Influence of the Hot-pressing Process on the Durability of Totora (Schoenoplectus Californicus C.A. Mey. Soják) Binderless Boards against Wooddecaying Organisms

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Abstract

Totora (Schoenoplectus californicus C.A. Mey. Soják) is a macrophyte from the Cyperaceae family that grows in the Americas. Recent studies have shown the feasibility of producing binderless boards using different tissues of totora stems. However, no data about the durability of raw totora stems or totora binderless boards have been published before. Therefore, dur-ability tests were conducted to study their durability against wood-decaying organisms. Results showed that binderless boards produced by hot-pressing process showed higher resistance against white-rot fungi and termites than the raw material. Chemical changes induced by the hot-pressing process were studied and compared with observed durability values to identify possible correlations.

Keywords: Totora; macrophyte; resistance; sustainability; biodegradation; fungi.

1. Introduction

Traditional materials are often part of sustainable productive cycles and are also important sources of economic income for several communities around the world (Brokamp et al. 2014; Fathurrahman et al. 2016; Mardorf 1985). However, many of these traditional materials are being replaced by cheaper or more convenient materials considering contemporary lifestyles (Heiser 1978; Hidalgo-Cordero and García-Navarro 2017). One of the strategies to recover the value of these traditional resources can be developing contemporary applications for these kinds of materials in accordance with current requirements.

One of these traditional materials is totora (Schoenoplectus californicus (C.A. Mey.) Soják), which is a macrophyte from the Cyperaceae family that grows in lakes and marshlands in the Americas from California to Chile, and some of the Pacific Islands (de Lange et al. 2008). Several traditional communities have long used this plant, and some of them continue to use it. The most remarkable example of the use of totora in the world are the Uros islands in Lake Titicaca. The people living on these islands have been using totora for more than 500 years to build a wide range of things such as handicrafts, huts, boats, and even the floating islands where they live.

Some studies have shown the potential benefits of totora from a sustainability point of view. In this sense it is worth mentioning totora´s fast-growth rate, which can be up to 57.99 t/ha/year of dry matter in rich substrates; that it can grow from the sea level to 4,000 m.a.s.l.; and that it can grow in fresh water or estuaries, which do not compete with agricultural soil or forest land; among other benefits (Hidalgo-Cordero and García-Navarro 2018b; Rondón, Banack, and Diaz-Huamanchumo 2003).

Durability of a material is one of the main aspects that define its applicability and use class in the construction sector. In the case of totora, there are some studies that have reported the durability of traditional totora boats and mentioned that one small raft of approximately 3 meters long, also known as "caballito de totora", used for fishing in the northern coastal regions of Peru can last approximately one month (Paredes and Hopkins 2018; Rondón, Banack, and Diaz-Huamanchumo 2003), whereas bigger balsas of around 8 meters long used in Lake Titicaca for fishing or as tourists transport can last from six months to one year (Hidalgo-Castro, Hidalgo-Cordero, and García-Navarro. 2019). Durability of some traditional totora constructive elements such as huts' roofs and weaved mats have been also studied and identified that the material is mostly affected by the exposure to moisture which leads to fungal attacks and the material's decaying (Hidalgo-Cordero 2007). However, in order to obtain more consistent data about totora durability, and to be able to compare these results to other materials' data, it is necessary to conduct the respective tests in accordance with current standards applicable to the construction sector.

In other fields of study, some authors have investigated the decomposition rate of raw totora in hydrological systems to analyze its biomass' decomposition rate. These studies have reported average half-life values between 269 days, in a study conducted at Lake Titicaca (Costantini et al. 2004), and 184 days, in a study conducted at a wastewater plant in South Carolina U.S. (Murray-Gulde et al. 2005). These half-life values are higher than those of other similar macrophytes species, which may indicate the higher resistance of totora against decaying agents compared with other macrophytes. Anatomically, totora stems have an internal aerenchyma tissue with air chambers that the plant uses for gas transportation, and an external rind that has a more compact structure where most of the structural, protective, and nutrient transportation functions occur (Corsino, Torres, and Maranho 2013).

Physical and chemical properties of the pith and rind of totora stems and their differences have been studied by Wille et al. (2016), and Hidalgo-Cordero, Fernando, and García-Navarro. (2018aa). The main differences are that fibers from the pith are around 10% longer than the ones from the rind (898 µm vs. 804 µm), that rind tissue has almost twice as much lignin content as the pith (16.42% vs. 8.9%), and that rind tissue has higher solvent extractives content than the pith (2.13% vs. 1.75%). These physical and chemical characteristics may influence the durability of these tissues against wood-decaying organisms.

The feasibility of producing binderless boards using totora tissues and their potential environ-mental benefits have been studied with promising results (Hidalgo-Cordero, García-Ortuño, and García-Navarro. 2020). Additionally, a production process described in the patent (García-Ortuño et al. 2012) for making binderless boards from different lignocellulosic materials using two hot-pressing cycles, which consists on hot pressing the material using low temperatures to achieve a first degree of self-bonding, then letting the board to cool down, and then performing another hot pressing cycle using low temperature again, has been reported to produce binderless boards with good mechanical properties using relatively low energy. As described in this patent, the second hot-pressing cycle, after letting the board to cool down can produce better mechanical properties than a single hot-pressing of the double the time (García-Ortuño et al. 2012; Hýsková et al. 2020).

Knowing that to assess the applicability of these kinds of boards in the construction sector it is important to study their durability considering the respective current standards, in this case the guidelines mentioned in EN 1995-1-1 (2016a) "Eurocode 5. Design of timber structures – Part 1–1: General Common rules and rules for buildings" (European Committee for Standardization 2016a) have been considered. In the durability section of the EN 1995-1-1 (2016a) standard, it is mentioned that timber and wood-based materials should have an adequate natural durability in accordance with EN 350 (2016b) standards or should otherwise receive a treatment to improve their durability to comply with the industry requirements (European Committee for Standardization 2016b).

In this study, the durability of raw totora stems and their tissues, namely the separated rind, and the separated pith against wood decaying organisms were tested. These data were compared with the durability of totora binderless boards made with one and two hot-pressing cycles at 150°C using the different totora tissues as described in the methodology section, to study the possible effects of these hot-pressing parameters on the durability of each tissue.

2. Experimental Methods

2.1 Materials

2.1.1 Raw totora

Raw totora was collected in July 2016 from the Paccha zone in Ecuador (2.90°S, 78.93°W). Totora stems were cut at 5cm above the water level during the flourishing stage of the plant. Stems were sun dried for 4 weeks until they turned yellowish and then were moved to a covered storage to complete their drying process at ambient temperature. Samples of the raw material were taken randomly from a stock of 20 stems. Stems were peeled off by hand in order to separate the rind from the pith part of the plant. Three kinds of raw material feedstocks were prepared, raw totora pith (TPr), raw totora rind (TRr), and raw whole totora stems (WTr).

2.1.2 Binderless boards

Totora binderless boards of 600x400x4 millimeters were produced using one and two hot-pressing cycles. The first hot-pressing cycle was of 15 minutes at 150°C with 3 MPa of pressure. Then the boards were let to cool down in vertical position. After the cooling process finished, some of the boards received a second hot-pressing cycle. The second hot-pressing cycle was of 10 minutes at 150° C with 3 MPa of pressure. Samples were taken randomly from a stock of four boards of each kind. For durability tests against fungi the samples used were of 25 x 25 x 4mm of each kind. For durability tests against termites the samples used were of 15 x 30 x 4 millimeters. The codification and production parameters of the different boards samples are shown in Table 1.

Table 1. Codification and parameters used to produce the different binderless boards.

Code	Temperature (ºC)	Pressing time (min)	Pressure (MPa)
TP150I	150	15	3
TP150II	150	15 + 10	3
TR150I	150	15	3
TR150II	150	15 + 10	3
WT150I	150	15	3
WT150II	150	15 + 10	3

TP150I. Totora pith board made with one hot-pressing cycle; TP150II. Totora pith board made with two hot-pressing cycles; TR150I. Totora rind board made with one hot-pressing cycle; TR150II. Totora rind board made with two hot-pressing cycles; WT150I. Whole totora board made with one hot-pressing cycle; WT150II. Whole totora board made with two hot-pressing cycles.

The raw tissues and the corresponding binderless boards are shown in Figure 1. Binderless boards were produced at the engineering laboratories of the Universidad Miguel Hernández de Elche, in Alicante-Spain.

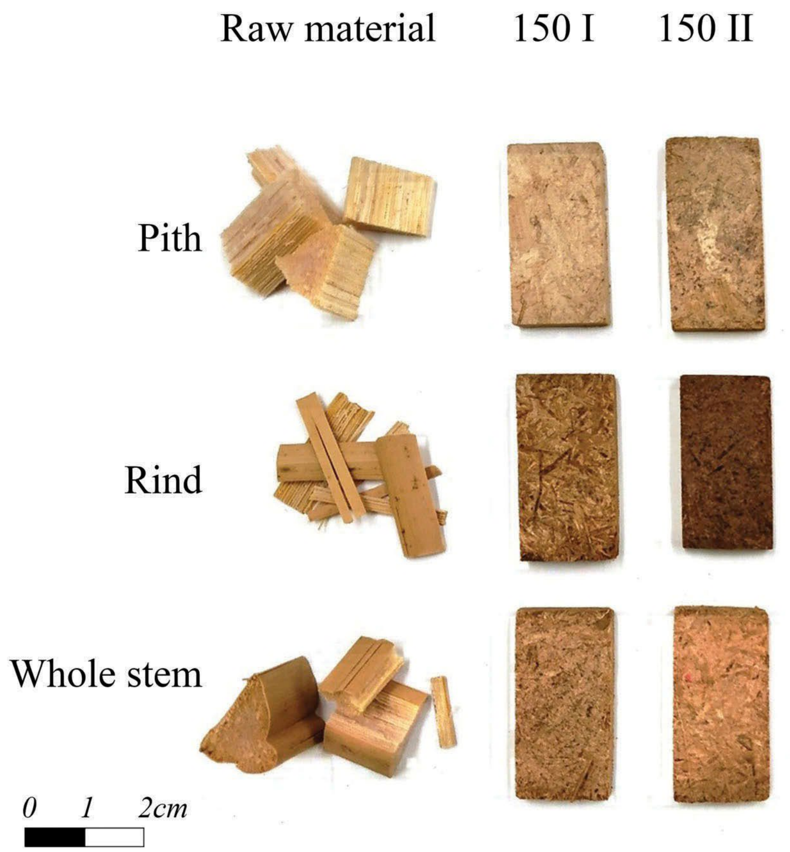

Figure 1. Totora raw tissues and binderless boards produced at 150°C with one and two hot-pressing cycles.

2.2 Durability test methodology

In order to evaluate the natural durability of raw totora feedstocks, and corresponding totora boards, the respective European Standard EN 350 (2016b) “Durability of wood and wood-based products. Natural durability of solid wood” was applied. This Standard establishes the application of CEN/TS 15083–1 (2005), to assess thedurability against fungal attack produced by basidiomycete fungi, and the applica-tion of EN 117 (2012) to assess the durability against subterranean termites. Durability tests against termites were conducted only on whole raw totora stems, not on the raw pith and raw rind separated. All binderless boards types were tested against termites. Statistical analyses were performed using the SPSS software. Alpha value for significance tests used was 0.1 due to the variability in these kinds of tests.

The wood reference species used in accordance with the standards were: Pinus sylvestris L. and Fagus sylvatica L. The test fungi used were: Postia placenta (Fries) Cooke Sensu J, Eriksson for brown rot, and Trametes versicolor (Linnaeus) Chalet for white rot. The termite species used was: Reticulitermes grassei (Clement).

2.3 Chemical analyses methodology

Chemical characteristic of raw totora stems have been studied by (Hidalgo-Cordero, Fernando, and García-Navarro. 2018aa). These values were compared with the chemical characteristics of totora binderless boards made with one and two hot-pressing cycles at 150°C to study the possible correlation between chemical changes of the material after the hot-pressing process and the observed samples' durability. Durability and chemical tests were conducted at the Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA), in Madrid-Spain.

3. Results and discussion

3.1 Results against fungi

The results after the application of the CEN/TS 15083–1 (2005) standard for the raw material and binderless boards are shown in Figure 2.

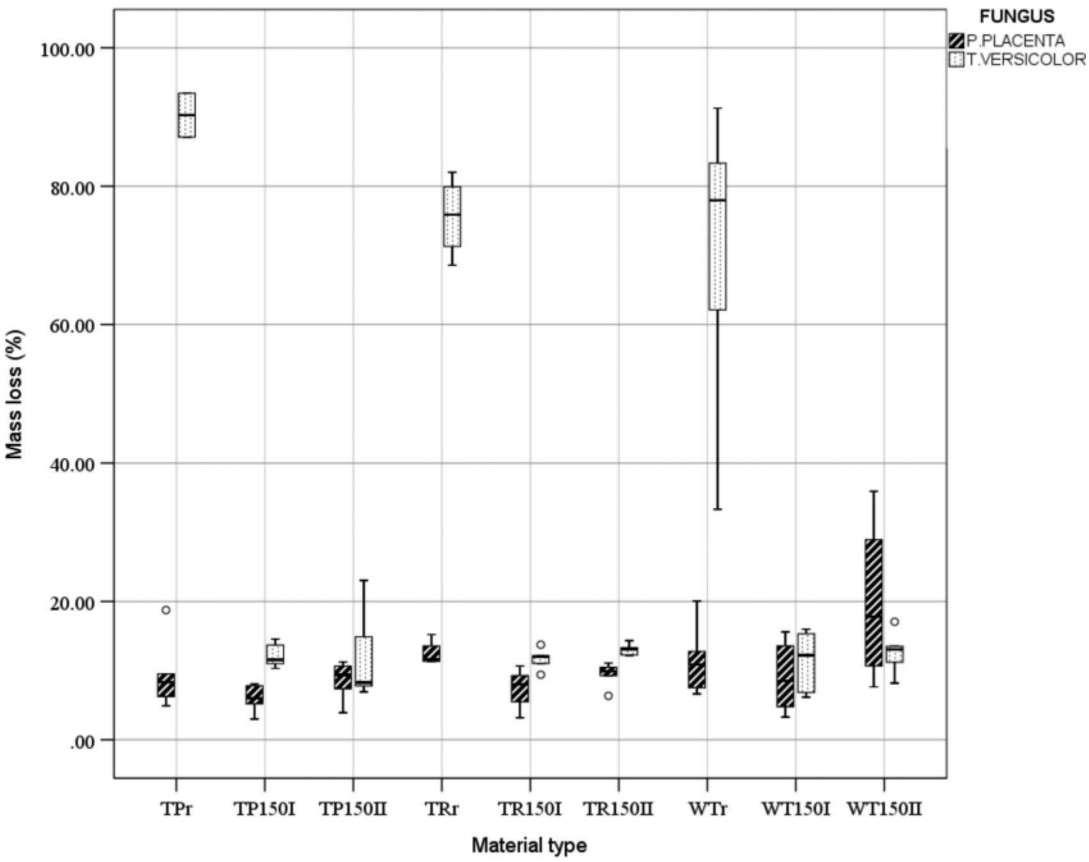

Figure 2. Boxplot of the mass reduction values of raw tissues and binderless boards against fungi species.

In general, the fungus that affected the raw material the most was T. versicolor as can be seen in Figure 3.

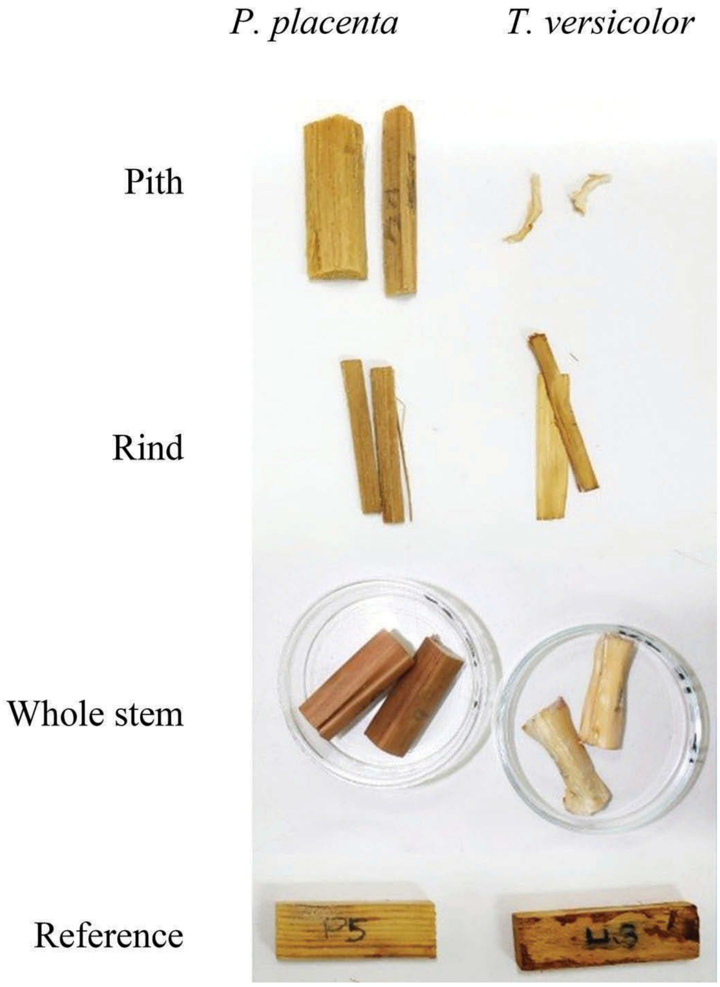

Figure 3. Raw totora pith, raw totora rind, raw whole totora stems, and wood reference samples after fungi attack.

Among the raw tissues the one that was more affected was the pith, which showed average mass reduction values of around 90%. However, the rind and whole stems showed higher resistance, which may be due to protective substances existent in the rind.

Binderless boards showed significantly higher resistance values compared with raw tissues against T. versicolor, and no significant differences were detected between binderless boards resistance against both fungi species. However, boards attacked by T. versicolor showed more visible signs of attack than the others as can be seen in Figure 4.

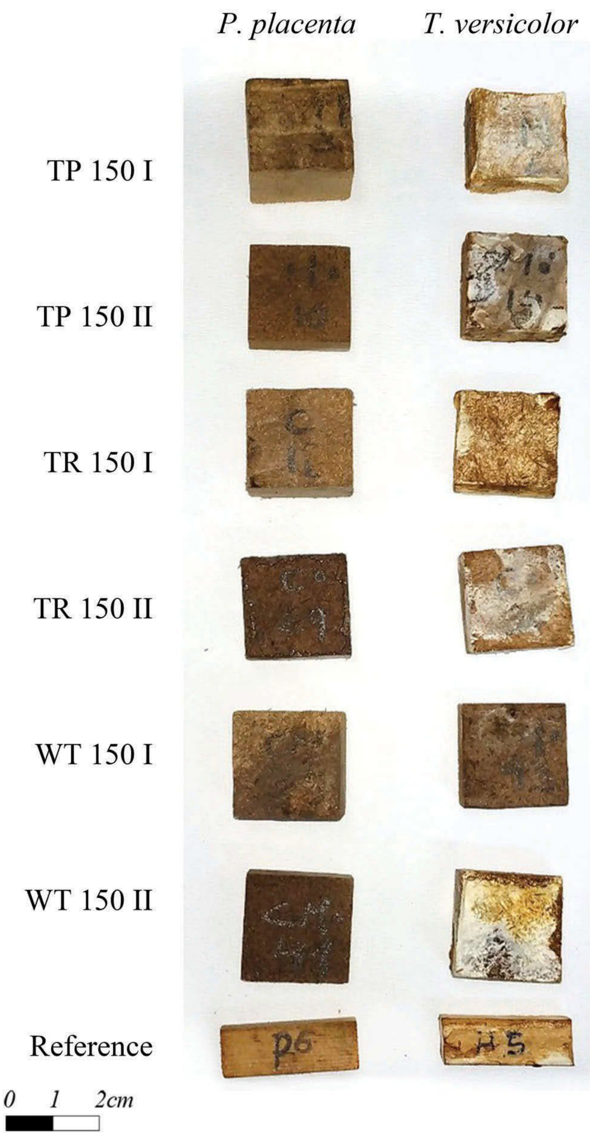

Figure 4. Binderless totora boards and wood reference samples after fungi attack.

ANOVA tests along with post hoc tests were performed to analyze the statistical differences of mass reduction values between the raw tissues and boards against the studied fungi.

Mass reduction values of raw totora tissues showed statistically higher sensitivity of all tissues against T. versicolor than against P. placenta. Comparing the sensitivity of each tissue separately, it was observed that raw pith samples showed significantly higher mass reduction values against T. versicolor than raw rind samples, whereas raw whole stem samples showed higher variability. Despite the higher lignin content of the rind and the fact that T. versicolor is supposed to attack lignified tissues, the more accessible structure of the pith tissue and the existence of protective substances such as waxes or other kinds of extractives on the rind, may have promoted higher degradation of the pith part of the plant by T. versicolor.

Comparing the mass reduction values of the raw tissues with binderless boards made with one hot-pressing cycle, significant durability improvements were detected for all binderless boards against T.

versicolor with $p < 0.1$. In the case of P. placenta, the only significant durability improve-ment was detected for binderless boards made with the rind tissue against raw rind with $p < 0.1$.

When comparing the durability of binderless boards made with one and two hot-pressing cycles, no significant differences were detected in any case. This may indicate that although the second hot-pressing cycle has been reported to improve the mechanical properties of totora binderless boards, the chemical reactions that affect the nutritive compounds occur with the first hot-pressing cycle, or that the higher durability is due to other factors such as the more compact structure of the binderless boards that makes it less accessible to wood decaying organisms.

3.2 Results against termites

In general, neither the raw whole stems nor binderless boards showed surviving working termites after the tests, although the raw material did show visible attacks that indicated that termites were feeding on it. This could be an indicator of the low nutritive value of the plant to termites that were not able to survive on it.

The results after the application of EN 117 (2012) standard for the raw material and binderless boards are shown in Figure 5.

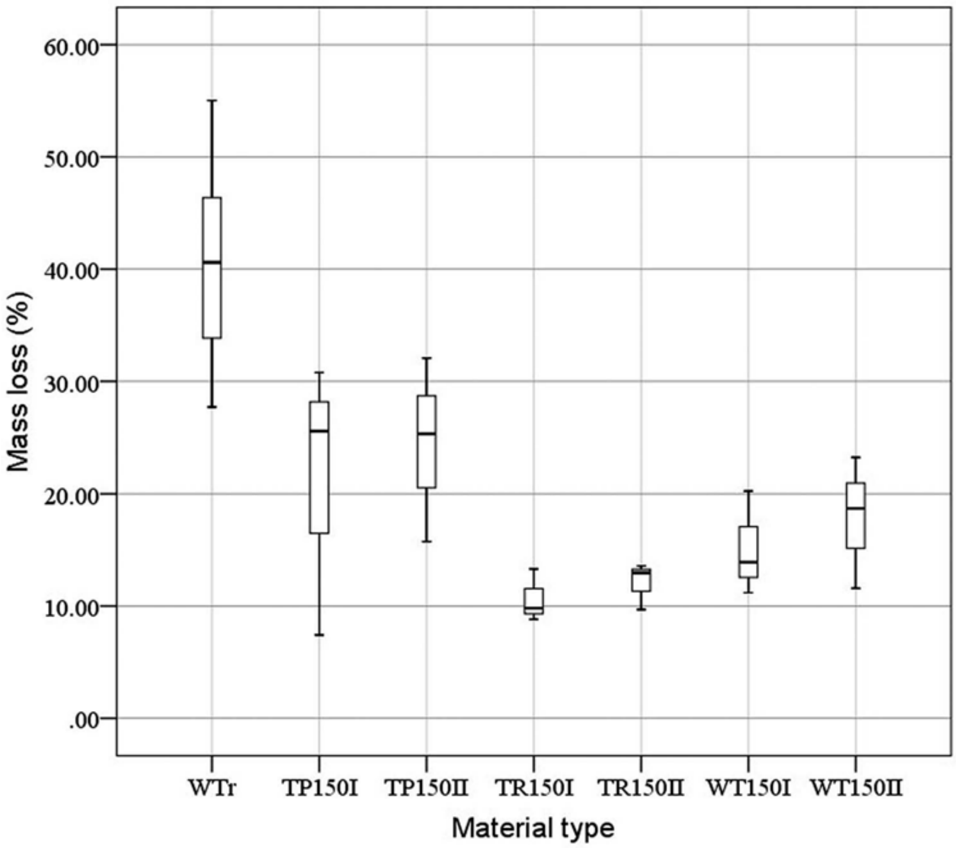

Figure 5. Boxplot of the mass reduction values of raw whole totora stems and totora binderless boards against termites.

ANOVA tests along with post hoc tests were performed to analyze the statistical differences of mass reduction values between samples in relation to type of material. Totora binderless boards made with all the feedstocks showed a significantly higher durability against termites than the raw whole stem samples with $p < 0.1$. Additionally, significant differences were observed between boards made with rind and pith, but no significant differences were detected between boards made with whole stems and boards made with pith or rind because of the higher variability of whole stem boards. Pith boards showed higher mass reduction values, while rind boards showed the lowest mass reduction values. This may indicate that in addition to the effect of hot-pressing process that increases the durability of binderless boards against termites, rind tissues contain some compounds that the plant uses as natural protection against biotic organisms (Corsino, Torres, and Maranho 2013) that inhibits the termites attack. In accordance with the durability classification, the raw totora as well as the binderless boards were classified as moderately durable against termites.

3.3 Chemical differences

The hot-pressing process for making binderless boards generated chemical changes in the material that affected their durability against wood decaying organisms. Chemical changes are shown in Table 2.

Table 2. Durability values compared to chemical differences of each feedstock after one and two hot-pressing cycles at 150°C.

Material	*P. placenta* %	*T. versicolor* %	Solvent extractives %	Hot water extractives %	Acid-insoluble lignin %	Cellobiose %	Glucans %	Xylans %	Arabinans %	Acetate %	HMF %
TPr	9.55	90.26	1.75	22.10	8.90	17.82	28.30	19.51	3.62	2.85	-
TP150I	6.02	12.12	1.73	14.32	13.96	5.37	43.48	18.46	2.39	3.12	0.37
TP150II	8.66	11.53	1.65	13.42	14.49	4.98	42.91	17.46	1.95	2.57	0.35
TRr	11.86	75.59	2.13	22.26	16.42	16.10	24.63	18.52	2.39	2.96	-
TR150I	7.45	11.72	1.46	12.77	22.08	6.30	35.60	17.39	1.71	3.58	0.42
TR150II	9.51	13.04	1.28	11.86	22.94	4.81	36.74	17.84	1.53	2.89	0.39
WTr	11.34	71.91	2.00	22.21	13.78	16.70	25.92	18.87	2.82	2.92	-
WT150I	9.04	11.46	1.61	14.77	21.34	4.80	34.70	16.24	1.51	3.13	0.39
WT150II	19.80	12.68	1.43	16.19	23.29	4.88	36.68	16.01	0.94	3.13	0.30

TPr. Raw totora pith; TP150I Totora pith board made at 150°C with one hot-pressing cycle; TP150II Totora pith board made at 150° C with two hot-pressing cycles; TPr. Raw totora rind; TR150I Totora rind board made at 150°C with one hot-pressing cycle; TR150II Totora rind board made at 150°C with two hot-pressing cycles; WTr. Raw whole totora stem; WT150I Whole totora stem board made at 150°C with one hot-pressing cycle; WT150II Whole totora stem board made at 150°C with two hot-pressing cycles.

The reduction of water extractives content, which are mainly low-molecular-weight sugars that undergo degradation and condensation reactions during the hot-pressing process leading to the breakage of hydroxyl groups, makes the material less hydrophilic leading to higher resistance against fungi attacks (Luo et al. 2014; Okuda and Sato 2004; Weiland and Guyonnet 2003)

The apparent increase of lignin content, which may be due to the reduction of other substances, and the denaturization of lignin at the studied hot-pressing parameters, may have also rendered the material less accessible to wood decaying organisms (Weiland and Guyonnet 2003).

The cellobiose content reduction indicate a further degradation of sugar chains derived from cellulose that at the same time caused the increase in glucans content (Sluiter et al. 2012). Xylans and arabinans content reduction may indicate an increase of the crystallinity of the xylose backbone (Sun, Lawther, and Banks 1996), which renders the material less accessible to wood decaying organisms after the hot-pressing process.

Additionally, the occurrence of hydroxymethyl furfural in the boards indicate the generation of by-products from hexoses induced by the heat and pressure (Sundqvist 2004) which may hinder the development of wood decaying of organisms.

Even if the second hot-pressing cycle showed further reactions of the material, and previous studies showed its positive influence on the mechanical properties of totora binderless boards compared with boards made using hot-pressing processes at higher temperatures or longer hot-pressing times, the durability values obtained after one and two hot-pressing cycles were not significantly different, which may suggest that the nutritive compounds that determine the material's durability react with the first hot-pressing cycle, and further reactions that happened with the second hot-pressing cycle did not affect the durability of the material.

4. Conclusions

Significant durability improvements were detected between all the raw materials and binderless boards against T. versicolor. Against P. placenta significant durability improvements were detected only for boards made with the rind tissue compared with the raw rind.

Durability of totora against termites was significantly better for binderless boards than the raw material. However, pith boards showed higher mass reduction against termites, which may suggest the existence of natural compounds on in the rind tissue that inhibits the termites attack.

The second hot-pressing cycle did not produce a significant variation in durability values in any case. This may indicate that although further chemical reactions were observed after the second hot-pressing cycle, which have been related to the improvements of mechanical properties of the boards, compounds that determine the wood-decaying organisms attack reacted at the first hot-pressing cycle. It can be also possible that other factors influence the durability such as the compactness of the material of the binderless boards, compared with the open structure of the raw material, especially in the case of the pith tissue. Further research is needed to study the influence of different hot-pressing parameters on durability and other boards' properties.

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