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SELECTION OF SUPERIOR CLONES OF *Corymbia* HYBRIDS BASED ON WOOD AND CHARCOAL PROPERTIES

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ABSTRACT

The use of fast-growing trees is a good economic strategy for charcoal production. Wood with adequate chemical and physical properties generally is positively correlated with charcoal quality. The objective of this research was to evaluate wood quality from fast-growing hybrids for charcoal production. Three *Corymbia citriodora x Corymbia torelliana* and four *Corymba torelliana x Corymba citriodora* hybrid clones were evaluated. Parameters used to evaluate wood quality were wood basic density, elemental and structural chemical composition, energy efficiency and thermogravimetric analysis and the parameters evaluated for charcoal quality were apparent relative density, gravimetric yield, high heating value, proximate analysis and energy efficiency. All clones had wood basic density superior than 0,5 g cm^{-3} and ash inferior than 1%, which are desirable for a good quality of charcoal. Lignin content did not differ among clones with an average less than the 28% recommended for energetic use. Although clones differed in wood parameters, as dry matter, high heating value, energy density, total extractives, holocellulose content, it did not reflect in charcoal quality differences. Wood from all clones had equal and satisfying high heating value of charcoal and energy efficiency quality for charcoal production and differed in apparent relative density and ash content.

Keywords: Bioenergy, carbonization, elemental compositions, heating values, thermal characterization.

INTRODUCTION

Brazil is one of the largest producers and consumers of charcoal in the world (FAO 2019) and has the potential to increase production. One strategy to increase production is to cultivate fast-growing trees associated with reduction of the cutting cycle which quickly reach an economically optimum size. Species cultivated for charcoal production have had their growth-cycle reduced from 7 years to 5 or 4 years due to successful breeding programs (Oliveira *et al.* 2010). Fast-growing trees need to be assessed for wood quality and charcoal production; hybrids breeding strategies have improved these parameters and produced superior clones.

Corymbia species stand out for charcoal production because of their desirable high wood volume and density (Lee 2007). In addition, some species are tolerant to diverse pests and diseases, as well as environmental stressors such as wind, cold, frost, and drought (Lee 2007). Interspecific hybrids of *Corymbia* have high biomass production and grow faster than open-pollinated seed batches (Lee et al. 2009). Creating hybrids from *Corymbia citriodora* and *Corymbia torelliana* genotypes increases the chance that the resulting plants will be more vigorous than either parent (Reis *et al.* 2014).

Selecting superior clones helps optimize charcoal production in order to meet industry requirements (Protásio *et al.* 2014, Protásio *et al.* 2015, Assis *et al.* 2015). The most important parameters for clone selection are wood basic density (WBD), dry matter (DM), high heat value (HHV), elemental chemical composition, lignin content (LIG), extractive content (EXT), holocellulose (HOLO) and energy density (ED) (Guo *et al.*

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2010, Gonçalves *et al.* 2015, Protásio *et al.* 2019).

Wood basic density directly correlates with the gravimetric yield during the carbonization process and with the apparent relative density of the charcoal (Moutinho *et al.* 2016, Andrade *et al.* 2018). For carbonization, wood basic density greater than 500 $kg.m^{-3}$ is desirable (Santos *et al.* 2011). Some factors that affect carbonization are lignin, extractive content, and holocellulose content (Silva and Ataíde 2019).

Lignin is positively correlated with charcoal yield (Pereira *et al.* 2013, Soares *et al.* 2014) and it is associated with the resistance to thermal degradation (Haykiri-Acma *et al.* 2010). Lignin is a complex polymer synthesized mainly from three monomers: p-hydroxyphenyl, guaiacyl, and syringyl, which differ in the number of methoxyl groups (Wang *et al.* 2017), and this important component of cell wall are significantly influenced by age of lignocellulosic material (Healey *et al.* 2016). A minimum lignin content of 28% is required for cost-effective charcoal production (Pereira *et al.* 2013).

Wood extractives are molecules that are extracted from wood and consist of waxes, fatty acids, resin acids, and terpenes. Extractives with resistant chemical bonds release high amounts of energy when broken (Fengel and Wegener 1989). The remaining fibrous residue after the extractives, lignin, and ash-forming elements have been removed from the biomass is called holocellulose. Species with low percentages of holocellulose and high contents of lignin and extractives should be selected for charcoal as this increase resistance to thermal degradation (Fialho *et al.* 2019, Pereira *et al.* 2013).

Charcoal quality can be assessed by proximate analysis, gravimetric yields, and apparent relative density. Proximate analysis determines the composition of charcoal after it is burned as moisture, volatile matter, fixed carbon, and ash. Fixed carbon is the portion of charcoal that remains as residue after removing volatile matter, moisture, and ash. For blast furnace operation, fixed carbon content greater than 75% is preferred (Bruzual 2015). Ash is the inorganic residue that remains after combustion; for steel use charcoal should have a maximum of 1,5% ash (Rousset *et al.* 2011). Ash may also affect burning and make gasification difficult due to interactions between the inorganic fraction and the combustible matter (Lin *et al.* 1994).

The purpose of this research was to evaluate seven fast-growing hybrid clones of *Corymbia* for charcoal production and to select the best clones for charcoal quality.

MATERIAL AND METHODS

Plant material and growth conditions

Three clones of *C. citriodora* x *C. torelliana* (Cc x Ct) and four clones of *C. torelliana* x *C. citriodora* (Ct x Cc) were used in this research (Table 1). The trees, 45 months old, came from a commercial plantation belonging to Aperam Bionergia, and were located at Itamarandiba, Minas Gerais, Brazil (17,86°S latitude and 42,86°W longitude). The climate is subtropical humid (Cwa), according to the Köppen classification (Peel *et al.* 2007), with an average annual temperature of 20,1 °C, average annual humidity of 78%, and average annual rainfall of 1.076 mm. The experiment was set up in a completely randomized design with seven clones and five biological replications per clone. Trees were spaced in 3 x 3 m.

Discs of approximately 2,5 cm thick were collected longitudinally in the position of 0%, 2%, 10%, 30%, 50%, 70%, and 100% of the commercial height of each tree (Downes *et al.* 1997, Trugilho 2009). The commercial height is the height at which the tree circumference is 9,4 cm measured from the 0% position which refers to the tree base. Wood volume per tree was calculated using the Smalian method. After wood volume analysis, the discs were fragmented into four wedges. Two wedges located on opposite sides of the discs were used for wood basic density analysis. The other two wedges were used for further analysis. The wood was evaluated for basic density, dry matter, high heat value, elemental chemical composition, extractive content, and energy density. The charcoal produced from each clone sample was evaluated for proximate composition, gravimetric yield, apparent relative density, and thermogravimetric analysis.

Table 1: Characteristics of the seven hybrid clones of *Corymbia*.

Clones	Crossing	Mean diameter* (cm)	Commercial height (m)	Volume without bark (m³)
Cc x Ct-1	*C. citriodora x C. torelliana*	$10,48^{(1,18)}$	$10,85^{(0,60)}$	$0,03900^{(0,0090)}$
Cc x Ct-2	*C. citriodora x C. torelliana*	$12,15^{(1,88)}$	$11,96^{(0,98)}$	$0,0530^{(0,0144)}$
Cc x Ct-3	*C. citriodora x C. torelliana*	$14,83^{(2,12)}$	$15,08^{(0,73)}$	$0,0927^{(0,0223)}$
Ct x Cc-4	*C. torelliana x C. citriodora*	$12,71^{(1,00)}$	$11,07^{(0,43)}$	$0,0572^{(0,0066)}$
Ct x Cc-5	*C. torelliana x C. citriodora*	$11,19^{(1,06)}$	$10,85^{(0,85)}$	$0,0469^{(0,0099)}$
Ct x Cc-6	*C. torelliana x C. citriodora*	$11.80^{(1,95)}$	$12,56^{(0,27)}$	$0,0654^{(0,0108)}$
Ct x Cc-7	*C. torelliana x C. citriodora*	$12,69^{(1,22)}$	$12,76^{(0,85)}$	$0,0632^{(0,0133)}$

* The mean diameter, from five trees per clone, refers to the diameter at breast height which is 1,30 m above ground level.

Wood property evaluations

Wood basic density (WBD) was determined using the standard ABNT NBR 11941 (2003). The dry matter content was obtained by Equation 1.

$$DM = Vws\,x WBD \qquad (1)$$

Where, DM: dry matter; Vws: wood volume without bark; WBD: wood basic density.

The ultimate analysis (quantification of C, H, N, O and S) and high heating value of the wood (HHVw) were performed in wedges from all disc's positions sampled.

The ultimate analysis was determined from material that was oven-dried in a universal analyzer (Elementar® Vario Micro Cube). Two milligrams of material were passed through 200-mesh sieve and were retained in the 270-mesh sieve was used. The ratios O/C and H/C were calculated according to Elaieb et al. (2018) and used to create a van Krevelen diagram (van Krevelen 1993, Ronsse *et al.* 2015).

The HHVw was determined using an IKA C200 digital calorimeter, according to ASTM E711-87 standard (ASTM 2004) and the energy density (ED) was obtained according to Equation 2.

$$ED = BD \times HHVw \qquad (2)$$

Where, ED: energy density ($Gcal.m^{-3}$); WBD: wood basic density ($kg.\ m^{-3}$); HHVw: high heating value of wood ($kcal.kg^{-1}$).

The total extractive content was determined with the standard TAPPI 204 om-88 (TAPPI 2001), replacing ethanol/benzene with ethanol/toluene. The insoluble lignin content was determined by the modified Klason method, according to the procedure recommended by Gomide and Demuner (1986). The soluble lignin content was obtained according to the procedure proposed by Goldschmid (1971). The total lignin content consists of both soluble and insoluble lignin. The percentage of ash in the wood was determined according to standard NBR 13999 (ABNT 2017). The holocellulose content was obtained by the sum of extractive, ash, and total lignin contents subtracted from 100.

Charcoal properties evaluation

Carbonization was performed using an electric furnace connected to a condenser cooled by water and connected to a collection vial for condensable gases. The samples were previously oven dried at 105±3 °C and placed in a metal container with nominal dimensions of 30 by 12 cm. The total carbonization time was 4 hours with a heating rate of 1,67 ºC min^{-1}. The carbonization started at a temperature of 100 °C, up to a maximum temperature of 450 °C, with a residence time of 30 minutes. After carbonization, the gravimetric yields (GYC), pyroligneous liquid (GYPL), and non-condensable gases (GYNCG) were all determined in relation to wood dry matter. Charcoal apparent relative density (ARD) was determined by immersion in water according to the hydrostatic method.

The high heating value of charcoal (HHVc) was obtained as described for HHVw. Proximate analysis was used to determine the contents of volatile materials (VM), ash (ASH), and fixed carbon (FC), according to the procedure established in standard ASTM D1762-84 (2007). The energy efficiency of the carbonization was calculated using Equation 3.

$$EE = \frac{HHVc * GYC}{HHVw} \qquad (3)$$

Where, EE: energy efficiency (%); HHVc: high heating value of charcoal ($kcal.kg^{-1}$); GCY: gravimetric charcoal yield (%); HHVw: high heating value of wood ($kcal.kg^{-1}$).

Thermogravimetric analysis (TG/DTG) was performed using a nitrogen flow rate of 50 mL min^{-1} using the automatic thermal analyzer DTG-60H (Shimadzu). Mean values were calculated by the equipment software TA60 Version 2.20. Samples of approximately 4 mg were subject to a gradient temperature, ranging from ambient temperature (25±5 °C) to 600 ºC, with a heating rate of 10 °C min^{-1}.

Statistical analysis

Multiple mean comparisons were performed using Scott-Knott test at $\alpha = 0,05$ for all wood and charcoal analyses. The analyses were performed using R Statistical software version 3.3.3 (R CORE TEAM 2016). Pearson’s correlation (Pereira *et al.* 2013, Andrade *et al.* 2018) and linear regression analyses at $\alpha = 0,05$ were conducted to test for correlation and relationships among parameters evaluated.

RESULTS AND DISCUSSION

Wood evaluations

Wood basic density (WBD) was evaluated in all seven clones. All clones had the desired amount of WBD carbonization which is greater than 500 $kg.m^{-3}$ (Santos *et al.* 2011). However, clone Ct × Cc-5 had the highest WBD which could be more beneficial for charcoal production (Table 2). WBD is one of the most important selection parameters for quality charcoal production because it is associated with better mechanical resistance (Chrzazvez *et al.* 2014, Moutinho *et al.* 2016). A positive correlation was observed between WBD and charcoal density (Brito and Barrichelo 1980). Denser wood results in more energetic charcoal.

The DM has been shown to be positively correlated with WBD (Zanuncio *et al.* 2015). However, for the clones evaluated, the DM was similar for all but one clone: Cc × Ct-3, which had the highest DM. The HHV is affected by chemical composition and wood moisture (Ashton and Cassidy 2007) and it reflects the amount of energy released when fuel is consumed. Highest HHV was observed in clones Cc × Ct-2, Cc × Ct-3, Ct × Cc-4, and Ct × Cc-6 (Table 2). These clones were only 3 years and 9 months old and had HHV ranging from 4577 to 4670 $kcal.kg^{-1}$. Seven-year-old trees from genus *Corymbia* had HHV ranging from 4570 to 4663 kcal.

kg^{-1} (Zanuncio *et al.* 2014a, Zanuncio *et al.* 2014b). These results highlight the potential of these clones to be used for charcoal production, especially since they have high HHV at almost half age of others *Corymbia* trees. The ED was highest for clone Ct × Cc-5 and lowest for clone Cc × Ct-2, and ED was positively correlated with WBD with correlation coefficient of 0,99 (p-value <0,01; R^2 = 0,98; y = 0,0044x + 0,1076; Figure 1). The two most important parameters that reflect productivity and wood quality are WBD and HHV (Protásio *et al.* 2017) and may be used for selection of clones for charcoal production.

Table 2: Mean values of WBD, DM, HHV and ED of the seven clones.

Clones	WBD (kg.m^{-3})	DM (kg)	HHVw (kcal.kg^{-1})	ED (Gcal.m^{-3})
Cc × Ct-1	545 $^{(9)}$ c	21,26 $^{(5,13)}$ b	4577 $^{(21)}$ b	2,49 $^{(0,03)}$ d
Cc × Ct-2	506 $^{(5)}$ d	26,84 $^{(7,30)}$ b	4670 $^{(57)}$ a	2,36 $^{(0,08)}$ e
Cc × Ct-3	597 $^{(15)}$ b	55,34 $^{(13,86)}$ a	4623 $^{(91)}$ a	2,76 $^{(0,18)}$ c
Ct × Cc-4	545 $^{(11)}$ c	31,15 $^{(3,96)}$ b	4659 $^{(41)}$ a	2,54 $^{(0,09)}$ d
Ct × Cc-5	641 $^{(14)}$ a	30,10 $^{(6,05)}$ b	4584 $^{(29)}$ b	2,94 $^{(0,18)}$ a
Ct × Cc-6	586 $^{(11)}$ b	38,35 $^{(6,68)}$ b	4617 $^{(29)}$ a	2,70 $^{(0,11)}$ c
Ct × Cc-7	545 $^{(7)}$ c	34,44 $^{(7,62)}$ b	4550 $^{(36)}$ b	2,48 $^{(0,14)}$ d
Mean Cc × Ct	549	34,48	4623	2556
Mean Ct × Cc	579	33,51	4603	2702
Overall mean	566	33,96	4611	2640
CVe (%)	7,90	36,77	1,31	8,40

Mean values followed by the same letter do not differ from each other at 5% probability by the Scott-Knott test. Means were calculated from the five biological replications of each clone. Overall mean was calculated from all clones within each particular hybrid (Cc x Ct or Ct x Cc). CVe: experimental coefficient of variation. Cc × Ct = *C. citriodora* × *C. torelliana*; Ct × Cc = *C. torelliana* × *C. citriodora*. WBD = wood basic density; DM = dry matter; HHVw = high heating value of wood; and ED = energy density.

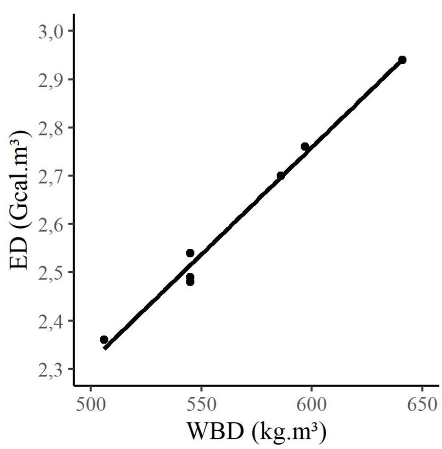

Figure 1: Positive correlation between WBD and ED.

Elemental and structural chemical composition of wood are important for charcoal production because they are the main chemical fuels (Basu 2010). Clones did not differ in elemental chemical composition nor lignin content but differed in EXT, HOLO, and ash content (Table 3). The lignin content recommended for charcoal production should be at least 28% and the clones evaluated had on average a lower content (Pereira *et al.* 2013). Clone Cc x Ct-1 had the highest amount of extractives and Cc x Ct-2 had the lowest. The composition of extractives may be beneficial and has previously been positively correlated to HHV of charcoal and FC (Fengel and Wegner 1989, Moya and Tenorio 2013). However, for the clones evaluated, no correlation was observed since the clones did not differ in HHVc and FC (Table 6).

Holocellulose degradation results in increased production of non-condensable and condensable gases during charcoal production (Pereira *et al.* 2012). Therefore, low holocellulose content is desirable. Clone Cc x Ct-1 had the lowest holocellulose content while clone Cc × Ct-2 had the highest holocellulose content (60,16 and 68,99% respectively; Table 3).

Ash content is not desirable since it is not degraded during the carbonization process. All of the clones evaluated had the desirable percentage of ash in wood (less than 1%) (Raad and Melo 2014). Clone Cc × Ct-3 had the lowest content and clone Cc × Ct-1 the highest (0,29 and 0,97% respectively; Table 3).

Table 3: Mean values of elemental chemical and structural chemical composition of wood.

Clones	Elemental chemical composition (%)			
	C	H	N	O
Cc × Ct-1	45,66 (2,98) a	5,63 (0,41) a	0,76 (0,04) a	47,94 (3,26) a
Cc × Ct-2	43,59 (1,77) a	5,48 (0,28) a	0,81 (0,03) a	50,12 (2,11) a
Cc × Ct-3	44,33 (2,19) a	5,53 (0,25) a	0,77 (0,02) a	49,37 (2,43) a
Ct × Cc-4	45,11 (1,99) a	5,57 (0,26) a	0,81 (0,02) a	48,51 (2,19) a
Ct × Cc-5	45,26 (0,56) a	5,60 (0,06) a	0,78 (0,09) a	48,37 (0,64) a
Ct × Cc-6	45,44 (0,71) a	5,61 (0,11) a	0,75 (0,03) a	48,20 (0,75) a
Ct × Cc-7	45,05 (0,71) a	5,56 (0,11) a	0,85 (0,12) a	48,54 (0,72) a
Mean Cc × Ct	44,53	5,55	0,78	49,14
Mean Ct × Cc	45,22	5,59	0,80	48,41
Overall mean	44,92	5,57	0,79	48,72
CVe (%)	4,21	4,55	8,31	4,40
Clones	Structural chemical composition (%)			
	EXT	LIG	HOLO	Ash
Cc × Ct-1	12,70 (2,80) a	26,16 (1,41) a	60,16 (1,98) c	0,97 (0,15) a
Cc × Ct-2	4,46 (0,45) d	26,00 (1,04) a	68,99 (1,24) a	0,55 (0,17) c
Cc × Ct-3	6,72 (0,90) c	25,90 (1,78) a	67,09 (2,34) b	0,29 (0,07) d
Ct × Cc-4	10,35 (0,56) b	26,24 (3,02) a	62,57 (2,81) b	0,84 (0,14) b
Ct × Cc-5	9,46 (1,36) b	25,71 (1,19) a	64,05 (2,44) b	0,78 (0,08) b
Ct × Cc-6	8,69 (0,88) b	26,94 (1,25) a	63,60 (1,28) b	0,77 (0,10) b
Ct × Cc-7	9,15 (0,28) b	27,31 (1,19) a	63,02 (1,19) b	0,52 (0,11) c
Mean Cc × Ct	7,96	26,02	65,41	0,60
Mean Ct × Cc	9,41	26,55	63,31	0,73
Overall mean	8,79	26,32	64,21	0,67
CVe (%)	14,79	6,39	3,11	18,08

Mean values followed by the same letter do not differ by the Scott-Knott test, at 5% probability. Overall mean: average from all of the clones within this particular cross. CVe: experimental coefficient of variation. Cc × Ct = *C. citriodora* × *C. torelliana*; Ct × Cc = *C. torelliana* × *C. citriodora;* numbers refer to the clone number; C = carbon content; H = hydrogen content; N = nitrogen content; O = oxygen; EXT = total extractive content; LIG = total lignin content; HOLO = Total holocellulose content; Ash = Ash content.

The oxidation elements C, H, and O influence the conversion of in natura biomass to biofuel and contribute to burning performance (Ronsse *et al.* 2015). These elements contribute most to the calorific value of fuel (Huang *et al.* 2009). Higher H/C ratios result in higher HHVw, and higher O and ash content results in lower HHV (Ahmad and Subawi, 2013). Clone Cc × Ct-2 had the highest H/C content and lowest O/C content (Figure 2). Clone Cc × Ct-2 had the highest H/C content and lowest O/C content combined (Figure 2) with a low ash content (Table 3). Clone Cc × Ct-3 also had high H/C content and the lowest ash content. However, no correlation was found between H/C content and HHVw, and O/C content and HHVw. These characteristics are important for selection of material with great potential for bioenergy.

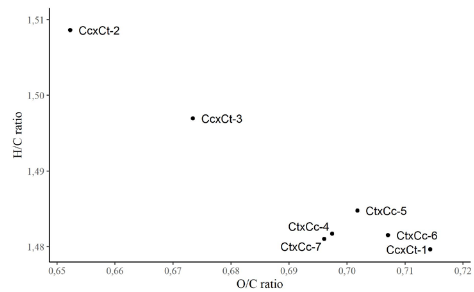

Figure 2: Van Krevelen diagram of seven selected *Corymbia* hybrids wood.

Thermogravimetric analysis indicates thermal stability by monitoring the weight change that occurs as a sample is heated. Through thermogravimetry/derivative thermogravimetry (TG/DTG) the present study shows that all clones had similar mass loss in the temperature from 40 °C to 400 °C (Figure 3) and TG/DTG displays four steps. The first step occurred between 40 – 100 °C and clones lost a mean of 5,81% of mass; the second step occurred between 100 °C to 250 °C and clones lost a mean mass of 4,52%; the third step represents the biggest average mass loss of 57,67% in a temperature range of 250 – 380 °C; the forth step occurred between 380 – 600 °C and the average mass loss was 11,75% (Table 4).

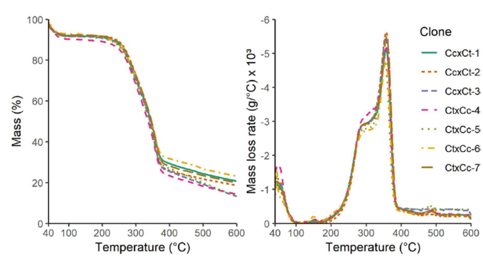

Figure 3: Thermogravimetry/derivative thermogravimetry (TG/DTG) curves from *Corymbia* hybrid clones wood samples under an inert atmosphere (pyrolysis conditions).

The greatest mass losses occurred in the range of 250 to 380 °C (Table 4) followed by the range of 380 to 600 °C. Thermal decomposition of holocellulose occurs between 220 and 400 °C (Yang *et al.* 2007). The TG/DTG curve shows that the HOLO degradation may occur mainly during the third step and the mass loss was approximately 60%, which was proportional to the HOLO content in the wood (64% of holocellulose) (Figure 3, Table 3). Clone Ct x Cc-6 had the highest percentage of residual mass, which corroborates with its higher content of EXT, ash, and a lower percentage of HOLO. Clones with higher residual masses are expected to have higher charcoal yields due to their higher thermal stability.

Table 4: Mass loss of *Corymbia* hybrid clones wood in function of temperature and percentage of residual mass obtained from the TG/DTG measurements.

Clones	Temperature ranges (°C)				Residual mass (%)
	40-100	100-250	250-380	380-600	
Cc x Ct-1	4,98	4,54	55,88	10,73	20,71
Cc x Ct-2	6,57	2,94	60,22	9,79	20,47
Cc x Ct-3	5,14	4,44	59,47	14,25	16,69
Ct x Cc-4	6,16	5,14	59,47	11,27	17,95
Ct x Cc-5	5,20	5,20	57,43	15,29	16,88
Ct x Cc-6	6,59	5,43	53,45	10,32	24,20
Ct x Cc-7	6,00	3,94	57,75	10,57	21,73

Charcoal evaluations

Gravimetric carbonization yields, gravimetric pyroligneous liquid yield, and gravimetric non-condensable gas yield were evaluated; however, no differences were observed among clones (Table 5). Apparent relative density (ARD) means varied among charcoal from different clones (Table 5). Clone Ct × Cc-5 had the highest mean and clone Cc × Ct-2 the lowest.BD and ARD were positively correlated, with a correlation coefficient of 0,96 (p-value <0,05; R^2 = 0,92; y = 0,9503x - 115,09; Figure 4). Although WBD cannot be used to predict charcoal yield directly, it can be a good parameter to consider. Positive correlation between WBD and ARD was previously reported in *Eucalyptus* spp. (Pereira *et al.* 2012, Andrade *et al.* 2018). ARD of charcoal in the range of 250 to 280 kg.m^{-3} provides better reduction performance in the blast furnace, savings in charcoal consumption, more FC which is transported and discharged at the steel mill. So, there is greater financial return when compared with the performance of lower density charcoal (Isbaex 2018).

Table 5: Mean values of apparent density of charcoal and gravimetric yields of carbonization.

Clones	ARD (kg.m^{-3})	GCY (%)	GYP (%)	GNCY (%)
Cc × Ct-1	426 (19) b	35,85 (0,70) a	42,29 (5,42) a	21,86 (5,00) a
Cc × Ct-2	358 (15) d	33,87 (0,67) a	46,44 (2,67) a	19,68 (2,01) a
Cc × Ct-3	443 (7) b	36,26 (2,76) a	43,66 (3,97) a	20,07 (3,72) a
Ct × Cc-4	406 (19) c	34,99 (0,40) a	43,14 (2,50) a	21,88 (2,13) a
Ct × Cc-5	501 (18) a	34,63 (0,60) a	44,68 (3,45) a	20,70 (3,28) a
Ct × Cc-6	431 (16) b	35,63 (2,43) a	42,02 (4,46) a	22,35 (3,14) a
Ct × Cc-7	397 (17) c	34,31 (0,51) a	46,12 (2,90) a	19,57 (2,49) a
Mean Cc × Ct	409	35,33	44,13	20,54
Mean Ct × Cc	434	34,89	43,99	21,13
Overall mean	423	35,08	44,05	20,87
CVe (%)	3,82	4,21	8,52	15,60

Mean values followed by the same letter do not differ from each other at 5% probability by the Scott-Knott test. CVe: Experimental Coefficient of Variation. Cc × Ct = *C. citriodora* × *C. torelliana*; Ct × Cc = *C. torelliana* × *C. citriodora*. ARD = apparent relative density; GCY = gravimetric carbonization yields; GYP = gravimetric yield of pyroligneous liquid and GNCY = gravimetric yield of non-condensable gases.

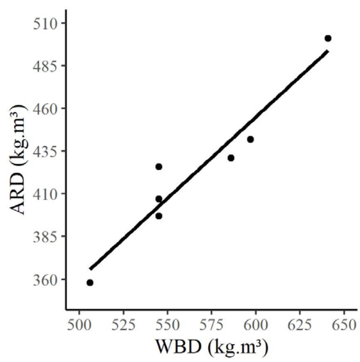

Figure 4: Positive correlation between WBD and ARD.

All clones had equal HHVc, VM, FC, and EE but differed in ash content (Table 6). No correlation was found between WBD and HHVc or EE which means that WBD is not a good parameter for clone selection in this study for charcoal quality. The HHVc is highly dependent on FC and VM (Trugilho and Silva 2001, Vale *et al.* 2001). Since these contents were equal among clones the HHVc also did not differ among clones. The ash content was high for Cc × Ct-1, Ct × Cc-4, and Ct × Cc-6, and low for Cc × Ct-2, Cc × Ct-3, Ct × Cc-5, and Ct × Cc-7 (Table 6). Ideally the ash content should be less than 1% (Raad and Melo 2014) which was observed only for clone Cc × Ct-3.

Table 6: Mean values of HHVc, proximate composition, and EE of charcoal.

Clones	HHVc (kcal kg^{-1})	Proximate analysis (%)			EE (%)
		VM	FC	ASH	
Cc × Ct-1	7358 $^{(93)}$ a	23,29 $^{(0,65)}$ a	75,39 $^{(0,71)}$ a	1,32 $^{(0,10)}$ a	57,61 $^{(0,96)}$ a
Cc × Ct-2	7445 $^{(113)}$ a	22,54 $^{(0,83)}$ a	76,31 $^{(0,97)}$ a	1,15 $^{(0,20)}$ b	54,00 $^{(1,23)}$ a
Cc × Ct-3	7354 $^{(260)}$ a	26,57 $^{(6,23)}$ a	72,54 $^{(6,11)}$ a	0,89 $^{(0,13)}$ b	57,62 $^{(3,71)}$ a
Ct × Cc-4	7342 $^{(76)}$ a	23,20 $^{(0,66)}$ a	75,39 $^{(0,84)}$ a	1,41 $^{(0,32)}$ a	55,13 $^{(0,51)}$ a
Ct × Cc-5	7388 $^{(28)}$ a	23,65 $^{(0,76)}$ a	75,33 $^{(0,68)}$ a	1,02 $^{(0,09)}$ b	55,80 $^{(0,91)}$ a
Ct × Cc-6	7308 $^{(107)}$ a	22,78 $^{(0,15)}$ a	75,76 $^{(0,41)}$ a	1,46 $^{(0,33)}$ a	56,40 $^{(4,05)}$ a
Ct × Cc-7	7432 $^{(84)}$ a	22,31 $^{(0,43)}$ a	76,59 $^{(0,51)}$ a	1,10 $^{(0,13)}$ b	56,04 $^{(0,81)}$ a
Mean Cc × Ct	7386	24,13	74,75	1,12	56,41
Mean Ct × Cc	7368	22,99	75,77	1,15	55,84
Overall mean	7375	23,48	75,33	1,19	56,09
CVe (%)	1,73	10,32	3,19	17,56	3,95

Mean values followed by the same letter do not differ by the Scott-Knott test, at 5% probability. CVe: experimental coefficient of variation. Cc × Ct = *C. citriodora* × *C. torelliana*; Ct × Cc = *C. torelliana* × *C. citriodora*. HHVc = High Heating Value of Charcoal; VM = Volatile Materials; FC = Fixed Carbon; EE = Energy Efficiency.

CONCLUSIONS

All clones tested have potential use for charcoal production due to good quality and equal results for the most important parameters evaluated for charcoal. Selecting clones Cc × Ct-2, Cc x Ct-3, Ct × Cc-5, and Ct × Cc-7 may be desirable due to their low ash content. Positive correlation was found between wood parameters WBD and ED, and wood versus charcoal parameters, WBD and ARD. However, there were no correlations between wood and charcoal quality parameters that could be used to select a clone that could reflect the charcoal quality since the quality of charcoal from different clones was very similar. Using hybrid clones of *Corymbia* for charcoal production may be a good alternative due to their fast growth and similar qualities of wood and charcoal to other species that have already been used.

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