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YIELD, QUALITY AND MARKET OF CHARCOAL IN EARTH OVENS IN XOXOCOTLA, VERACRUZ

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Abstract: This study was carried out with the purpose of knowing the yield, quality and price of charcoal in Mexico, produced in its traditional artisanal form, that is, in earth ovens. We worked with charcoal producers in the communities of "Corratel" and "El Pelado" in the municipality of Xoxocotla, Veracruz. Four oak trees (*Quercus laurina* and *Quercus crassifolia*) were felled and cubed to determine the charcoal yield (kg) produced in earth ovens. The quality of the charcoal produced was analyzed and the following parameters were evaluated: calorific value, moisture content, ash content, fixed carbon content and volatile content; aspects of commercialization and potential market were analyzed. Density data were obtained for the oak wood, the wood was cubed before charcoal production, and all the charcoal was weighed at the end of the process. To cover the quality analysis, charcoal samples were taken from three different kiln heights: high, medium and low. The results obtained determined that about 8.5 m^3 oak wood rolls are required to produce one ton of charcoal. To cover the market analysis, production costs were obtained and interviews and surveys were conducted with producer-consumers. The average yield obtained per cubic meter of wood was 18%. The highest calorific values are contained in the charcoal located in the highest part of the kiln, and with respect to the quality related to the parameters evaluated, all the charcoal had good characteristics, meeting most of the international marketing standards. The product is mainly marketed locally and a large part is destined for direct consumption. The results show that the earth kilns have low yields, their combustion is vertical with little uniformity; the market demand for charcoal is high and the supply does not meet consumption needs. One deficiency of charcoal produced by artisanal methods is that it does not fully comply with international requirements and specifications, which does not contribute to its international positioning.

Keywords: *Quercus laurina*, *Quercus crassifolia*, proximate charcoal analysis, quality, price.

INTRODUCTION

Charcoal production and marketing is an activity that has been practiced for centuries and continues to be very high and productive. This activity represents a complement to the income of rural producers and an important source of employment (Fernández, 2012; Jaramillo-Villanueva *et al.*, 2023). According to FAO (2017) worldwide 50% of forest wood is destined for firewood and charcoal. In Mexico, firewood contributes 80% of the energy of rural households for domestic purposes, where 48% of the energy demand is provided by firewood and charcoal (Díaz, 2000; Serrano-Medrano *et al.*, 2014; Ríos *et al.*, 2017; Jaramillo-Villanueva *et al.*, 2023). The production of charcoal and firewood in Mexico in 2016 was 630 900 m^3 roll, with the main charcoal producers being the states of Durango and Sonora (Carrillo Ávila, 2021).

The participation of the state of Veracruz was 670 m^3 . In the same year, the *Quercus* genus registered a charcoal production of 138 935 m3 at the national level (SEMARNAT, 2017). The municipality of Xoxocotla, Veracruz, has as its main economic activity the use of its forest resources, charcoal production is carried out intensively using as material complete trees of the *Quercus* genus of various characteristics, that is, commercial logs of excellent quality, poorly shaped logs, tips and branches. The market currently demands quality standards that oblige charcoal producers to implement technology transfer lines to improve the quality of their production and reduce their costs, reflected in higher economic profit. Approximately 90% of producers use the technique of charcoal production in rudimentary earth ovens (INEGI, 2009), whose production technique does not allow high yields, its elaboration is handmade, without a homogeneous quality (Carrillo Ávila *et al.*, 2021).

All oaks share common biological characteristics: woody stems, leathery or hard leaves and acorn fruits. Their growth form is commonly as trees with heights of 3 to 40 m, or as shrubs with heights of 10 to 60 cm. Its development is slow, so they are also long-lived, living up to 1500 years. They grow mainly in temperate zone forests, although they can also be found in scrublands, pastures and intercalated in some dry forests (Rzedowski, 2006). They are capable of resprouting. The same individual is hermaphroditic and they present polymorphism, which consists of variation in the shape of the trunk, leaves, flowers, fruits and general appearance (Romero Rangel *et al.*, 2014). Variations in calorific value between species and their components (stem, branch and leaves) are related to differences in the chemical composition of biomass (Senelwa and Sims, 1999). Wood and its by-products present average values of calorific value from 2.4 to 2.7 kJ/g, volatile materials between 14.44 and 15.01%, ash between 5.00 and 5.77%, fixed carbon from 76.00 to 78.14%.

Charcoal is a solid, fragile and porous product containing a high percentage of carbon. During the carbonization process, physical and chemical changes occur, on average 80% of its structure is the result of distillation or incomplete combustion of the wood in the absence of air and as a consequence there is an increase in the energy content per unit weight.

Materials with higher density (greater than 0.50 g/cm^3) are more appreciated for charcoal production since there is a direct relationship between density, yield and charcoal quality. The most important property that makes charcoal an important source of energy is its calorific value, which, for four oak taxa, fluctuates between 15.78 and 20.28 MJ/kg (Ruíz Aquino *et al.*, 2015; Herrera Fernández *et al.*, 2017; Ruiz Aquino, 2020).

During timber harvesting, approximately 35.0% is left in the forest in the form of tips, branches, and branches, or is used for firewood or charcoal. In most cases, the entire authorized volume is used for charcoal production. The study was carried out to determine the yield and quality of charcoal produced from oak wood.

MATERIALS AND METHODS

The municipality of Xoxocotla, Veracruz is part of the natural region known as "Las Grandes Montañas" (The Great Mountains), located between the parallels 18° 36' - 18° 40' N and the meridians 97° 08' - 97° 14' W; its altitude ranges between 2100 and 2700 meters. Xoxocotla, Veracruz's main activities are lumber production, charcoal production and sawmilling wood for rustic furniture.

To meet the objectives of the study, the following activities were carried out. Four oak trees from the communities of Corratel and El Pelado were felled and cubed; the species were identified as *Q. laurina* (slender oak) and *Q. crassifolia* (tolompo oak). Three earth ovens were constructed and the volume used in each oven was recorded. To determine the volume, each complete tree was cubed: trunk, branches and stump. The diameters and lengths of all the sections or logs obtained from each tree were measured using the Huber and Smalian formula. The land was prepared, the "chabete" was built and then the total volume of firewood was placed in a circular shape until the earth oven was integrated (Figure 1).

The process was considered finished, based on the coloration of the smoke and the carbonization time. The constant practice of this activity has led producers to an empirical knowledge of the average time estimated between eight and ten to carry out the combustion and achieve greater efficiency of the furnace.

The proximate analysis of charcoal was performed according to the technical specifications of ASTM D1762-2007 Standard Test

Cubing of roundwood, firewood, charcoal burning in an earth oven and packaging.

Method for Chemical Analysis of Wood Charcoal. The density of green wood was evaluated, and the charcoal was evaluated for moisture content, volatile materials, ash and fixed carbon content. Sieves of numbers 20, 40, 60, 80 and 100 were used; subsequently a representative sample was taken from each lot sampled according to the mentioned standard in the following proportions of the sieves: 40 (14.5%), 60 (18.7%), 80 (7.0%) and 100 (3.4%) and the amount of material retained in the latter (56.4%), was used to perform the analyses.

For each proximal characteristic, three replicates were carried out in each batch. A Nabertherm laboratory muffle was used, varying the heating temperatures and temperature application times, depending on the test performed. A Parr 1266 isoperibol bomb calorimeter was used to determine the calorific value of the charcoal, applying four replicates on samples from each furnace height. Surveys were conducted with producers and consumers to obtain information on the supply, demand and potential market for coal at the local and state level.

RESULTS AND DISCUSSION

The production of oak charcoal has been considered to have characteristics that favor high levels of quality and yield (Antal and Gronli, 2003). The volume of oak wood used in the three kilns, as well as the yield, are shown in Table 1. From this it is derived that, to produce one ton of charcoal, an average of 8.47 ± 0.2 m^3 of wood is required. The temperatures used in this type of kilns are variable and not controllable, so that, in the transformation process, the yields can vary between 10 and 20%; however, the results indicate that from each ton of dry base raw material, an average of 18% of the product is obtained.

These results are within the acceptable range when taking into account the characteristics of the kiln and the results reported by authors such as Wolf and Vogel (1985), who indicate a yield between 10 and 20%. Although the yield is closer to the higher value of the range defined in this production system, it is still evidence that the production in ground kilns is of low conversion efficiency.

This production method, due to its low efficiency, directly affects the producers' economy; however, it is important to highlight that it is still the most used technique in the region studied, due to the lack of technical knowledge of the process, together with the lack of economic support for the transfer and/or dissemination of other production technologies.

The utilization of charcoal is conditioned to its efficient use and to the optimum quality for which it is produced. The values of the proximal properties of charcoal were analyzed with the SAS 9.0 statistical package. It consisted of evaluating the effect of the physical and chemical characteristics of charcoal quality at three levels within the kiln: high, medium and low. A single-factor analysis of variance (ANOVA) was used to express the results, with a confidence level of 95%. In Mexico, there are no standardized quality specifications for the local, regional, national or international market; the evaluations of studies carried out

	Contents of: (%)				Production and yield			
Oven	Humidity	Volatile material	Ashes	Fixed carbon	Calorific value (cal/g)	Volume (m3)	kg	%
1	5.14	8.41	2.45	89.08	7 729.91	1.69	204.5	18.6
2	4.94	2.92	2.92	85.77	7 671.58	1.42	163.0	17.7
3	5.24	14.56	3.16	82.28	7 245.43	4.23	501.0	18.2

Table 1. Proximal analysis of charcoal. Average values.

base their analysis on the less demanding FAO standards, which require a minimum range of 5% and a maximum of 25% moisture in relation to their gross weight. Among the most demanding standards are the European, Asian and American ones.

The percentages of moisture content presented a normal distribution, whose values showed statistically significant differences ($\rho \leq 0.0001$). The numerical values of moisture in the three kilns on average are slightly higher than 25%, except for kiln 2, where the moisture value of the charcoal obtained was recorded at 4.94%. The results show that there is no definite pattern of moisture distribution within the kiln. In kiln 1, the highest moisture is concentrated in the middle zone and the lowest in the upper zone, which could be attributable to a non-uniform distribution of temperature during the carbonization process.

The determined average moisture content of 5% and in accordance with the specifications of coal quality with respect to the allowable moisture content by FAO (1983), it can be confirmed that the coal produced in earth kilns has good quality. When comparing with the burning performed in kilns built with different materials, it was obtained that the charcoal moisture distribution partially coincides with what was reported by Ordaz (2003) and Rojas (2014), who used a Brazilian beehive type kiln and Japanese type metallic kiln, obtained charcoal moisture values of 3.72 and 4.12%, 6.32 and 5.51%, 9.57 and 5.73% in the upper, middle and lower parts, respectively. Ordaz used *Quercus sp*. wood, while Rojas used *Eucalyptus camldulensis* firewood.

The contents of volatile materials in charcoal are considered an important chemical characteristic, the effects of which are reflected in the char yield from its density. Volatiles refer to all liquid and tarry residues that are not completely removed during the carbonization process and are linked to the time of the carbonization process. The content of volatile materials in charcoal depends basically on the production process and the technology used. It has been determined that metal kilns, pit-type kilns and clay kilns produce coals with the highest content of volatile materials compared to the traditional earth kiln method. In the latter, although there is no temperature control, it is possible to reach degrees above 500 °C, nor is it possible to control the circulating gases, which causes an excessive burning of the charred wood, resulting in a better refinement of the charcoal.

Statistical differences were observed in the content of volatile materials in the coal produced in each kiln ($\rho \leq 0.0001$). Differences were also found in the interactions between zones defined in kiln height (high, medium and low), the highest percentages of values in volatile content were presented in the middle and high part of kiln 3, while the lowest value was identified in the middle part of kiln 1, which reflected an irregular process in the charring of firewood.

Low values of volatile material make ignition difficult, but present a clean combustion, in contrast to high volatile contents that produce a lot of smoke during combustion and generate a greater volume of charcoal (FAO, 1983). Under the description of quality issued by FAO (1983), a good commercial charcoal can have a content of volatile substances of

13% when the temperature oscillates in 500ºC and 7% of volatiles at temperatures of 700ºC. Under this consideration, the charcoal produced in earth kilns in this study can be classified as good quality because its values range between 8.41%, 11.31% and 14.56% in kilns 1, 2 and 3, respectively, in addition to showing rapid ignition, presence of flame and high spark production (Garcia, 2008), however, the low values in volatile material content also lead to a characteristic that is not very desirable in the market: a "brittle" charcoal.

In this context, it is defined that the ash content (minerals such as clay, silica and oxides of calcium, magnesium, etc.) should be less than 5%. This characteristic is undesirable in charcoal due to the inconvenience of accumulation that they cause in the deposits of boilers, stoves and roasters (Carrillo-Parra *et al*., 2013) In this parameter, significant statistical differences were found in each kiln ($\rho \leq 0.0001$), as well as in the interactions between levels, highlighting that the only interaction that did not present differences was kiln 3 in its high vs. low interaction. These values are comparable and slightly lower than those reported by Carrillo-Parra *et al*., 2013) for hard species such as *Prosopis sp*. (2.8%) and *Ebenopsis sp*. (3.2%). For FAO (1983) the ash content should be around 3%, under this consideration, the average values of the three kilns in this study, meet the aspects of good quality.

With respect to the fixed carbon content, the results showed significant statistical differences ($\rho \leq 0.0001$) in each furnace, as well as in the interactions between the levels. Fixed carbon is considered to be the most important characteristic of fuel materials, since it determines the quality and quantity of flasks formed during combustion. It could be seen that where a higher temperature was reached during the carbonization process, a better refinement of the coal was achieved, which resulted in a low content of volatile substances and was reflected in the increase in the percentage of fixed carbon, whose values ranged between 82 and 89%, which represents a coal with higher ignition efficiency. FAO indicates that the fixed carbon content in charcoal should vary in a minimum and upper range of 50 to 95%, respectively.

From other studies carried out by different authors, it can be deduced that the difference in values obtained in this variable is probably attributable more to the species than to the type of kiln used, where it is shown that the lowest values of carbon content were determined by Pacheco (2005), Amilcar (2012) and Carrillo-Parra *et al*. Thus, the average values of fixed carbon for the *Acacia caven* species whose charcoal was produced in clay kilns was 58.01% (Pacheco, 2005); for charcoal produced in pit-type kilns of *P. piscipula and L. castilloi,* they were 63.3% and 68.4%, respectively (Canul Tun, 2013). For charcoal from *Prosopis laevigata* and *Ebenopsis ebano*, the values determined were 70.8 ± 4.5 % and 68.4 ± 4.6 %, respectively (Carrillo-Parra *et al., 2013)*.

Despite obtaining good coal quality with earth kilns, this production method is not environmentally friendly because, due to the heat emitted during the process, the moist soil at the top of the kiln also loses its moisture and transforms into loose silt, which slides down into the crevices thus cutting off the oxygen supply (Nabukalu and Gieré, 2019).

CALORIFIC VALUE

Through the wood carbonization process, greater energy efficiency is achieved by obtaining a greater amount of heat per unit of surface area in the charcoal. The charcoal obtained from the three kilns showed similar calorific value. The analysis of variance of the calorific value indicated that there were no statistical differences in kiln 1 ($\rho=0.1401$) as well as in kiln 2 ($\rho=0.1837$). However, there were differences in furnace 3 ($\rho=0.0021$).

These results agree with those reported by Ordaz (2003) for charcoal at each height level of the Brazilian beehive-type kiln, who obtained energy values for oak of 7 625.7, 7 457.9 and 6 6 680.2 cal/g in the upper, middle and lower parts of the kiln, respectively. On the other hand, Rojas (2014), in a Japanese type metallic kiln, obtained for *Eucalyptus camaldulensis* charcoal a calorific value of 7 940.6 cal/g in the upper part, 7 092.5 cal/g in the middle part and 6 835.4 cal/g in the lower part.

Carrillo-Parra *et al.* (2013), in a pit-type kiln, with *Prosopis laevigata* and *Ebenopsis ebano* charcoal, without making references to the corresponding part of the kiln, obtained average calorific value of 30 241 KJ/kg and 29 725 KJ/kg, respectively. Pacheco (2005) used a clay kiln and reported a calorific value of 6 700 cal/g for *Acacia caven* charcoal.

The technology used in this study corresponds to the simplest and cheapest, differs from those used by the cited authors and it is highlighted that the pyrolytic behavior is similar in the different production techniques used, registering higher calorific values in the coal located in the highest part of the furnace.

It is evident that the calorific value depends fundamentally on its chemical composition, there being direct relationships between the carbon content and the calorific value. It is observed that a high volatile content leads to a slightly higher calorific value, compared to a coal with a high fixed carbon content, and this is due to the difference between the calories obtained from carbon and hydrogen (Marcos, 1989; Rivera and Uceda, 1987; Earl, 1975).

Despite the high annual charcoal production volumes worldwide (51.2 million tons in 2017) and nationally (1.2 million tons, representing approximately 2% of global production) (Nabukalu and Gieré, 2019; Carrillo *et al.*, 2021), its production, distribution and sale are in informality (Morales *et al.*, 2018), presenting a strong intermediation to the detriment of producers, which induces to think that the real production could be higher (Nabukalu and Gieré, 2019). Forest degradation and deforestation in the charcoal trade are indiscriminate and the processes used to produce charcoal from lignocellulosic materials increase the risks of forest fires and deteriorate air quality, which calls for future innovations in production methods to reduce the negative impacts of environmental degradation (Nabukalu and Gieré, 2019).

The market study shows that there are two groups of charcoal producers: subsistence producers who market charcoal as a means to obtain their total income and allow them to buy consumer goods, i.e., to cover their basic food needs. This type of producer is 90% representative and not all of them are registered in a register; they have little interest in economics and cost control, as well as in the environmental impact.

The second group produces and markets their charcoal under the business concept. They need to circulate and increase the invested capital and it is important the economy and the control of their production costs. This group is not limited to artisanal technology, but has diversified its production using other technologies such as: parva, pit, Brazilian beehive type, half-orange or Rabo Quente ovens (Antal and Gronli, 2003). In 90% of the producers interviewed, the operations of the production process are manual, lacking mechanized equipment. The average useful life of the ovens ranges between 6 and 20 years, except for the parva and pit ovens.

The cost per m^3 determined for the oak wood used as raw material is $ 500.00, the cost of charcoal production including labor was estimated at $6,500.00. The capacity of the kilns visited was variable; each producer builds them according to their needs, which means that the amount of pyrolyzed wood and its yield are also variable. In the ground kilns, the production capacity ranges between two and four tons of charcoal per burn, while in the beehive and half-orange kilns, the capacity varies between 5 and 17 tons of charcoal per burn (Table 2).

Raw material ($/t)	Total cost of (production ($/t)	Coal production per kiln (t/burner)	
		Ground	Beehive and Half orange
2 700.00	4 500.00	2 a 4	5 a 17

Table 2. Production cost per ton of oak charcoal.

From the analysis of the information collected and analyzed, it was found that the average charcoal producer surveyed produces 100 tons of product per year, which at wholesale price ranges between $5.50 and $6.50 per kg, the income from the sale of the product ranges from $550,000.00 to $260,000.00 pesos per year, depending on its production and sale price. The annual cost of charcoal production was estimated at $54,000 pesos per ton, although some producers exceed 400 tons per year and have total production costs of $21,600,000 pesos.

In the 100-ton equivalent annual production scheme, average monthly revenues are defined as between $8,333.00 and $33,333.00. Producers often sell below their total costs in order to keep a customer or maintain a stable economic supply.

The estimated net profit of oak wood, in its alternative use as raw material for charcoal production, was determined between $167.00 and $667.00 per m^3 , which is considered acceptable and appropriate, since it represents between 37 and 148% of the cost of the m^3 log of wood.

The production of charcoal in earth ovens is not very homogeneous in terms of moisture content and size (at the local level this characteristic is not relevant), in general it has a high content of impurities. The functional companies are mostly family businesses, with an artisanal technological level, and maintain a ratio of 6 and up to 8:1 m^3 r/t of product in the transformation of charcoal, which, from an environmental point of view, is considered unsustainable. In addition, the level of income is low when compared to the work invested in production.

CONCLUSIONS

1. The carbonization of firewood in earth ovens is an activity of low efficiency and productivity, which indicates an inefficient use of timber resources.

2. The average yield obtained per cubic meter of wood was 18%, or 0.118 t/m^3 of wood.

3. Charcoal produced in earth ovens is considered to be of good quality, as it contains a low amount of volatile materials and a high percentage of fixed carbon.

4. The quality obtained meets most international marketing standards.

5. The highest values of calorific value are contained in the coal located in the highest part of the kiln, but it should be considered that the size of each ground kiln is variable, and that each producer builds it according to his needs, so the amount of wood to be pyrolyzed and its yield are also variable.

With the information obtained, attention should be given to the regulation and use of sustainable technologies in coal production.

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