15,518.8 kg. After the carbonization process, the average quantity of charcoal harvested per kiln was 3464.6 ± 1775.1 kg, giving a carbonization yield of 10.2%. Results of a comparative analysis of the quantities of charcoal harvested per kiln, differentiated by village, revealed significant disparities ($p < 0.05$). Specifically, the yields were 13.2% in Sela, 11.3% in Luisha, 8.6% in Mwawa, and 6.2% in Maksem (Table 3).

Table 3. Quantity of wood composing the kilns and carbonization yields.

Village	Wood Qty (kg)	Kiln Volume (m^3)	Charcoal Qty (kg)	Yield (%)
	Mean ± St. Dev.	Mean ± St. Dev.	Mean ± St. Dev.	
Luisha (*n* = 6)	36,250.8 ± 12,705.2	50.3 ± 17.6	4090.7 ± 1117.7	11.3
Maksem (*n* = 5)	20,616.4 ± 10,694	28.6 ± 14.8	1276.4 ± 997.8	6.2
Mwawa (*n* = 4)	46,514.3 ± 23,532.3	64.6 ± 3.7	4010.0 ± 1641.8	8.6
Sela (*n* = 5)	33,905.4 ± 4955.8	47.1 ± 6.9	4465.0 ± 1505.6	13.2
Total (*n* = 20)	33,808.5 ± 15,518.8	46.9 ± 21.5	3464.6 ± 1775.1	10.2
***p*-Value**	0.078	0.078	0.005 *	

* *n*—sample size; Qty—quantity; and St. Dev.—standard deviation.

3.3. Factors Influencing Kiln Yields

3.3.1. Quantitative Variables

An examination of the correlations (Table 4) highlighted that larger kilns generally produced higher yields compared with smaller ones (R^2 = 0.652). Consequently, the length (R^2 = 0.671) and width (R^2 = 0.670) of these kilns exhibited a positive correlation with the quantity of harvested charcoal. A significant relationship was also observed between the quantity of charcoal harvested per kiln and the time taken by the charcoal producer to cover the wood with earth during the construction of the kiln (R^2 = 0.604). However, the diameter and moisture content of the wood showed no correlation with the quantity of harvested charcoal (Table 4).

Table 4. Correlation matrix of quantitative variables and the quantity of charcoal produced.

	Kl	Kw	Kh	Kv	Wmc	Wd	Ndw	Ndf	Ndh	Qty of Wood kg	Qty of Charcoal Harvested
Kl	1	0.368	0.109	0.913 **	0.267	0.010	0.561 *	0.348	0.428	0.913 **	0.671 **
Kw	0.368	1	0.050	0.597 **	0.511 *	−0.087	0.220	0.263	0.335	0.597 **	0.670 **
Kh	0.109	0.050	1	0.334	0.049	−0.114	−0.135	−0.261	−0.135	0.334	−0.152
Kv	0.913 **	0.597 **	0.334	1	0.441	−0.060	0.493 *	0.300	0.366	1.000 **	0.652 **
Wmc	0.267	0.511 *	0.049	0.441	1	−0.364	0.196	0.059	0.161	0.441	0.226
Wd	0.010	−0.087	−0.114	−0.060	−0.364	1	0.215	0.209	−0.091	−0.060	0.231

Table 4. *Cont.*

	Kl	Kw	Kh	Kv	Wmc	Wd	Ndw	Ndf	Ndh	Qty of Wood kg	Qty of Charcoal Harvested
Ndw	0.561 *	0.220	−0.135	0.493 *	0.196	0.215	1	0.136	0.022	0.493 *	0.604 **
Ndf	0.348	0.263	−0.261	0.300	0.059	0.209	0.136	1	0.289	0.300	0.303
Ndh	0.428	0.335	−0.135	0.366	0.161	−0.091	0.022	0.289	1	0.366	0.461 *
Qty of wood kg	0.913 **	0.597 **	0.334	1.000 **	0.441	−0.060	0.493 *	0.300	0.366	1	0.652 **
Qty of charcoal harvested	0.671 **	0.670 **	−0.152	0.652 **	0.226	0.231	0.604 **	0.303	0.461 *	0.652 **	1

(Kl—kiln length; Kw—kiln width; Kh—kiln height; Kv—kiln volume; Wmc—wood moisture content; Wd—wood diameter; Ndw—number of days the wood was covered with earth; Ndf—number of days between fire setting and the beginning of the charcoal harvest; Ndh—number of days of harvesting; Qty—quantity). ** Correlation significant at the 0.01 level (two-tailed); * Correlation significant at the 0.05 level (two-tailed).

3.3.2. Qualitative Variables

The MCA revealed the relationships between the quantity of charcoal produced per kiln and the qualitative variables that may have influenced the yield. There was a strong correlation between the quantity of charcoal harvested per kiln and the tree species used (93.9%). There was also a significant dependence on the type of substrate on which the kiln was built (80.3%). The quantities of charcoal harvested from the kilns constructed on soils with concretions were lower than from kilns built on soils without concretions. Finally, the quantity of charcoal from a kiln was also influenced by the orientation of the kiln in relation to the prevailing wind, with a correlation of 67.8%. The quantity of charcoal harvested from those kilns oriented in the direction of the wind was higher than from kilns oriented against the wind (Figure 3).

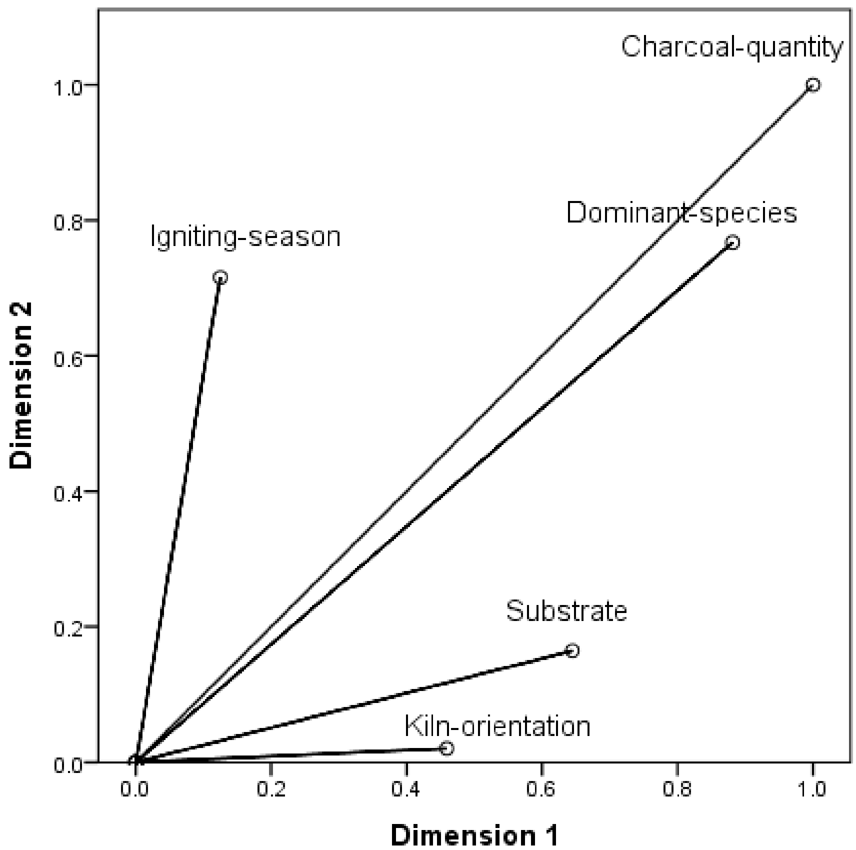

Figure 3. Correlations between the quantities of charcoal produced and the carbonization season, kiln orientation, substrate, and tree species used.

4. Discussion

4.1. Method Used

The results of the present study emerged from a combined approach using multiple methods. The choice of kiln monitoring over directly surveying charcoal producers was motivated by the fact that our observations allowed for direct and meticulous data collection at the kiln level, providing a more objective and reliable understanding of the carbonization process. The number of kilns monitored allowed for generalization of the results to the entire study area, this approach being widely employed in research on the characterization of carbonization yields [18,29,32].

Additionally, in order to select the kilns to be included in this study, a preliminary sampling of the number of households to be surveyed in the area was conducted using the Bernoulli formula. This approach is commonly employed to determine the sample size from a previously known population [39,40].

The number of kilns monitored in this study was equivalent to that used by Ref. [18] in a comparison between two different regions of the DR Congo. This was deemed applicable for the same area, albeit the villages differed. However, it is important to note that this method had some limitations related to the challenging conditions of regular accessibility to the collection sites, in addition to relying on the availability of the kiln owners for data collection.

Regarding the methodological limitations, the high variability trends, with a standard deviation exceeding ±50%, were justifiable by several factors. Firstly, charcoal production is an activity that is subject to numerous variables, including the quality of the wood used, the environmental conditions during carbonization, the size and design of the carbonization kilns, as well as the skills and practices of the producers [51]. These factors can lead to significant differences in charcoal yield among the different production units. Moreover, the diversity of the tree species used for carbonization can also contribute to variability in the results. Each wood species has unique characteristics in terms of density, moisture content, chemical composition, and carbonization potential, which can significantly influence charcoal yield. Additionally, local environmental conditions, such as air humidity, temperature, and wind direction, can also impact the carbonization process and thus the yields obtained [20]. Finally, the skills and individual practices of the charcoal producers can considerably vary from one unit to another, and this can also contribute to variability in the results [52].

4.2. Characteristics of Kilns Built in the Rural Area of Lubumbashi

4.2.1. Diameter, Wood Moisture Content, and Kiln Dimensions

We found that the kilns contained approximately 46.9 m^3 of wood, equivalent to 33,808.5 kg. This substantial dimension distinguishes them from those constructed in other regions, including the DR Congo, such as the Batéké Plateau (15,837 kg) and Yangambi (8444 kg) [18], and in Mampu (~24,000 kg) [53]. This disparity can be attributed, first, to the richness in tree species of the accessible miombo forest and, second, to an inefficient carbonization technique requiring an increased amount of wood for substantial charcoal production. It is noteworthy that controlling carbonization becomes increasingly challenging as its scale increases [54]. This observation aligns with the conclusions of Ref. [55], in their comparative study on carbonization in Mozambique, Malawi, Tanzania, and Zambia, in which they emphasize that the design of traditional kilns was similar, but their size varied.

Our results highlight the diversity of the studied kiln diameters, with an average of 72.2 cm. This variability is explained by the use of trunks and branches of different sizes, in accordance with the common practices of the charcoal producers. Additionally, according to Ref. [56], the dimensions of the wood used for carbonization can vary depending on the vegetation available in the charcoal-producing area, this generally being larger in forests than in savannas. Our findings align with the proposal of Ref. [30], who were in favor of using wood of various diameters during improved carbonization, with the aim of achieving optimal combustion and thus improved yields.

The moisture content of the wood used was 26.3%. This is explained by the common practice of not drying the wood after harvesting it. According to Ref. [57], the use of wood with a high moisture content has negative implications for pyrolysis and increases greenhouse gas emissions. This aligns with the findings of Ref. [58] from Madagascar, where the use of non-dried wood for carbonization led to a moisture content of 34%. The wood moisture content influences the time taken for the carbonization to occur [59,60], as demonstrated by the results of Ref. [49], who showed that wood moisture content below 30% can decrease the carbonization time in a kiln.

4.2.2. Tree Species Used for Charcoal Production

There was a notable diversity of tree species used, with a particularly high frequency of *Julbernardia paniculata*, *Brachystegia microphylla*, and *B. spiciformis*. This is because these three species are among the most predominant genera in the Miombo ecosystem [61]. Being members of the Fabaceae family, these species support the findings of Ref. [19], who noted that they were among the most preferred by charcoal producers in the Lubumbashi region. This is consistent with the Miombo in Angola, where most species used in carbonization belong to the Fabaceae [60]. The fruit tree species used in the rural area of Lubumbashi have been identified as being representative of the Miombo [61].

4.2.3. Kiln Yield

The carbonization yield in the rural area of Lubumbashi is assessed as being 10.2%, demonstrating a relatively low efficiency. This performance aligns with the typical yields of traditional kilns, as indicated by Ref. [62], who reported that yields from tropical wood kilns rarely exceed 15%–20%. Similar findings have been observed in the villages around Lubumbashi, with a yield of 10%, according to the study by Ref. [19]. By contrast, charcoal producers in the Plateau Batéké in the DR Congo, utilizing improved carbonization techniques, achieved yields around 28.1% [18].

The disparity in yields among the villages highlights the complexity of the factors influencing carbonization, as found in previous studies [30,58,63]. Research conducted on the outskirts of Boma in the DR Congo also identified significant variability in the number of bags of charcoal harvested, with substantial differences in kiln yields, even within the same environment [29].

The kiln dimensions, the quantity of wood used, the duration of earth coverage, the tree species, the kiln orientation with respect to the wind, and the substrate significantly influenced the quantity of charcoal harvested. The size of the kiln, especially its length and width, played a crucial role in the carbonization yield, confirming the results of Ref. [64] and even those of Ref. [65]. The wood density used impacted not only the quantity but also the quality of the charcoal, as illustrated by the different densities of *Acacia auriculiformis* and *A. mangium* in the DR Congo [66] and *A. tortilis* and *A. mellifera* in Kenya [67].

Extended covering duration of the kiln led to an increased charcoal harvest, emphasizing the importance of careful insulation, which must ensure proper sealing of the kiln to prevent heat loss [68]. The tree species used, the orientation of the kiln with respect to the prevailing wind, and the type of substrate also influence kiln yields. Different tree species produce charcoals with distinct physicochemical compositions, and aligning the kiln with the wind promotes combustion. Substrates with concretions can generate high temperatures, although with temperatures above 400 °C, the yield decreases, prompting the producers to avoid rocky areas [63,69].

4.3. Implications for Carbonization and Conservation of Forest Resources

The socioecological implications of these findings are manifold. Firstly, the construction of large kilns, requiring substantial amounts of wood from various Miombo tree species, raises concerns regarding environmental sustainability [14,69,70]. There has been notable pressure on local forest resources, as the carbonization process demands a significant quantity of wood [16]. The low average carbonization yield of 10.2% indicates a relatively low efficiency of the process, meaning that only a fraction of the wood used is converted into charcoal [26,28]. This may have economic implications for charcoal producers, as a substantial amount of raw material is needed to achieve significant yields [16,29]. In addition, the variability in yield among villages highlights the influence of local practices and environmental conditions on the carbonization process [20].

Parameters such as kiln size, quantity of wood used, covered time, orientation to the wind, substrate type, and tree species play a crucial role in carbonization yield [17,27,28]. This underscores the need to adopt more sustainable and efficient practices, taking into account these factors to enhance both process efficiency and forest resource conservation [71]. Noting the absence of a significant correlation between moisture content and wood dimensions with the quantity of harvested charcoal, it is important to explore other variables in order to optimize carbonization practices to minimize losses and maximize yields, while promoting the conservation of local forest ecosystems.

Thus, to enhance the efficiency of carbonization, it is essential to implement targeted strategies that address key factors influencing the wood-to-charcoal conversion process [72], including tailoring the carbonization parameters by tree species, which promotes a more efficient use of wood resources by aligning the species characteristics with market demands and optimizing the charcoal yield and quality; improving the charcoal quality by prioritizing large wood pieces based on diameter; selecting kilns that promote uniform heating and efficient air circulation, which is essential for consistent carbonization results; regularly maintaining and monitoring kiln performance, allowing the prompt identification and resolution of operational issues; and providing training, supported by collaboration with local extension services and research institutions, which would facilitate knowledge transfer and the effective implementation of recommended strategies [27,73].

Our study provides a comprehensive assessment of current carbonization activities, including quantification of charcoal production volumes and rates. By accurately measuring these parameters, we have provided a foundational understanding of the extent of charcoal production in the rural area of Lubumbashi. This quantification serves as a crucial reference point for assessing the economic, social, and environmental implications of charcoal production in the region [74]. Additionally, we identified and analyzed the determinants of charcoal yield, shedding light on the factors influencing the efficiency of the wood-to-charcoal conversion process. Through empirical investigation and statistical analyses, variables, such as wood species, moisture content, type of kiln, and operational practices, were examined [22,23]. By elucidating the relationships between these factors and charcoal yield, we offer tangible insights into enhancing the efficiency and sustainability of charcoal production methods in the rural area of Lubumbashi. Ultimately, the findings of this study contribute to the broader discourse on renewable energy and natural resource management [75,76]. Charcoal plays a significant role as a renewable energy source in many developing countries, including the DR Congo. Therefore, understanding the determinants of charcoal production efficiency is essential for promoting sustainable energy practices and mitigating the environmental impact of deforestation and forest degradation associated with charcoal production [71,77].

5. Conclusions

In this study, we aimed to quantify the carbonization yield in the rural area of Lubumbashi. Monitoring 20 kilns owned by professional charcoal producers confirmed our hypothesis. The kilns contained an average of 46.9 m^3 of wood, and the main species of charcoal were *Julbernardia paniculata*, *Brachystegia microphylla*, and *B. spiciformis*. The average carbonization yield was 10.2%, indicating inefficiency in current practices. Variations in yield among the villages (Luisha 11.3%, Maksem 6.2%, Mwawa 8.6%, and Sela 13.2%) attested to the influence of various parameters and the individual expertise of the charcoal producers, regardless of the similarity of the techniques employed. The factors identified as influencing yield included kiln size, amount of wood used, covered time, tree species, kiln orientation to the prevailing wind, and construction substrate. Conversely, wood dimensions and moisture content demonstrated no significant correlation with the quantity of charcoal harvested per kiln. To address this situation, it is recommended that the skills of the charcoal producers be enhanced by adopting improved carbonization techniques aimed at increasing their yields and income. Further in-depth research is needed on the factors we identified so that our understanding of carbonization in this specific region can be enhanced.

Finally, as the results are closely linked to the unique geographical situation and prevailing carbonization practices in the rural area of Lubumbashi in the DR Congo, caution should be exercised when attempting to extrapolate these conclusions to diverse geographical contexts or other carbonization configurations. It is imperative to consider distinct local factors that shape carbonization activities before applying this knowledge elsewhere with the aim of improving carbonization yield.

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