Resistance of *in natura* and Torrefied Eucalyptus Wood to *Cryptotermes brevis* (Isoptera)

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The shorter natural durability and low energy density of eucalyptus wood hampers its use in generating energy. Torrefaction or pre-carbonization, which is treatment in low oxygen with temperatures between 200 °C and 300 °C, accumulates carbon and lignin, decreases the hygroscopicity, increases the energy efficiency, and reduces the attractiveness of wood to xylophagous organisms, such as termites. The objective of this study was to evaluate the resistance of fresh and torrefied *Eucalyptus urophylla* (20 min at temperatures of 180 °C, 220 °C, and 260 °C) to dry wood termites (*Cryptotermes brevis*), following IPT standards. The torrefaction process increased the resistance to dry wood termite attack after 45 d of exposure, with mass losses five times greater in the *in natura* wood compared with the wood torrefied at 260 °C. The larger visual damage to the *in natura* chips confirmed its lower resistance to dry wood termites. Torrefaction at 260 °C increased the resistance to dry wood termites and was more efficient with a lower mass loss and wear, and caused a greater mortality of dry wood termites.

Keywords: Biomass; Heat treatment; Termites

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INTRODUCTION

Termites are one of the most successful insect groups and they feed on dead plant material and cellulose, usually in the form of wood, litter, soil, and animal manure (Guerreiro *et al*. 2014; Cruz *et al*. 2015). The dry wood termite *Cryptotermes brevis* (Isoptera, Kalotermitidae) damages lignocellulosic objects, such as books, furniture, firewood, and wood structures with a moisture content lower than 30%. This insect does not need contact with soil and may compromise the physical and mechanical properties of *Eucalyptus* sp. wood (Peralta *et al*. 2004; Arango *et al*. 2006; Knapic *et al*. 2018).

Cryptotermes brevis is the most common wood termite species and one of the most researched because it is easily disseminated with small, almost imperceptible colonies that can be transported in furniture and wood pieces (Gonçalves and Oliveira 2006; Maistrello 2018). Dry wood termites prefer woods with sapwood, which is more nutritious. Heartwood normally has a greater natural resistance because of its extractives (Da Silva *et al*. 2007).

Wood that is used for power generation is chipped, usually in the field or at a factory. However, due to the large water content in the freshly cut wood, it is necessary to subject this material to a drying period of 90 days or until it reaches the equilibrium moisture content (EMC). Termites can colonized the wood during this time, which modifies its properties and reduces its energy potential.

Undesirable wood characteristics that may limit its potential for energy production, as well as termite damage, are of concern to the forestry industries in the energy field. Torrefaction increases the carbon and lignin relative proportions in the wood, which reduces the damage by termites (Da Silva *et al*. 2018; He *et al.* 2018; Wang *et al*. 2018). This process consists in subjecting the wood to high temperatures in an oxygen-poor atmosphere to avoid its combustion and to minimize environmental impacts (Van der Stelt *et al*. 2011). This treatment alters the chemical composition of the material, increasing the lignin contents and energy density, while reducing the hygroscopicity and attractiveness of the material to xylophagous organisms (Shang *et al*. 2014; Wang *et al*. 2018).

The objective of this study was to evaluate the resistance of *Eucalyptus urophylla* chips, *in natura* and after torrefaction, to biological deterioration by the dry wood termite *C. brevis*.

EXPERIMENTAL

Materials

The wood chips used were from seven-years-old *Eucalyptus urophylla* trees from experimental plantings in Viçosa, Minas Gerais state, Brazil (20º 45' 14" S and 42º 52' 55" W).

The material *in natura*, and torrefied were exposed to the dry wood termite *C. brevis* according to the method IPT 1157 (1980), with some adaptations.

Methods

Material torrefaction

The wood chips were sieved and those that passed through a 31.5-mm sieve and were retained on a 16-mm sieve were used in the experiment. The selected chips were oven-dried at 103 °C ± 2 °C to a 0% dry basis moisture content and then torrefied for 20 min at the temperatures of 180 °C, 220 °C, and 260 °C.

Torrefaction was conducted with an endless screw reactor developed in the Panels and Wood Energy Laboratory (LAPEM/UFV, Viçosa, Brazil) (Da Silva *et al*. 2018). The prototype of this equipment was a semi-continuous screw reactor that reuses volatile gases in the heating system (Fig. 1). The primary structure of this reactor has three systems essential to most reactors that facilitate the dry torrefaction: (I) transport; (II) heating; and (III) cooling. The first system moves the biomass for the homogenization process, which can be classified as continuous, intermittent, or mixed. The second system produces and transfers heat to the biomass under controlled conditions for direct or indirect heating. The third system releases the torrefied biomass within the safe temperature limits.

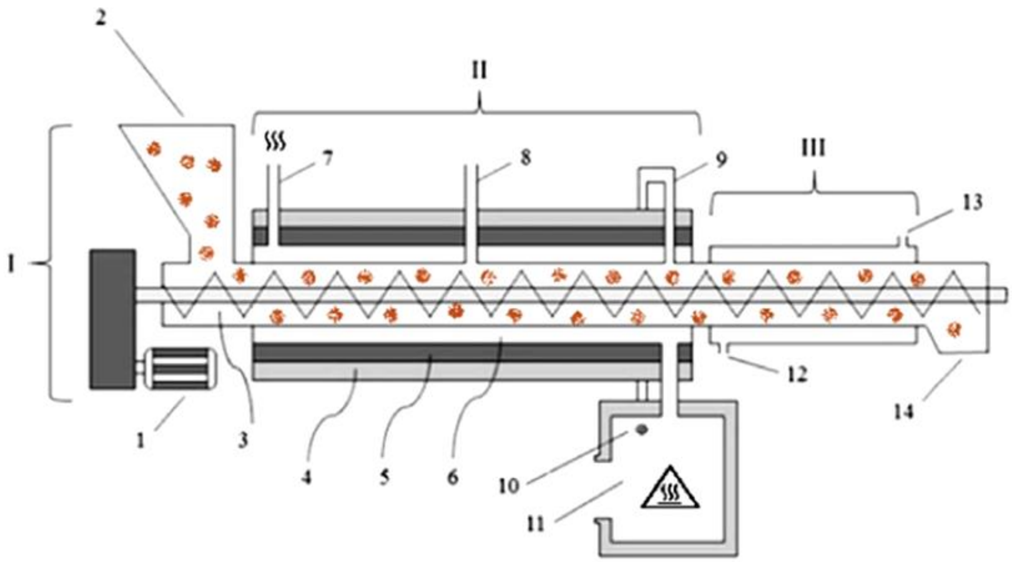

Fig. 1. Lateral view of the layout of the prototype screw reactor developed by a Brazilian university (Universidade Federal de Viçosa) for thermal treatment of lignocellulosic biomass: I- transport system; II- heating system; III- cooling system; 1- motor; 2- input biomass; 3- worm-screw; 4- insulating layer; 5- refractory layer; 6- heating gas flow; 7- heating gas output; 8- first chimney; 9- second chimney; 10- connection chimney with the burner; 11- connecting burner; 12- water supply; 13- water exit; and 14- torrefied biomass exit

Gravimetric yield, chemical characterization, and hygroscopic equilibrium moisture content

The gravimetric yield of torrefaction process was calculated by the ratio between the mass of torrefied material produced and the wood dry mass used.

The hygroscopic equilibrium moisture content of the material, calculated on a dry weight basis, was determined using chip samples that had been placed in a climatic chamber at 20 °C and 65% relative humidity until a constant mass was reached. The chip samples were ground and sieved in a 40-mesh to 60-mesh screen to determine the structural chemical composition according to TAPPI standards. The wood was prepared for chemical testing according to TAPPI T264 cm-97 (1996). The extractives, lignin, and cellulose and hemicellulose contents were determined according to TAPPI T204 om-88 (1988), TAPPI T222 om-98 (1996), and TAPPI T223 om-84 (1996), respectively. The ash content was determined according to ABNT NBR 8112 (1986).

Termite testing

Young, healthy unwinged *C. brevis* termites were collected manually from colonized school chairs.

Eucalyptus chips, torrefied and *in natura*, were oven-dried at 103 °C ± 2 °C to a constant weight, weighed, and placed in a climatic chamber for two weeks at 25 °C ± 2 °C and 65% ± 5% relative humidity for acclimatization.

Petri dishes contained 39 workers and one *C. brevis* soldier with 5 g of dry wood chips. There were six replicates for each treatment condition, according to IPT 1157 (1980).

Holes were drilled in the lids of the Petri dishes to allow gas exchange with the environment. The experiment was maintained in a laboratory (25 °C ± 2 °C and 65% ± 5%

relative humidity). The wood mass loss and termite mortality were determined after 45 days and the damage was rated from 0 to 4 by four examiners. The termite damage was based on the average rating of each examiner and corresponded to none (0), superficial damage (1), moderate damage (2), accentuated damage (3), and deep damage (4), following IPT 1157 (1980).

The food preference assay was evaluated in the six Petri dishes with 39 workers and one *C. brevis* soldier each. Two wood chips were placed per Petri dish, which totaled eight wood chips exposed simultaneously to termites, according to IPT 1157 (1980).

Statistical analysis

The equilibrium moisture content (EMC), chemical composition, and biological assay were analyzed using a completely randomized design for the four treatments (*in natura* and three torrefaction temperatures) with six replicates. The averages were grouped using the means test ($p \leq 0.05$). Statistical analyses were performed with Statistica 8.0 software (StatSoft Inc., Tulsa, OK, USA).

RESULTS AND DISCUSSION

The hygroscopic equilibrium moisture content of the torrefied and *in natura* chips ranged from 5.1% to 12.5% (Table 1). It decreased as the torrefaction temperature increased and the lowest value was found with the treatment at 260 °C. Torrefaction at 220 °C and 260 °C decreased the hygroscopic equilibrium moisture content by 56.0% and 59.3%, respectively, compared with the control (*in natura*). The wood hygroscopicity reduction was caused by the degradation of cellulose and hemicellulose, which required temperatures lower than that for lignin degradation (Waters *et al*. 2017). Consequently, the water adsorption capacity (Skaar 1972; Engelund *et al*. 2013) and hygroscopic equilibrium moisture content were lower (Li *et al*. 2016). This reduction was desirable for energy purposes because a smaller amount of energy is spent to evaporate water from the chips (Swithenbank *et al*. 2011; Whittaker and Shield 2017). The wood chemical components degradation resulted in loss of the material, reducing the gravimetric yield, with the lowest value in the material torrefied at 260 °C, with 71.7%.

Table 1. Hygroscopic Equilibrium Humidity and Chemical Composition of the *in natura* and Torrefied *Eucalyptus urophylla* Chips

Parameter	*In natura*	Torrefaction Temperature		
		180 °C	220 °C	260 °C
Gravimetric yield	-	97.73 ± 0.45 a	86.89 ± 0.39 b	71.72 ± 0.61 c
Hygroscopic Equilibrium (%)	12.49 ± 1.96 a	9.11 ± 0.61 b	5.50 ± 0.15 c	5.08 ± 0.21 c
Holocellulose (%)	69.21 ± 1.00 a	70.17 ± 0.51 a	60.48 ± 1.43 b	45.64 ± 0.75 c
Total Lignin (%)	26.87 ± 0.91 b	25.37 ± 0.72 b	32.26 ± 1.20 b	47.54 ± 0.16 a
Extracts (%)	3.63 ± 0.05 d	4.24 ± 0.10 c	7.00 ± 0.15 a	6.47 ± 0.27 b
Ashes (%)	0.29 ± 0.05 b	0.22 ± 0.03 b	0.28 ± 0.0,03 b	0.35 ± 0.02 a

Averages followed by the same letter, per line, do not differ significantly ($p > 0.05$)

Holocellulose (sum of the cellulose and hemicellulose contents) was the main chemical component in the wood degraded by the heat treatment, with a decrease from

69.2% in the control to 45.6% in the chips treated at 260 °C. Hemicellulose is less thermally stable and degrades between 220 °C and 315 °C, while cellulose degrades at higher temperatures, usually from 300 °C to 360 °C, and thus requires more energy for depolymerization and to break its monomers (Pereira *et al*. 2013). Therefore, the reduction in the holocellulose content was mainly because of hemicellulose degradation above 220 °C (Yang *et al*. 2007).

The total lignin content in the chips torrefied at 260 °C increased by 76.9% compared with the *in natura* chips. Lignin degradation begins at 160 °C, but traces of this structure can still be found after treatment at 900 °C (Yang *et al*. 2007). Lignin is the most thermally stable chemical compound in the cell wall and is therefore desired for energy purposes because it increases the calorific value of the material and the gravimetric yield from torrefaction and carbonization (Candelier *et al*. 2013; Pereira *et al*. 2013).

The total extractives content increased with the torrefaction temperature up to 220 °C. Hemicellulose degradation generates compounds that remain in the biomass as molecules with fragile connections with the fibers, which are removed by alcohol/toluene and increase its extractives content after treatments at up to 220 °C (Brito *et al*. 2008; Colin *et al*. 2017). These hemicellulose degradation compounds and the polar extractives, which degraded between 130 °C and 250 °C (Mészáros *et al*. 2007), are volatilized at higher temperatures. This explained the decrease in the extractives content at 260 °C. An increase in the extractives content after treatments at up to 220 °C has been reported for grasses (Wei *et al*. 2017) and coniferous woods (Colin *et al*. 2017).

The ash content increased with the torrefaction temperature, and was 20.7% higher in the material torrefied at 260 °C than in the *in natura* chips. This may have been because of the organic mass losses of the biomass caused by hemicellulose degradation, which reduced the volatile material percentage. The ash content is characteristic of the initial biomass and varies between species and clones (Couto *et al*. 2017; Souza *et al*. 2017). It is necessary to reduce the biomass ash content because this material reduces the energy production and increases equipment corrosion after combustion (Pereira *et al*. 2013; Zachar *et al*. 2018).

Deterioration by the dry wood termites and the mass losses were reduced for the torrefied material, where the mass losses were 59.8% lower in the wood torrefied at 180 °C compared with that in the *in natura* chips (Table 2). High temperatures chemically modified the wood, degraded and changed the wood carbohydrates, which is a food source for termites, and generated extractives with fungicide and insecticide properties (Silva *et al.* 2004; da Silva *et al*. 2007; Brocco *et al*. 2017). This reduced the material hygroscopicity (Thybring 2017) and increased the material acidity, which hindered termite development (Paes *et al*. 2007; Pereira *et al*. 2016).

The mass losses from the damage caused by *C. brevis* in the wood chips were lower than 1.7%. This may seem low, but the evaluation lasted 45 d with only 40 termites per plot. Dry wood termite colonies have 300 individuals on average, which would cause greater mass losses (Guerreiro *et al*. 2014).

Table 2. Average Mass Losses, Mortality, and Wear Grade of the *in Natura* and Torrefied *Eucalyptus* Wood Chips

Parameter	*in natura*	Torrefaction Temperature		
		180 °C	220 °C	260 °C
Mass Loss (%)	1.69 a	0.68 b	0.63 b	0.33 b
Mortality (%)	60.0 a	67.0 a	65.5 a	68.3 a
Wear Grade	2.65 a	2.25 a	2.18 a	1.89 a

Averages followed by the same letter, per line, did not differ significantly ($p > 0.05$)

Torrefaction of the material generated and accumulated extractives sufficient to minimize damage by the dry wood termites because certain substances, such as lignin and extractives, make wood more resistant to deterioration by xylophagous organisms (Knapic *et al*. 2018). Lignin and phenolic extracts produced during the torrefaction process can reduce the insect food availability, thus reducing the attack intensity and mass loss, even without causing termite death. Phenolic extracts have chelating agents that are capable of forming complexes with metals and protecting the wood and, when more concentrated, act as natural preservatives (fungicides and insecticides) (Brocoo *et al*. 2017).

The termite mortality rate in the torrefied eucalyptus chips increased by an average of 65.2%, which was higher than that reported in the literature for seven forest species (58.6%) (Gonçalves and Oliveira 2006) and heat-treated *E. grandis* wood (32.3%) (Pessoa *et al*. 2006). The increase in the insect mortality rate for the torrefied chips was because of the high increase in the lignin content during this process, presence of phenolic organic compounds from thermal degradation by torrefaction, and reduction in the holocellulose, as it was reported for *E. grandis* wood (Pessoa *et al*. 2006).

Wood damage was recorded for all of the treatments, which indicated that torrefaction did not fully protect the wood. The attack degree and mass loss decreased as the torrefaction treatment temperature increased. These results were similar to those obtained with *E. grandis* wood that was torrefied at 200 °C with near moderate wear, and was emphasized in the *in natura* wood (Pessoa *et al*. 2006).

Chemical components generated during torrefaction of the *E. urophylla* wood chips may have contributed to the lower mass loss, higher mortality, and lower wear degree by the termites. The higher mortality could have resulted from direct action on the termites or from the imbalance caused to their symbionts, because chemical substances like terpenoids, terpenes, quinones, polyphenols, and other extractives have been widely studied as repellents and/or are toxic to termites or their symbionts (Tisseverasinghe and Jayatilleke 1973; Bultman and Parrish 1979; Scheffrahn 1991; Cornelius *et al*. 1995). The quantity of microorganisms in the termite intestines may have become insufficient to digest cellulose, which influenced the eating habits of these insects and led to their death (Lepage 1986).

The weight losses caused by the dry wood termites were four times higher in the *in natura* chips compared with the chips treated at 180 °C (Table 3), which confirmed the dry wood termite preference for the *in natura* wood. This may have been associated with the lignin concentration in the torrefied material, and indicated an increased wood resistance to xylophagous termite attack.

Table 3. Mass Losses, Mortality, and Wear Score of the *in natura* and Torrefied Eucalyptus Wood Chips Subjected to Dry Wood Termites in the Food Preference Test

Parameter	*in natura*	Torrefaction Temperature		
		180 °C	220 °C	260 °C
Mass Loss (%)	5.52 a	1.30 b	0.02 b	0.04 b
Wear Score	2.33 a	0.67 b	0.00 b	0.00 b
Mortality (%)	42.00			

Means followed by the same letter, per line, do not differ significantly ($p > 0.05$)

The *in natura* wood chip wear was higher than for the thermally treated chips, with moderate damage in the *in natura* chips, superficial damage in the chips treated at 180 °C, and no damage in the chips treated at 220 °C and 260 °C. The lower feed preference for the chips torrefied at 220 °C and 260 °C was explained by the change in the water adsorption capacity. The chips became less hygroscopic as the temperature increased (Knapic *et al*. 2018). The number of water molecules between and inside of the polysaccharide molecules (cellulose and hemicelluloses) and the hydrogen bonds formed between the polysaccharide hydroxyls of the wood and water decreased (Wahl *et al*. 2004). The lower hygroscopicity made it difficult for the termites to recognize the food substrate (Weiland and Guyonnet 2003). Changes in the chemical composition of the wood may include the production of new free molecules that can act as insecticides and fungicides, as well as cause changes in the lignin cross-linking. The present results confirmed that the wood durability increased as the heat treatment temperature increased (Maistrello 2018).

The increase of the torrefaction temperature decreased the gravimetric yield as determined during the experiment. At the same time, the temperature increase also increased resistance against termites. Therefore, these two variables can contributed to reduced damage by these insects and fungi (Chaouch *et al.* 2010).

CONCLUSIONS

1. Torrefaction degraded unstable chemical components at high temperatures. Therefore, the content of lignin, extractives, and ash increased and the holocellulose content decreased.

2. Torrefied material had lower water adsorption capacity, resulting in lower equilibrium moisture content (EMC).

3. Torrefaction increased the wood chip resistance to the dry wood termites, with a greater efficiency and weight losses higher in the *in natura* chips compared with the chips treated torrefied; and the dry wood termites fed preferentially in the *in natura* wood.

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