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Carbonization Activity in the Rural Area of Lubumbashi (DR Congo): Quantification and Yield Determinants

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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. The study quantifies the yield of carbonization in the rural area of Lubumbashi, DRC, and identifies its determinants. By analyzing 20 kilns from professional producers in different villages, the study reveals that these charcoal producers build large kilns, containing an average of 46.9±21.5 m3 of wood from 19 species of miombo trees. The average carbonization yield is 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 size of the wood did not correlate significantly 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

The forest takes on a crucial importance for human well-being, as emphasized by Ref. [1]. It offers a multitude of essential products, from food resources to traditional medicine ingredients and building materials, making a significant contribution to our daily lives [2]. In economic 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 socio-cultural role, by protecting the flora and fauna, gives the forest an inestimable value [6], although its protection represents a crucial challenge given the benefits it provides [7].

In fact, tropical and subtropical rainforests, 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 were 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, covering nearly 62% of the forest in the Democratic Republic of Congo (DRC), 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 DRC in particular recording a deforestation rate of 0.4% between 2001 and 2019 [10].

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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 [13–16]. Mining and charcoal production are emerging as the main drivers of deforestation in this region, and the increased demand for charcoal has led to intensive exploitation of forest resources, accentuating deforestation and contributing to the ecological degradation of surrounding rural areas [17]. 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 [18]. 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 [19].

Although the charcoal industry in Lubumbashi generates an estimated added value of 50 million US dollars, 59% of this value is allocated to charcoal producers [18], the traditional kiln method used is rudimentary and results in a low carbonization yield, often less than 10% [20]. In DR Congo, this yield varies from region to region, estimated at 28.1% in Plateau Batéké and 12.8% in Yangambi [21], with an estimate of around ± 10% in Lubumbashi [22]. Control of the carbonization process and other factors, such as wood diameter, moisture content, carbonization temperature and air supply, are essential to improve this yield [23].

The moisture content of the wood influences the carbonization time, the quality of the charcoal produced and the energy efficiency of the production process [24]. Controlling the carbonization process is crucial to increasing charcoal yield and quality [25]. It is also imperative to reduce heterogeneity inside the kiln by controlling the carbonization temperature to increase production [26]. Quantifying carbonization yield involves evaluating the conversion of wood into charcoal, expressed as a percentage of the initial weight of carbonized wood [27,28]. Various methods are used for this assessment, each providing specific data on the carbonization process. These approaches include direct weighing of wood before and after carbonization, measurement of the volume of the charcoal kiln produced, chemical analysis of wood samples before and after carbonization to determine yield by assessing changes in chemical composition, and measurement of gases produced during carbonization, such as carbon dioxide (CO2) and carbon monoxide (CO) [29]. Nevertheless, in situ monitoring of the kilns is 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 [21,30].

Thus, the present study quantifies the carbonization yield in the rural area of Lubumbashi and identifies its determinants. We postulate that carbonization yield is influenced by various factors, such as kiln size, wood dimension and moisture content, the type of soil on which the kiln is built, the orientation of the kiln in relation to the wind, and the tree species used [11,31,32]. We also suppose that traditional practices, characterized by the use of simple materials such as straw, branches and earth to cover the wood, contribute to a lower carbonization yield [21,22,29,33].

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 Democratic Republic of Congo (as illustrate in Figure 1). The region has a CW climate type according to the Köppen classification [34], characterized by its humidity, with average annual precipitation of 1230 mm [35,36]. The average temperature is 20°C, with cooler months in June and July and warmer months in October and November [35,37]. The area is situated on latosols, classified into red earth, red-ochre earth, and yellow earth based on their iron oxide content [12]. The dominant vegetation is the miombo woodland [11], subjected to increasing anthropogenic pressure and a decrease in its surface area [38,39]. The major environmental challenges perceived by local communities include deforestation and loss of soil fertility [40]. In addition to charcoal production, the miombo forest is

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essential to the local population, who depend on its resources for food, subsistence agriculture, fishing, caterpillar, mushroom and honey harvesting [36].

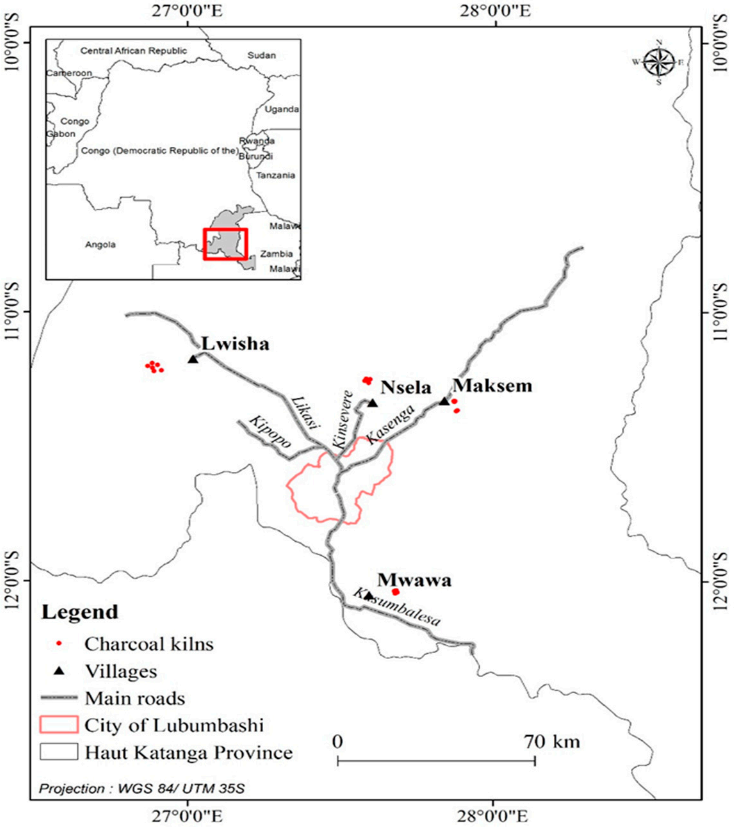

Figure 1. Location of the city of Lubumbashi in the DRC and the surrounding area where charcoal is produced. (The dark triangles represent the villages and the red dots represent the kilns).

2.2. Methods

2.2.1. Village selection and sampling

The four villages selected for this study, namely 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 July 7th to August 7th, 2020, these four villages were selected due to their significant charcoal production, evidenced by the abundant presence of charcoal bags and the frequent activity of transporters and vendors. Their respective geographical positions to the Northeast, Northwest, and South relative to Lubumbashi also motivated this selection to ensure a comprehensive representation of the area.

The study followed 20 kilns used by professional charcoal producers in the rural area of Lubumbashi, resulting from the 258 households in the four villages. Therefore, these professional charcoal producers were distinguished by the substantial production of charcoal sacks per kiln, with a minimum of 40 bags, in accordance with previous studies [19,41]. Their activity is permanent, as they are engaged in charcoal production throughout the entire year. The size of this sample was determined using the Bernoulli formula [42,43], as described in equation 1 below.

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

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

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2.2.2. Data collection

The data collection took place from January 4th to September 28th, 2022, with a carbonization monitoring sheet used to track the 20 kilns built by the participants, distributed as follows: 6 in Luisha, 5 in Maksem, 4 in Mwawa, and 5 in Sela. Information on carbonization practices was collected at each stage, from the moment of tree felling to the harvesting of charcoal. Appointments with the charcoal producers were scheduled based on different stages of the process, taking into account the variability of village locations relative to the city of Lubumbashi.

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

For each tree species composing the kilns, the vernacular name was gathered in collaboration with the charcoal producers, and the scientific name was identified using the corresponding report of Ref. [44], the studies conducted by Ref. [45] as well as Ref. [36]. The number of days required for the charcoal producer to cover his kiln, the quality of insulation (layer of earth covering the stacked wood), the orientation of the kiln in relation to the wind, and the substrate on which the kiln was constructed were also recorded to assess the variables influencing the efficiency yield carbonization. These are critical elements in the carbonization process since an appropriate covering time affects the efficiency of 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, playing a crucial role in the carbonization yield.

2.2.3. Data analysis

The yield of the kilns was calculated to assess the level of carbonization practices efficiency among charcoal producers in the rural area of Lubumbashi, using the formula proposed by Ref. [27], which involves calculating the ratio between the mass of charcoal produced and the mass of wood used to produce charcoal, expressed as a percentage (Equation 2):

$$MY_a = \frac{M_{ca}}{M_{aw}} 100 \quad (2)$$

$\boldsymbol{MY_a}$: Mass yield of carbonization on anhydrous wood in % ; $\boldsymbol{M_{ch}}$: Mass of anhydrous charcoal in kilograms ; $\boldsymbol{M_{aw}}$: Mass of anhydrous wood in kilograms

Starting from the above formula and recognizing that it is challenging to find wood with an anhydrous mass in the field, we have written the equation as follows, taking into account the moisture content of the wood used:

$$C_y = \frac{M_c}{M_w} 100 \quad (3)$$

$\boldsymbol{C_y}$: Carbonization yield in % ; $\boldsymbol{M_c}$: Masse of charcoal ; $\boldsymbol{M_w}$: Mass of wood used with its moisture content in kilograms.

In addition to yield calculation, the characterization of yields was carried out by studying the characteristics of the monitored kilns, following the approach outlined in Ref. [46]. Descriptive statistics were employed to comprehensively present both qualitative and quantitative data. The four villages under study, sharing common characteristics as high-intensity charcoal-producing villages, were subjected to comparisons and are considered repetitions in order to generalize the results within the study area . To determine whether the species composition of trees in the kilns varied significantly among the villages, the chi-square test was applied. Furthermore, analysis of variance (ANOVA) 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 [47,48]. To identify the factors influencing 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 carbonization duration and the covering period of the kiln [49–51]. Next, for 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 [52]. The statistical analyses were conducted using SPSS version 21, with a 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 results reveal that the kilns built by professional charcoal producers in the rural area of Lubumbashi displayed an average length of 7.2±2.5 m, a width of 3.6±0.7 m, and a height of 1.8±0.2 m. Regarding the wood stored in these kilns, the overall mean for all studied categories indicated a diameter of 72.2±7.0 cm and a moisture content of 26.3±12.6% (Table 1).

Table 1. Kiln Dimensions, Diameter, and Moisture Content of Wood within 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

* with n = sample size ; St. Dev. : Standard Deviation.

3.1.2. Wood species used in charcoal production

A total of 19 tree species were recorded in the four charcoal-producers villages in rural area of Lubumbashi. Despite the Chi-square test did not reveal any significant differences in species use among these villages ($P > 0.05$), three species were notable in the kilns of the charcoal producers studied. These include Julbernardia paniculata, found in 15 of the 20 kilns examinated, as wel as Brachystegia microphylla, identified in 9 of the 20 kilns. "Furthermore, fruit trees from the miombo woodland, such as Uapaca nitida (observed in 3 out of 20 kilns), Anisophyllea boehmii (present in 1 out of 20 kilns), and Parinari curatellifolia (identified in 5 out of 20 kilns), were also used in charcoal production (Table 2).

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

N°	Vernacular name	Scientific name and 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

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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
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; * to indicate that, it is a fruit tree.

3.2. Carbonization yield

This study highlights that the kilns constructed by the examined charcoal producers contain an average of 46.9±21.5 m3 of wood, equivalent to 33808.5±15,518.8 kg. After the carbonization process, the average quantity of charcoal harvested per kiln is 3464.6±1775.1 kg, determining a carbonization yield of 10.2%. A comparative analysis of charcoal quantities harvested per kiln, differentiated by village, reveals significant disparities ($P < 0.05$). Specifically, the yield is 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)	36250.8±12705.2	50.3±17.6	4090.7±1117.7	11.3
Maksem (n=5)	20616.4±10694	28.6±14.8	1276.4±997.8	6.2
Mwawa (n=4)	46514.3±23532.3	64.6±3.7	4010.0±1641.8	8.6

Sela (n=5)	33905.4±4955.8	47.1±6.9	4465.0±1505.6	13.2
Total (n=20)	33808.5±15518.8	46.9±21.5	3464.6±1775.1	10.2
P Value	0.078	0.078	0.005*	

* n: sample size, kg: kilogram; %: percentage, Qty: quantity; St. Dev. : Standard Deviation.

3.3. Factors influencing kiln yields

3.3.1. Quantitative variables

The examination of correlations (Table 4) highlights that in Lubumbashi, in the rural area, larger kilns generally demonstrate higher yields compared to smaller ones (R2=0.652). Consequently, the length (R2=0.671) and width (R2=0.670) of these kilns exhibit a positive correlation with the quantity of harvested charcoal. A significant relationship is 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 (R2=0.604). On the other hand, the diameter and moisture content of the wood show no correlation with the quantity of harvested charcoal

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

	Lk	**Wk**	**Hk**	**Vk**	**Wmc**	**Dw**	**Ndw**	**Ndf**	**Ndh**	**Qty of wood kg**	**Qty of charoal harvested**
Lk	1	0.368	0,109	**0.913****	0.267	0.010	**0.561***	0.348	0.428	**0.913****	**0.671****
Wk	0.368	1	0,050	**0.597****	**0.511***	-0.087	0.220	0.263	0.335	**0.597****	**0.670****
Hk	0.109	0.050	1	0.334	0.049	-0.114	-0.135	-0.261	-0.135	0.334	-0.152
Vk	**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
Dw	0.010	-0.087	-0,114	-0.060	-0.364	1	0.215	0.209	-0.091	-0.060	0.231
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

* With Lk : Length of the kiln ; Wk : Width of the kiln; Hk : Height of the kiln ; Vk : Volume of the kiln ; Wmc : Wood moisture content ; Dw : Diameter of the wood ; Ndw : Number of days of wood covering with earth ; Ndf : Number of days between fire setting and the beginning of the charcoal harvest ; Ndh : Number of days of harvesting ; Qty : Quantity. **. The correlation is significant at the 0.01 level (two-tailed). *. The correlation is significant at the 0.05 level (two-tailed).

3.3.2. Qualitative variables

Multiple Correspondence Analysis highlights the relationships between the quantity of charcoal produced per kiln and the qualitative variables that could influence yield. This analysis reveals a strong correlation between the quantity of charcoal harvested per kiln and the tree species used (93.9%). Furthermore, it demonstrates a significant dependence on the type of substrate on which the kiln is built (80.3%). The quantities of charcoal harvested from kilns constructed on soils with concretions were low compared to kilns built on soils without concretions. Finally, the quantity of charcoal from a kiln is also influenced by the orientation of the kiln in relation to the wind, with a correlation of 67.8%. The quantity of charcoal harvested from kilns oriented in the direction of the wind was high compared to that from kilns oriented against the wind (Figure 2).

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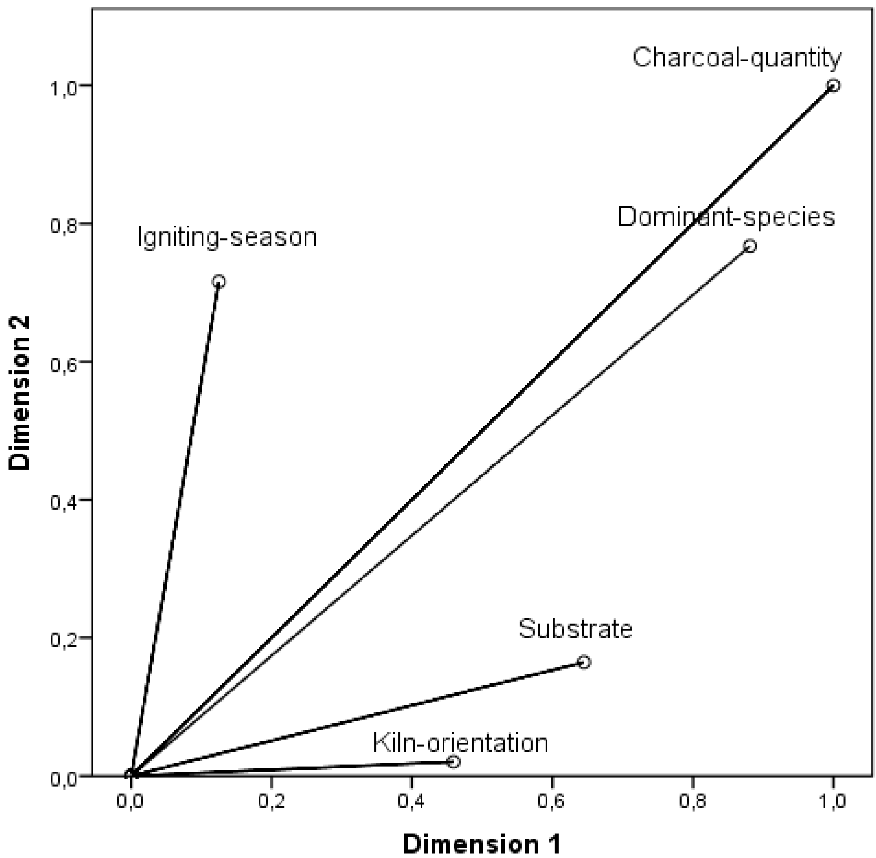

Figure 2. Correlations between the quantities of charcoal produced and the carbonization season; the kiln orientation; the substrate and tree species used.

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 direct surveys of charcoal producers was motivated by the fact that monitoring carbonization allows for direct and meticulous data collection at the kiln level, providing a more objective and reliable understanding of the carbonization process. The representativeness of the number of monitored kilns allowed for generalization of the results to the entire study area, as this approach is widely employed in research on the characterization of carbonization yields [21,30,33].

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 [40,42,43].

The number of kilns monitored in this study is equivalent to that used by Ref. [31], in a comparison between two different regions of the DRC, which was deemed applicable for the same area, although the villages differ. However, it is important to note that this method has some limitations related to the challenging conditions of regular accessibility to collection sites, in addition to relying on the availability of kiln owners for data collection

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4.2. Characteristics of kilns built in the rural area of Lubumbashi

4.2.1. Diameter, wood moisture content and kiln dimensions

Our findings indicate that the kilns erected by charcoal producers in the rural area of Lubumbashi contain approximately 46.9 m3 of wood, equivalent to 33,808.5 kg. This substantial dimension distinguishes them from those constructed in other regions, including the DRC, such as the Batéké Plateau (15,837 kg) and Yangambi (8,444 kg) [21], and in Mampu 24 tons, approximately 24,000 kg) [53]. This disparity can be attributed, on the one hand, to the richness in tree species of the accessible miombo forest for charcoal producers, and on the other hand, 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, emphasizing that the design of traditional kilns is similar, but their size varies.

Our results highlight the diversity of kiln diameters constructed by professional charcoal producers in the studied villages, 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 charcoal producers. Additionally, according to Ref [56], the dimension of wood used for carbonization varies depending on the vegetation formation present in charcoal-producing areas, being larger in forests than in savannas. Our findings align with the proposal of Ref. [31], in favor of using wood of various diameters during improved carbonization, aiming to achieve optimal combustion and thus improve yield.

Regarding the moisture content of the wood used by charcoal producers, our results reveal a moisture content of 26.3%. This observation is explained by the common practice of not drying the wood after harvesting. According to Ref. [57], the use of wood with high moisture content has negative implications for pyrolysis, increasing greenhouse gas emissions. This aligns with the findings of Ref. [58], in their study in Madagascar, where the use of non-dried wood for carbonization led to a moisture content of 34%. Wood moisture content influences the carbonization duration [59,60], as demonstrated by the results of Ref. [54], showing that wood moisture content below 30% can decrease the carbonization time of a kiln.

4.2.2. Tree species used for charcoal production

The kilns examined in this study exhibited notable diversity in terms of tree species, with a particularly high frequency of Julbernardia paniculata, Brachystegia microphylla, and Brachystegia spiciformis. This observation can be attributed to the fact that these three species are among the most predominant genera in the miombo ecosystem [61]. Additionally, as members of the Fabaceae family, these species corroborate the findings of Ref. [22], who noted that they were among the common preferences of charcoal producers in the Lubumbashi region. This is consistent with the miombo in Angola, where most species used in carbonization belong to the Fabaceae [62]. Moreover, fruit tree species used in the rural area of Lubumbashi are identified as representative of fruit trees present in the miombo [63]. [13], also reported the use of exotic fruit trees in the carbonization process in the Lubumbashi region.

4.2.3. Kiln yield

The carbonization yield in the rural area of Lubumbashi is assessed at 10.2%, demonstrating a relatively low efficiency. This performance aligns with the typical yields of traditional kilns, as indicated by Ref. [64], reporting that yields from tropical wood kilns rarely exceed 15 to 20%. Similar findings were observed in the surrounding villages of Lubumbashi, with a yield of 10%, according to a previous study of Ref. [22]. In contrast, charcoal producers in the Plateau Batéké in the DRC, utilizing improved carbonization techniques, achieved yields in the range of 28.1% [21].

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The disparity in yields among villages highlights the complexity of factors influencing carbonization, corroborating previous studies [31,58,65]. Research conducted in the outskirts of Boma in the DRC has also identified significant variability in the number of charcoal bags harvested, with substantial differences in kiln yields, even within the same environment [30].

The kiln dimensions, the quantity of wood used, the duration of coverage with earth, tree species, kiln orientation with respect to the wind, and substrate significantly influence the quantity of harvested charcoal. The size of the kiln, especially its length and width, plays a crucial role in carbonization yield, confirming the results of Ref. [66], and even those of Ref. [67]. The wood density used not only impacts the quantity but also the quality of charcoal, as illustrated by the example of different densities of Acacia auriculiformis and Acacia mangium in the DRC [68], as well as Acacia tortilis and Acacia mellifera in Kenya [69].

An extended covering duration of the kiln leads to increased charcoal harvest, emphasizing the importance of careful insulation. This must ensure proper sealing of the kiln to prevent losses [70]. The tree species used, the orientation of the kiln with respect to the wind, and the substrate also influence kiln yields. Different tree species produce charcoals with distinct physicochemical compositions, and aligning the kiln with the wind promotes combustion. Substrate with concretions can generate high temperatures, but beyond 400°C, the yield decreases, prompting producers to avoid rocky areas [65,71].

4.3. Implications for carbonization and conservation of forest resources

The socio-ecological 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 [17,72–74]. There is notable pressure on the local forest resource, as the carbonization process demands a significant quantity of wood [13,22,75]. The low average carbonization yield of 10.2% indicates a relatively low efficiency of the process, meaning that only a fraction of the used wood is converted into charcoal [27,29]. This may have economic implications for charcoal producers, as a substantial amount of raw material is needed to achieve significant yields [19,30]. Furthermore, the variability in yield among villages highlights the influence of local practices and environmental conditions on the carbonization process [23].

Parameters such as kiln size, quantity of wood used, covering time, orientation to the wind, substrate type, and tree species play a crucial role in carbonization yield [23,31,32]. 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 [76]. Noting the absence of a significant correlation between moisture content and wood size with the quantity of harvested charcoal, it becomes important to explore other variables and optimize carbonization practices to minimize losses and maximize yield, while promoting the conservation of local forest ecosystems.

5. Conclusions

This study aimed to quantify the carbonization yield in the rural area of Lubumbashi. Monitoring 20 kilns owned by professional charcoal producers confirmed our hypotheses. The average carbonization yield stands at 10.2%, indicating inefficiency in current practices. Variations in yield among villages attest to the influence of various parameters and the individual expertise of charcoal producers, regardless of similar techniques employed. Factors identified as influencing yield include kiln size, amount of wood used, covering time, tree species, kiln orientation to the wind, and construction substrate. Conversely, wood size and moisture content demonstrated no significant correlation with the quantity of harvested charcoal per kiln. To address this situation, it is recommended to enhance the skills of charcoal producers in the rural area of Lubumbashi in adopting improved carbonization techniques aimed at increasing yields and income. Furthermore, in-depth experimental research, incorporating the identified factors, is necessary to enhance understanding of carbonization in this specific region.

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Data Availability Statement: The data related to the present study will be available upon request from the interested party.

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References

1. Krieger, D.J.: Economic Value of Forest Ecosystem Services: A Review. The wilde.Soc. 2001, 1-31.
2. Talukdar, N.R.; Choudhury, P.; Barbhuiya, R.A.; Singh, B.: Importance of Non-Timber Forest Products (NTFPs) in rural livelihood: A study in Patharia Hills Reserve Forest, northeast India. Trees For. People.2021,3,100042. https://doi.org/10.1016/j.tfp.2020.100042
3. Mahailet, A. La contribution de la filière bois au développement de l'économie camerounaise: une analyse à partir des choix d'industrialisation. Thèse de doctorat, Université du Littoral-Côte d'opale, Lille, France, 2019. p.373.
4. Harzallah, I. L'écotourisme forestier: importance et rôle économique des forêts récréatives de la wilaya de M'sila. Mémoire de Master, Université Mohamed Boudiaf-M'sila, Algérie, 201. p.63.
5. Lescuyer, G.: Locatelli, B.: Rôle et valeur des forêts tropicales dans le changement climatique. Bois forêts Trop. 1999, 260, (2), 5-18.
6. Kokou, K.; Sopkon, N.: Les forêts sacrées du couloir du Dahomey. Bois forêts Trop. Trop. 2006, 288, 15-23.
7. Mpanzu, B.P.; Ngonde, N.H.; Bonkena, P.: Forêts, exploitation et consommation du bois-énergie en République Démocratique du Congo: Cas des provinces de Kinshasa, du Kwango et du Kongo Central. Tropicultura 2018, 36, 3, 553-564.
8. Pendrill, F.; Persson, U.M.; Godar, J., Kastner, T.: Deforestation displaced: trade in forest-risk commodities and the prospects for a global forest transition. Environ. Res. Lett. 2019, 14,1-14. https://doi.org/10.1088/1748-9326/ab0d41
9. Tchatchou, B.; Sonwa, D.J.; Tiani, A.M.: Déforestation et dégradation des forêts dans le Bassin du Congo : Etat des lieux, causes actuelles et perspectives. Papier occasionnel, CIFOR : Bogor Barat, Indonésie, 2015; p. 47, ISBN 978-602-1504-69-7.
10. Eba'a, R.; Hiol Hiol, F.; Lescuyer, G.; Mayaux, P.; Defourny, P.; Bayol, N.; Saracco, F.; Kankeu, R.; Pokem, D.; Nasi, R.: Les forêts du bassin du Congo: Etat des forêts 2021, CIFOR : Bogor Barat, Indonésie, 446, (2021). https://doi.org/10.17528/cifor/008565.
11. Malaisse, F.: Le Katanga, une mosaïque d'écosystèmes en mutation: une approche globale. Prologue. In Anthropisation des paysages Katangais ; Bogaert, J., Colinet, G., Mahy, G., Eds.; Presses Universitaires de Liège-Agronomie: Gembloux, Belgique, 2018 ; pp.17-39.
12. Malaisse, F.: L'homme dans la foret claire zambezienne. Contribution a l'etude de l'ecosysteme foret claire (Miombo). Afr. Econ. Hist. 1979, 38. https://doi.org/10.2307/3601202.
13. Useni, S.Y.; Malaisse, F.; Cabala, K.S.; Munyemba,K.F.; Bogaert, J.: Le rayon de deforestation autour de la ville de Lubumbashi (Haut Katanga, RD Congo): Synthèse. Tropicultura 2017, 35, 3, 215-221.
14. Cabala, K.S.; Useni, S.Y.; Amisi, M.Y.; Munyemba, K.F.; Kankumbi, K.F.; Bogaert, J.: Activités anthropiques et dynamique des écosystèmes forestiers dans les zones territoriales de l'Arc Cuprifère Katangais (RD Congo). Tropicultura 2022,40,3,4,1-27. https://doi.org/10.25518/2295-8010.2100
15. Useni, S.Y.; Mpanda, M.M.; Khoji, M.H.; Cirezi, C.N.; Malaisse, F.; Bogaert, J.: Vegetation Fires in the Lubumbashi Charcoal Production Basin (The Democratic Republic of the Congo): Drivers, Extent and Spatiotemporal Dynamics. Land. 12, 2171 (2023). https://doi.org/10.3390/land12122171
16. Cabala, K.S.; Useni, S.Y.; Sambieni, K.R.; Bogaert, J.; Munyemba, K.F.: Dynamique des écosystèmes forestiers de l'Arc Cuprifère Katangais en République Démocratique du Congo : Causes, transformations spatiales et ampleur. Tropicultura 2017, 35, 192-202, (2017).

17. Kabulu, D.J.-P.; Vranken, I.; Bastin, J.-F.; Malaisse, F.; Nyembwe, S.; Useni, S.Y.; Ngongo, L.M.; Bogaert, J.: Approvisionnement des ménages Lushois en charbon de bois : quantités, alternatives et conséquences. Anthropisation des territoires Katangais ; Bogaert, J., Colinet, G., Mahy, G., Eds.; Presses Universitaires de Liège-Agronomie: Gembloux, Belgique, 2018 ; pp.297-308.
18. Péroches, A.; Nge, O.A.; Gazull, L.; Dubiez, E.: Rapport d'étude sur la filière bois-énergie de la ville de Lubumbashi. Programme de consommation durable et de substitution partielle au bois-énergie, CIRAD, 2021.
19. Trefon, T.; Hendriks, T.; Kabuyaya, N.; Ngoy, B.: L'économie politique de la filière du charbon de bois à Kinshasa et à Lubumbashi : Appui stratégique à la politique de reconstruction post-conflit en RDC. Institute of Development Policy and Management University of Antwerp, Belgium, 2010.
20. Rasoazanamanana, T.: Effets externes de la production de charbon de bois. Grand Mémoire d'études approfondies, Université d'Antananarivo, Antananarivo, Madagascar, 2009. p. 69.
21. Schure, J.; Pinta, F.; Cerutti, P.O.; Kasereka, M.L.: Efficiency of charcoal production in Sub-Saharan Africa: solutions beyond the kiln. Bois Forêts Trop. 2019, 340, 57-70. https://doi.org/10.19182/bft2019.340.a31691
22. Nge, O.A. Diagnostic socioéconomique et environnemental de la chaine de valeur charbon de bois à Lubumbashi (Haut-Katanga, RDC): Perspectives pour une gestion durable des ressources ligneuses de Miombo. Thèse de Doctorat, Université de Lubumbashi, Lubumbashi, RDC, 2021. p. 296.
23. Trégourès, A.: La structuration des filières d'approvisionnement en bois énergie dans la province du Zambèze (Mozambique). Programme sous-national de réduction des émissions de carbone liées à la déforestation et à la dégradation forestière (REDD+). Mémoire de Mastère Spécialisé Forêt, Nature et Société (AgroParis Tech), Paris, France, 2015. p. 120.
24. 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. https://doi.org/10.3390/fuels5010001.
25. Rodrigues, T.; Braghini, J.A.: Charcoal: A discussion on carbonization kilns. J. Anal. Appl. Pyrolysis. 2019, 143, 104670. https://doi.org/10.1016/j.jaap.2019.104670
26. Oliveira, A.C.; Ramos, D.C.; Pereira, B.L.C.; Carneiro, A.C.O.: Carbonization temperature and charcoal properties at different positions in rectangular kiln. Rev. Bras. Ciênc. Agrár. - Braz. J. Agric. Sci. 2020, 15, 1–8. https://doi.org/10.5039/agraria.v15i4a8493
27. Schenkel, Y.; Bertaux, P.; Vanwijnsberghe, S.; Carré, J.: Une évaluation de la technique de la carbonisation en meule. Biotechnol.Agron.Soc.Environ. 1997, 1,2, 113-124.
28. Mundhenk, P.; Gomis, O.; Sy, M.C.: Comparaison des rendements de production de charbon de bois entre la meule traditionnelle et la meule Casamance dans la forêt communautaire de Sambandé. PERACOD 2010, 20.
29. Girard, P.: Quel futur pour la production et l'utilisation du charbon de bois en Afrique? Unasylva 2002, 53, 30-35.
30. Mbuangi, L.M.; Ntoto, M.R.; Kisombe, M.; Khonde, B.C.: Les enjeux socioéconomiques et écologiques de la production du charbon de bois dans la périphérie de la ville de Boma en RDC. Journ. intern. Sc et Tech. de l'eau et d'env. 2021, 3, 42-54.
31. Schure, J.; Hubert, D.; Ducenne, H.; Kirimi, M.; Awomo, A.; Mpuruta-Ka-Tito, R.; Mumbere, G., Njenga, M.: Carbonisation 2.0 : Comment produire plus de charbon de bois tout en réduisant la quantité de bois et d'émissions de gaz à effet de serre ? Dossier n° 1. Série de dossiers sur le bois-énergie durable, 2021.
32. Mencarelli, A.; Cavalli, R.; Greco, R.; Grigolato, S.: Comparison of Technical and Operational Conditions of Traditional and Modern Charcoal Kilns: A Case Study in Italy. Energies 2023,16, 7757, 1-18. https://doi.org/10.3390/en16237757
33. Issifou, Y.A.; Tonouewa, F.M.; Biaou, H.S.; Houehanou, D.T.; Idrissou,Y.: Technique de carbonisation du bois au Nord-Ouest du Bénin, Afrique de l'Ouest. Afr. Sc.2020, 16, 2, 49-58.
34. Malaisse, F.; Ilunga, K.: The influence of deforestation on the hydric balance of soils in the Lubumbashi environment (Shaba, Zaïre). Bulletin de la Société Royale de Botanique de Belgique. Fasc.1986, 2, 161-178.
35. Dikumbwa, N.; Alexandre-Pyre, S.; Nawej, T.S., Malaisse, F.: Etude des températures des sols de trois écosystèmes naturels du Haut-Katanga. Geo-Eco-Trop, 2020, 44,2, 237-253.
36. Malaisse, F.: Se nourrir en forêt claire Africaine: Approche écologique et nutritionnelle. Les presses Agronomiques de Gembloux, Gembloux, Belgique, 1997. ISBN 2-87016-045-3.
37. Bruneau, J.C.; Numbi, A.M.: Nature et citadinité à Lubumbashi (Congo-RDC) : A la recherche d'un équilibre perdu. Esp. trop. 2011, 20, 553-562.
38. Kabulu, D.J.-P; Bamba, I.; Munyemba, K.F.; Defourny, P.; Vancutsem, C.; Nyembwe, N.S.; Ngongo, L.M.; Bogaert, J.: Analyse de la structure spatiale des foreets au Katanga. Ann. Fac. Sc. Agro, 2018, 2, 12-18.
39. Useni, S.Y.: Analyse spatio-temporelle des dynamiques d'anthropisation paysagère le long du gradient urbain-rural de la ville de Lubumbashi (Haut-Katanga, République Démocratique du Congo), Bois forêts trop. 2019, 342,2. , 342, (2), (2019).

40. N'tambwe N.D.; Muteya, K.H.; Kasongo, K.B.; Sambiéni, K.R.; Malaisse, F.; Useni, S.Y.;Masengo, K.W.; Bogaert, J.: Towards an Inclusive Approach to Forest Management: Highlight of the Perception and Participation of Local Communities in the Management of miombo Woodlands around Lubumbashi (Haut-Katanga, D.R. Congo). Forests 2023, 14, 687. https://doi.org/10.3390/f14040687
41. Münkner, C.A.; Bouquet, M.; Muakana, R.: Analyse des chaines de valeur ajoutée en bois-énergie et bois d'œuvre de la ville de Lubumbashi dans la province du Katanga. Programme Biodiversité et forêt, GIZ, 2015,9.
42. Muteba, K.D.: Caractérisation des modes de consommation alimentaire des ménages à Kinshasa : Analyse des interrelations entre modes de vie et habitudes alimentaires. Thèse de Doctorat, Université de Liège Gembloux-Agro Biotech, Gembloux, Belgique, 2014. p.179.
43. Sabuhungu, E.G.: Analyse de la demande en charbon de bois par les ménages urbains de Bujumbura au Burundi. Thèse de Doctorat, Université de Liège Gembloux-Agro Biotech, Gembloux, Belgique, 2016. p.192.
44. OSFAC.: Cartographie de la stratification des classes de végétation des forêts Miombo, Haut- Katanga RDC, Rapport final. 2009.
45. Meerts, P.; Hasson, M.: Arbres et arbustes du Haut-Katanga. Editions Jardins Botaniques de Meise: Brussels, Belgium, 2016. p. 386.
46. Mana, P.; Rajaonarivelo, S.; Milleville, P.: Production de charbon de bois dans deux situations forestières de la région de Tuléar. Sociétés paysannes, transitions agraires et dynamiques écologiques dans le Sud-Ouest de Madagascar. Sc pays. 2001, 199-210.
47. Rousson, V.: Statistique appliquée aux sciences de la vie. Collection statistique et probabilités appliquées. Springer, Paris, France, 2013; p. 320, ISBN 978-2-8178-0393-7.
48. Alemayehu, H., Abebe, T., Asabeneh, A.: Analysis of Charcoal Producers Perceptions of Its Production, Forest Degradation, and Governance in Wolaita, Southern Ethiopia's Dry Afromontane Forests. Int. J. For. Res. 2023, 1–13. https://doi.org/10.1155/2023/3352702
49. Kouicem, M.: Sur quelques méthodes d'analyses multivariée et applications. Mémoire de Master, Université Kasdi Merbah Ouargla, Algérie, 2020. p.74.
50. Nyarko, I., Nwaogu, C., Miroslav, H., Peseu, P.O.: Socio-Economic Analysis of Wood Charcoal Production as a Significant Output of Forest Bioeconomy in Africa. Forests 2021,12, 568. https://doi.org/10.3390/f12050568
51. Ramamonjisoa, N.; Rajoelison, L.G; Rakoto, R.H.; Rabenilalana, F.M.: Etude de l'importance socioéconomique des Produits Forestiers Non Ligneux et des Produits Agroforestiers en vue de l'amélioration des revenus de la population locale: Cas de la zone de Mandraka, Région Analamanga. Eastern and Southern Africa Patnership Program (ESAPP), 2008.
52. Seboka, Y.: Charcoal production: Opportunities and barriers for improving efficiency and sustainability. Harnessing Carbon Finance to Promote Sustainable Forestry, Agro-Forestry and Bio-Energy. UNDP 2008,102-126.
53. Bisiaux, F.; Peltier, R.; Muliele, J.-C.: Plantations industrielles et agroforesterie au service des populations des plateaux Batéké, Mampu, en République Démocratique du Congo. Bois Forêts Trop. 2009, 301, 21-32. https://doi.org/10.19182/bft2009.301.a20404
54. García-Quezada, J.; Musule-Lagunes, R.; Prieto-Ruíz, 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 2022, 16, 333. https://doi.org/10.3390/en16010333
55. Falcão, M.P.: Charcoal production and use in Mozambique, Malawi, Tanzania, and Zambia: Historical overview, present situation and outlook. 2008.
56. Kouami, K.; Yaovi, N.; Honan, K.A.: Impact of charcoal production on woody plant species in West Africa: A case study in Togo. Sci. Res. Es. say. 2009, 4,(9), 881-893.
57. Canal, W.D.; Carvalho, A.M.; Figueiró, C.G.; Carneiro, A.D.; Fialho, L.D.; Donato, D.B.: Impact of Wood Moisture in Charcoal Production and Quality. Flor.Amb.2020, 27,1. https://doi.org/10.1590/2179-8087.099917
58. Temmerman, M.; Andrianirina, R.; Richter, F.: Performances techniques et environnementales du four de carbonisation Green Mad Retort à Madagascar. Bois forêts Trop. 2019,340, 43-55. https://doi.org/10.19182/bft2019.340.a31700
59. Akossou, A.Y.; Gbozo, E.; Darboux, A.E.; Kokou, K.: Influence of wood humidity of tree species (Prosopsis africana,Anogeissus leiocarpa and Tectona grandis) on the production of charcoal by the traditional wheel. J. Pet. Technol. Altern. Fuels, 2013,4,4, 64-71.
60. Orabi, M.A.; Bahnasawy, A.H., Ali, S.A.; Ashour, T.H.; Yehia, I.: Development of environment friendly kilns for production of charcoal. Misr J. Agric. Eng. 2020, 37,3, 313-324. https://doi.org/10.21608/mjae.2020.34719.1004
61. Chidumayo, E.N.: Is charcoal production in Brachystegia-Julbernardia woodlands of Zambia sustainable? Bio Bioen. 2019,125, 1–7. https://doi.org/10.1016/j.biombioe.2019.04.010

62. Kissanga, R.; Catarino, L.; Máguas, C.; Cabral, I.R., Chozas, S.: Assessing the Impact of Charcoal Production on Southern Angolan Miombo and Mopane Woodlands. Forests. 2023,15,78. https://doi.org/10.3390/f15010078
63. Hick, A.; Maud, H.; Kizila, W.P.; Tshibungu, A.; Seleck, M.; Mahy, G.: Ces essences importantes que l'on retrouve en Forêt Claire (miombo). Université de Liège – Gembloux Agro-Bio Tech – Unité Biodiversité de paysage, 2013.
64. Binzangi, K.; Tshibangu, K.; Degreef, J.; Malaisse, F.:Le deboisement en Afrique tropicale. Tech. Déf. Sud. 1994, 36-37.
65. Montagne, P.; Creahay, R.; Rasamindisa, A.; Razafimahatratra, S.: Bonnes pratiques de carbonisation à Madagascar. Projet CARAMCODEC, 2009, 30.
66. Luwaya, E.; Chisale, P.; Yamba, F.; Malin, M.: A parametric analysis of conversion efficiency of earthen charcoal making kiln using a numerical method. 10th International conference on heat transfer, fluid mechanics and thermodynamics, 2014. Orlando, USA, 271-280,
67. Mekuria, W., Sengtaheuanghoung, O.; Hoanh, C.T.; Noble, A.: Economic contribution and the potential use of wood charcoal for soil restoration: a case study of village-based charcoal production in Central Laos. Int. J. Sustain. Dev. World Ecol. 2012,19, 415–425 . https://doi.org/10.1080/13504509.2012.686070
68. Louppe, D.: Projet Makala Module 6: Transfert et renforcement des compétences. Rapport de mission auprès du projet Makala (version provisoire), Kinshasa et Kisangani (RDC), 2011.
69. Frayer, A.: Production de charbon de bois dans le District d'Isiolo-Kenya. Estimation de l'activité et évaluation des conséquences sur la ressource forestière existante. Rapport de stage ingénieur, AgroParisTech, Paris, France, 2007.
70. Girard, P.: Formation à la valorisation énergétique de la biomasse lignocellulosique, Pole Régional de Thermochimie. 1997, 251-259.
71. Ganhoun, G.: Influence de l'essence de bois et de la température de carbonisation sur le rendement pondéral et la qualité du charbon de bois. Thèse de doctorat, Université d'Abomey-Calavi, Abomey-Calavi, Benin, 2020. p.151.
72. Schure, J.; Mvondo, S.A.; Awono, A.; Ingram, V.; Lescuyer, G.; Sonwa, D.; Somorin, O.: Etat de l'art du bois énergie en RDC: Analyse institutionnelle et socioéconomique de la filière bois énergie, 2010.
73. Shuku, N.: Impact de l'utilisation de l'énergie-bois dans la ville province de Kinshasa en République démocratique du Congo (RDC). Mémoire de Maitrise, Université du Québec à Montréal, Canada, 2011. p.168.
74. Khoji, M.H.; N'tambwe, N.D.; Mwamba, K.F.; Strammer, H.; Munyemba, K.F.; Malaisse, F.; Bastin, J.-F., Useni,S.Y.; Bogaert, J.: Mapping and Quantification of Miombo Deforestation in the Lubumbashi Charcoal Production Basin (DR Congo): Spatial Extent and Changes between 1990 and 2022. Land. 2023, 12, 1852 https://doi.org/10.3390/land12101852
75. Khoji, M.H.; N'tambwe, N.D.; Malaisse, F.; Waselin, S.; Sambiéni, K.R.; Cabala, K.S.; Munyemba, K.F., Bastin, J.-F., Bogaert, J., Useni, S.Y.: Quantification and Simulation of Landscape Anthropization around the Mining Agglomerations of Southeastern Katanga (DR Congo) between 1979 and 2090. Land. 2022, 11, 850. https://doi.org/10.3390/land11060850
76. Raoliarivelo, L.I.; Rabeniala, R.; Masezamana, H.M.; Andrianarisoa, J.H.; Randriamalala, R.J.: Khoji, H., N'tambwe, D., Malaisse, F., Waselin, S., Sambiéni, R., Cabala, S., Munyemba, F., Bastin, J.-F., Bogaert, J., Useni, Y.: Impact de la fabrication de charbon de bois sur la production et la disponibilité fourragère de pâturage en zone subaride, cas de la commune de Soalara-Sud, Toliara II, Rapport final, 2010, p. 56.