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Composite materials from totora (*Schoenoplectus californicus*. C.A. Mey, Sojak): Is it worth it?

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ABSTRACT

Totora (*Schoenoplectus californicus*. C.A. Mey, Sojak) is an annual-cycled macrophyte from the Cyperaceae family that has been used by indigenous people of the Americas for more than 500 years to produce a wide range of objects from handicrafts to boats and huts. In this study, the hot-pressing process was applied to produce boards from totora particles without added adhesives. First, the physical and mechanical properties of totora binder-free boards are described. Secondly, several factors that influence the properties of totora boards are taken into account. However, is it worth it to produce such boards? In this paper, the reasonability of potential production of these boards is considered from a complex point of view. Although totora shows several benefits such as its fast-growth rate, high dry matter productivity, and potential environmental benefits; the water uptake (92–341%), thickness swelling (75–227%) and internal bonding (18–85 kPa) of the binderless boards made with the parameters described in this study could not comply with current standards. Further research on treatments or different production parameters can lead to better properties.

1. Introduction

Increasing demand for biomass-based products and limit supply of wood have led researchers to focus on non-conventional resources such as agricultural wastes or non-wood-forest products that may help diversify the sources of raw materials applicable in the industry, which may generate sustainable and economic benefits.

Among these alternative biomass sources is totora (*Schoenoplectus californicus* (C. A. Mey) Soják), which is a sedge that grows in lakes and marshes in the Americas from California to Chile and some of the Pacific Islands (Fig. 1) [1]. This plant has been used for long time by several traditional communities, some of them continue to use it today, such as the communities nearby Lake San Pablo in Ecuador or the Uros in Lake Titicaca, who use this plant to make mats, huts, boats, and even floating islands [2]. Studies have identified the potential environmental benefits of this plant such as its fast-growth rate that can produce up to 56 t/ha/year of dry matter in rich substrates [3], its short renovation time which makes it possible to be harvested twice a year, its water cleaning capacities [4], among others. These characteristics makes it an interesting material to be studied for its applicability in the contemporary construction sector [5].

Studies about the anatomy of totora stems have described two main tissues: an internal pith made of air chambers and stellar cells known as aerenchyma, and an external rind with a more compact structure that performs different anatomical functions and has different chemical characteristics [6].

Additionally, studies of similar species have demonstrated the potential of these kinds of plants to achieve self-bonding under certain hot-pressing conditions [7–9]. The self-bonding capability can lead to the production of binder-free boards that do not contain any added adhesives. Binder-free boards may be interesting alternatives considering the increasing rigorousness of regulations on some of the conventional glues used in many of the wood-based boards available in the current market [10]. Some studies have shown the feasibility of producing binder-free boards with different tissues of totora stems; however, the mechanisms through which ligno-cellulosic materials achieve self-bonding and their relation to board properties have not been completely elucidated and vary depending on the feedstock and hot pressing parameters used in the production process [11].

Additionally, in order to define the applicability of these materials, mechanical properties are one of the key factors to analyze. Flexural characteristics in the plastic range are an important mechanical property to consider. Most research deals with the elastic range of the diagram up to the limit of proportionality, while only a small amount of research deals with deformations in the plastic range, from the limit of proportionality to the yield point where plastic deformation occurs

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Fig. 1. Totora stand in Lake San Pablo-Ecuador.

[12].

The aim of this paper is to evaluate the reasonability of potential production of totora boards from a complex point of view. Not only mechanical and physical properties of these boards are taken into account, but we are also considering totora productive potential, the price of the raw material or prediction of totora availability on the market.

2. Material and methods

For the board production, totora plant (*Schoenoplectus californicus*. C.A. Mey, Sojak) was used. Dry totora stems from Ecuador were supplied. The board production scheme is shown in the Fig. 2. The stems were disintegrated using a laboratory shredder, and three types of tissue were separated – pith, rind and whole totora stems (mixture of pith and rind). Fiber mat was manually layered and then pre-pressed using a universal testing machine. Pre-pressed fiber mat was placed into a hot press and preheated for 4 min. Two pressing temperatures were selected: 180 °C and 200 °C. Pressing time was 10 min. A description of the different parameters used for producing each board is shown in Table 1.

Table 1
Description of produced totora boards.

Code		Pressing temperature	Part of the stem	Density (kg/m^3)
TP	180	180 °C	Pith	891 (12.9)
TP	200	200 °C	Pith	1051 (3.2)
TR	180	180 °C	Rind	929 (8.9)
TR	200	200 °C	Rind	1061 (3.9)
WTS	180	180 °C	Whole totora stem	964 (5.5)
WTS	200	200 °C	Whole totora stem	1043 (8.0)

2.1. *Values in brackets represent coefficient of variation*

Internal bonding strength and 2-hour thickness swelling were selected to evaluate the properties of the developed boards. Internal bonding was measured in accordance with standard EN 319 [13], thickness swelling and water uptake were measured in accordance with standard EN 317 [14]. The measured properties were compared with commercially produced boards; namely type 3 oriented strand board (OSB) and type P2 particleboard (PB).

A state-of-the-art literature review was done on totora plant and raw material. The entire analysis covers aspects such as availability of totora stems with respect to market prices and volumes, totora board developments, and material selection criteria [15]. Both primary and secondary data were processed using economic-mathematical methods. In order to comprehensively evaluate the possibility of using totora stems for the production of composite materials, the methods of description,

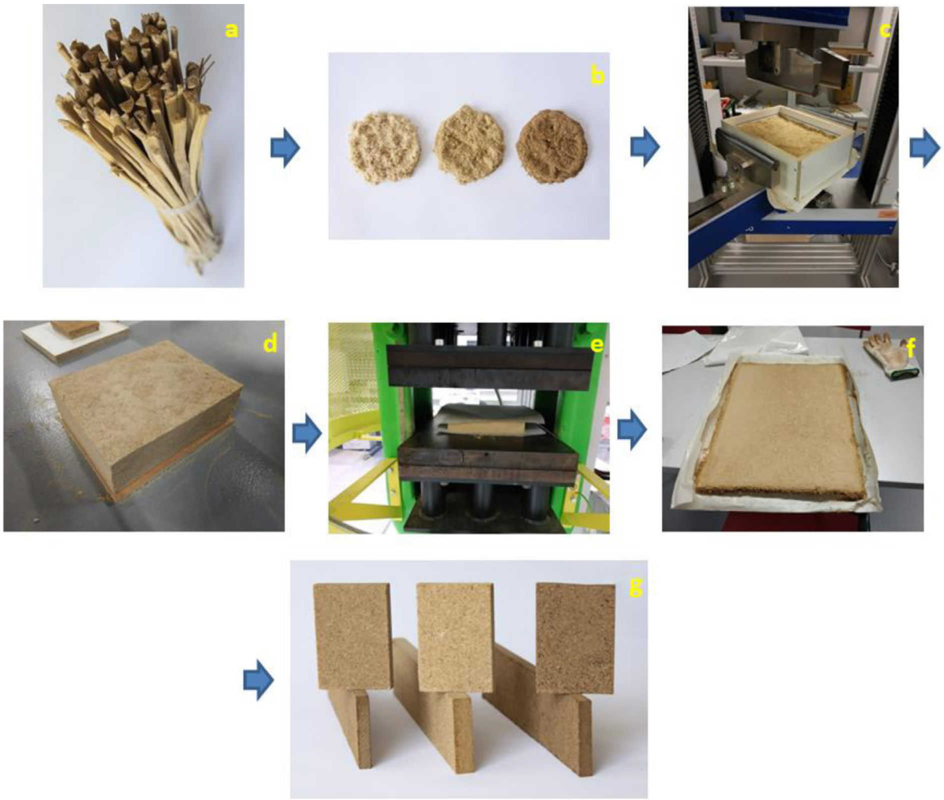

Fig. 2. The board production scheme. (a) dried totora stems, (b) disintegrated totora tissue, (c) pre-pressing, (d) pre-pressed totora mat, (e) pre-pressed mat in the hot press, (f) pressed board, (g) cut samples.

analysis, synthesis and comparison were used in the discussion part.

3. Results

3.1. Totora productive potential

Since totora is an annual cycled macrophyte, many of the emerging stems of the plant die naturally after the flourishing stage and new shoots are grown every year. Therefore, a well-managed harvesting process should not generate a big impact on the natural cycle of the plant. Additionally, the mowing activities help with cleaning the senescent and dead matter from the plant, limiting the methane production of the wetland and encouraging the regrowth of new shoots, which increase the planťs density. For example, a natural totora stand may have a density of around 200 stems/m^2, while a totora stand which is being constantly mowed can have a density of around 320 stems/m^2, hence a higher productivity per unit area [16]. The totora plant can remain productive for more than 25 years as long as the root system is not destroyed and correct management and care of the plant is done [17]. On the other hand, a lack of management and overuse can lead to the degradation of the totora stand [1,18,19].

3.2. Dry matter productivity of totora stands

Data about the productivity of totora is scarce and scattered. Studies have shown that totora dry matter production can be up to 58 t/ha/year in nutrient-enriched substrates such as constructed wetlands for wastewater treatment [3]. However, in normal conditions, the maximum reported dry matter production is around 37 t/ha/year, with an average of 20 t/ha/year depending on different factors such as location, rain patterns, substrate and the plant age, among others [1,20]. The maximum yield values in enriched substrates of totora are similar to the values reported for other macrophyte species that have been used in phytoremediation wetlands, and higher than the yield reported for some agricultural wastes in terms of t/ha/year, as can be seen in Fig. 3.

In Lake Titicaca, totora has been considered one of the main resources for the local people because of its different uses and applications. The dry matter yield of totora has been studied by several authors who have reported different data. A study conducted by Galiano [22] indicated an average productivity of totora of about 311.02 t/ha of green matter, considering 12% content of dry matter, a dry matter yield of 37.66 t/ha was calculated in the Puno bay of the Peruvian part of the lake. Another study conducted by the Binational Project of Lake Titicaca (PELT) studied the productivity of approximately 40,000 ha of totora, of which 62% where in the Peruvian part and 38% in the Bolivian part of the lake. It was shown that the average green matter yield was between 130 and 280 t/ha in the Peruvian part and 150–290 t/ha in the Bolivian part with a total production of 10,955,000 t of green matter [23].

In the lakes of the northern parts of the Andean region of Ecuador, distributed in a radius of 100 km, approximately 400 ha of natural totora stands have been identified [17,24]. A study about the productivity of totora in Lake San Pablo-Ecuador was conducted and 80 ha of totora were identified. It was reported that a cultivated plot of 1,682 m^2 was able to produce 2,562 kg of dry matter per mow. Considering that a cultivated plot is usually mowed twice a year, it is possible to estimate a dry matter yield of approximately 30 t/ha/year in this case [25].

3.3. Analysis of the totora production chain

In order to analyze the raw totora productive cycle, data available from studies conducted in Ecuador and Peru were considered. From the available data from Ecuador, it could be observed that manual mowing was the least efficient part of the production process. It accounted for almost 50% of the raw material value. Harvesting time varied a lot depending on the depth of the marshland, the type of stand, and the expertise of the mower. In Lake San Pablo-Ecuador, one person could harvest approximately 50 m^2 in 50 min, whereas in Yaguarcocha lake-Ecuador, approximately 900 m^2 were harvested by 6–7 people in 12 days [17]. Simbaña [25] studied the costs of planting and harvesting a totora plot of 1,682 m^2 in Lake San Pablo. Although the initial investment includes plating costs, once the plant is established and is correctly managed, it can remain productive for more than 25 years. The costs percentages of each part of the process were reported as follows: seedlings 1%, terrain preparation 8%, planting 5%, maintenance 10%, transport 16%, equipment 10%, and mowing 49%. On the other hand, in the studies conducted by PELT and ADESU in Lake Titicaca in 2003 on the economic validation of totora productive cycle, the costs estimations were performed using surveys. The percentages each part represents were reported as follows: seedlings 25%, terrain preparation 5%, planting 5%, maintenance 6%, transport 20%, equipment 14%, and mowing 25% [26].

As can be seen in Table 2, the seedlings costs represent a much higher percentage in the case of Lake Titicaca. This might be because in the case of Lake San Pablo in Ecuador, the studied plot area was much smaller; therefore, the planters could have been able to obtain the seedlings from previously existing plants or nearby plants by themselves, whereas in Lake Titicaca, the area was almost 10 times bigger, and the seedlings may have to be bought from a nursery. However, other activities are much more efficient when planting larger areas, such as the mowing activities which accounts for only 25% of the cost in Lake Titicaca compared to almost 50% of the cost in Lake San Pablo. Both of the analyzed studies were conducted in 2003. We can see that the production price of one kg of dry totora stems in Lake Titicaca was

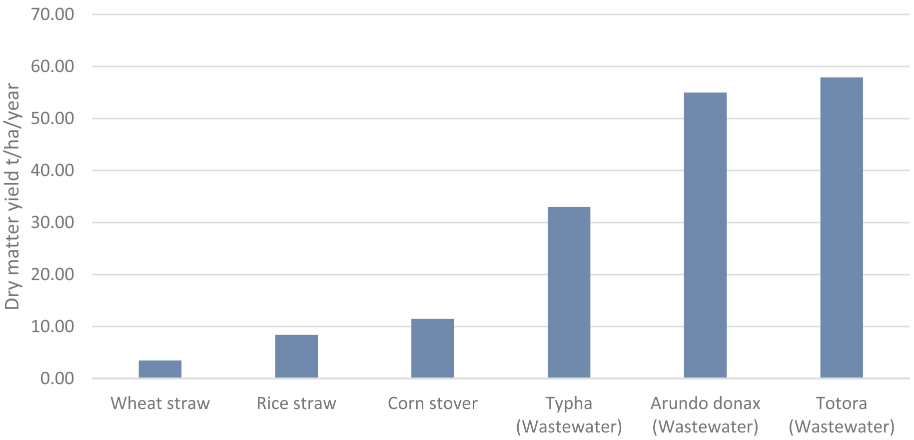

Fig. 3. Dry matter yield of different biomass sources. Figure made with data obtained from FAOSTAT, [3,21].

Table 2
Comparison of costs and item percentages of planting and harvesting one hectare of totora in Lake San Pablo and Lake Titicaca.

	Lake San Pablo-Ecuador		Lake Titicaca-Peru/Bolivia	
	Cost (USD)	Percentage (%)	Cost (USD)	Percentage (%)
Seedlings	4	1.10	150	25.08
Terrain preparation	28	7.68	30	5.02
Planting	20	5.49	30	5.02
Maintenance	36	9.87	33	5.52
Transport	60	16.46	120	20.07
Equipment	36.6	10.04	85	14.21
Harvesting	180	49.37	150	25.08
Total	364.6	100.00	598	100.00

almost the half of that reported in Ecuador, which is thought to be due to the greater planting area in Lake Titicaca, which can optimize most of the processes. The reported market price for one kg of dry totora was about 0.25 USD in Lake Titicaca. The market price of totora stems in Ecuador was not reported in that study.

Currently, the market price of one kg of dry totora stems sold in Lake San Pablo-Ecuador is around 0.35 USD, which could be reduced for wholesale orders depending on the transaction conditions. Considering that the planting and harvesting processes are still performed mainly by hand, the efficiency of totora production can be significantly improved by employing new harvesting technologies. For instance, some harvesting machines used for mowing common reed (*Phragmites australis*) in northern Europe are able to mow between 1 and 1.5 ha/hour [27]. This could increase the harvesting efficiency and reduce raw totora prices, thereby making it more competitive against other biomass sources.

4. Constructed wetlands for phytodepuration as potential raw material source

Constructed wetlands planted with macrophyte species have shown to have several benefits in addition to water quality improvement, such as their low operational costs [28], bioenergy source [29], and CO_2 capturing [30]. Additionally, stricter regulations on wastewater quality and water management have encouraged research on increasing the efficiency of existing treatment plants by incorporating alternative systems, such as constructed wetlands to comply with the requirements at low initial and operational costs [31]. Several authors have studied totora in constructed wetlands that showed high resistance to different pH levels (from 3 to 11), and high heavy metal removal capacities [4,32–34]. Additionally, a study conducted in Chile about greenhouse gas emissions and energy consumption of a horizontal subsurface flow constructed wetland (HSSF), planted with totora and *Phragmites australis* intended for serving a 700-people equivalent population, reached the conclusion that the HSSF wetland emitted almost a third of GHG emissions (12–22 $kgCO_2eq/p.e/yr$ vs. 67.9 $kgCO_2eq/p.e/yr$) and consumed approximately a third of primary energy (24–27 MJ/m^3 vs. 96 MJ/m^3) compared to a conventional wastewater treatment plant [30]. The feasibility of totora to be used as a phytoremediation species in constructed wetlands may indicate the possibility of achieving synergy by pairing the water-quality improvement with the raw material supply chain. For instance, in the Imperial Valley-California constructed wetlands planted with totora were studied for treating agricultural drain water [35]. In that study it was concluded that a system of approximately 4 ha of wetlands can treat 18 cm/day of water flow, removing 41% of the total phosphorus, 25% of the total nitrogen, and 40% of the total suspended solids. In the Imperial Valley area the authors identified more than 80 potential treatment sites with more than 1500 ha for constructed wetland treatment plants [35], which could produce around 10,000 t of dry matter every year if the system is paired with the reeds management plan as part of the productive cycle of the system. Another study conducted by the Environment, Mining and Industry Foundation (MEDMIN) in a rural area in Bolivia showed that a constructed wetland of 2500 m^2 planted with totora could work as a prior step for increasing the efficiency of the conventional purification plant intended for a population of 500 people [36]. Other studies have pointed out the importance of treating wastewater generated in industrial parks, where centralized treatment systems, including constructed wetlands, could be planned to address the removal of different kinds of contaminants [37]. Therefore, it could be possible to achieve synergy between the water cleaning service that the plant provides, and at the same time providing raw material that can be used in the industrial sector.

However, it is important to know what kind of contaminants the water contains to define the best strategy for managing the wetland, and whether it is convenient or not to cut the totora stems or allow for detritus accretion to prevent toxic levels of contaminants accumulated in the sediment layers. For example, Murray-Gulde, Huddleston, Garber, & Rodgers [38] have reported that in South Carolina, 3.2 ha of constructed wetlands were used to reduce the copper concentration of water discharges that did not comply with some of the requirements recently introduced on wastewater quality standards. In this case it was not recommendable to cut the stems, for it was stated that since the biomass production of totora surpassed the detritus decomposition rate, it was a good species to sustain a system of sediment accumulation, where the senescent stems acted as carbon sources for bacteria that helped digest some of the contaminants, and at the same time, sediments accretion favored by senescent stems provided binding zones for reducing the bio-availability of the heavy metal that remained trapped in the progressive deposits of sediments layers preventing the risk of the wetland to achieve toxic levels of contaminants. Considering that water quality and protection of water sources has become one of the main concerns of our day, and that regulations on wastewater treatment are becoming stricter [38], constructed wetlands are one of the interesting solutions that comply with these requirements in situations such as in rural areas, agricultural irrigation systems, industrial wastewater treatment plants, and urban wastewater treatment plants [39].

4.1. Wetlands for environmental restoration as raw material source

Natural wetlands have been identified as important carbon storage places and biodiversity promoters [40]. Several projects for recovering marshlands and wetlands use totora as one of their main species; for instance, the wetland restoration project of the San Francisco Bay Estuary in the U.S., where more than 24,000 ha are planned to be restored along the coastal marshes [41]. This wetland could be periodically managed to remove mature plants and limit the methane production from senescent aerial stems, which can become an important raw material source at the same time. Another restoration project is taking place at Lake Titicaca in Peru and Bolivia, where more than 30,000 ha are planned to be restored along the lake shores aimed at recovering their environmental characteristics and encourage the management of the totora plant by the local people. This could also generate income sources for local communities that can use totora to develop local industries or handicraft making. The situation is different in Ecuador. While in the lakes where the communities that know how to work with totora and see it as a valuable resource, such as in Lake San Pablo (140 ha), and Yaguarcocha lake (90 ha), people keep the lake well managed to encourage the totora regrowth and increase the stems density; there are other cases for example in Colta lake (80 ha), where people do not regard totora as a valuable resource anymore and the lake has become overgrown with totora plants. Therefore, the local administration started a project in 2010 to “clean” the lake with an investment of nearly 1,000,000 USD, aimed at removing approximately 70 ha of totora plants to keep the shores open and gain free water surface, which could facilitate tourist activities at the lake [42,43]. In cases like

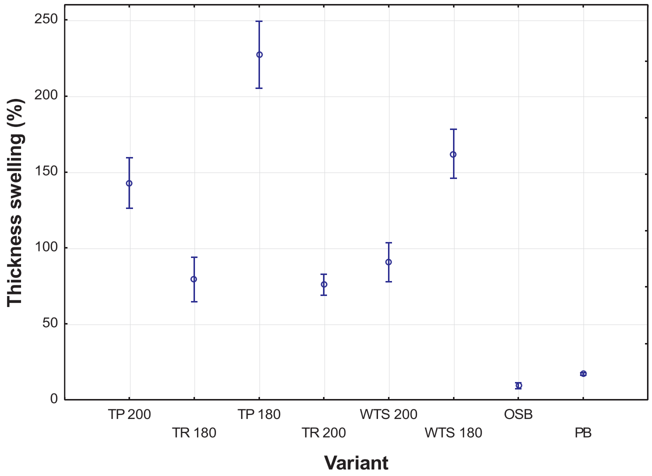

Fig. 4. Influence of board type on 2 h thickness swelling TR 180 – board from rind, pressing temperature 180 °C, TR 200 – board from rind, pressing temperature 200 °C, TP 180 – board from pith, pressing temperature 180 °C, TP 200 – board from pith, pressing temperature 200 °C, WTS 180 – board from pith and rind, pressing temperature 180 °C, WTS 200 – board from pith and rind, pressing temperature 200 °C, OSB – oriented strand board, PB – particleboard.

this, it could be possible that the same industry carries out the totora extraction as a public service, and thereby the raw material acquisition may become an income source instead of an expense in the productive cycle.

4.2. Comparison of thickness swelling, water uptake and internal bonding

From the thickness swelling and water uptake charts, it can be seen that the absorbent capacity of totora boards is very high (Fig. 4). The Totora stem is built from cellulose and hemicelluloses tissues that are hydrophilic and almost in all variants of totora board, the 2-hour water uptake was more than 100% of dry board mass. Since no adhesive is used, and self-bonding effect is based on sugars and the thickness swelling is also high. The highest thickness swelling was achieved by boards made from totora pith (Fig. 5). However, post treatments could be studied to limit the water uptake of the boards. Internal bonding values were extremely low, and these values do not fulfil standards and are much lower than the internal bonding values of commercially sold boards (Fig. 6). However, pre-treatments can be studied to improve the mechanical properties of totora binderless boards and identify potential applications.

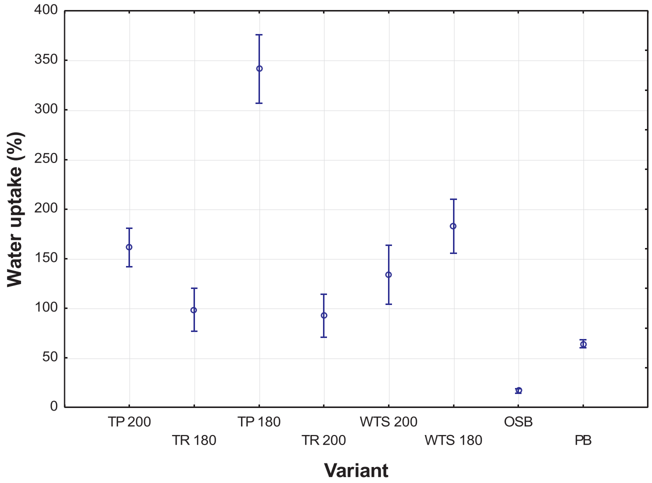

Fig. 5. Influence of board type on 2 h water uptake TR 180 – board from rind, pressing temperature 180 °C, TR 200 – board from rind, pressing temperature 200 °C, TP 180 – board from pith, pressing temperature 180 °C, TP 200 – board from pith, pressing temperature 200 °C, WTS 180 – board from pith and rind, pressing temperature 180 °C, WTS 200 – board from pith and rind, pressing temperature 200 °C, OSB – oriented strand board, PB – particleboard.

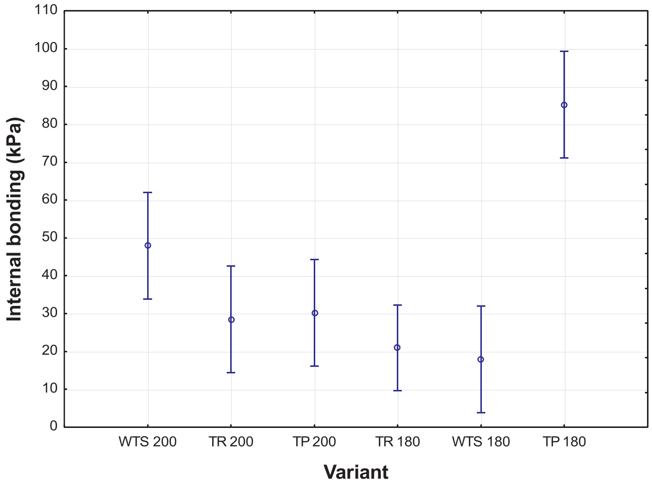

Fig. 6. Influence of board type on internal bonding TR 180 – board from rind, pressing temperature 180 °C, TR 200 – board from rind, pressing temperature 200 °C, TP 180 – board from pith, pressing temperature 180 °C, TP 200 – board from pith, pressing temperature 200 °C, WTS 180 – board from pith and rind, pressing temperature 180 °C, WTS 200 – board from pith and rind, pressing temperature 200 °C, OSB – oriented strand board, PB – particleboard.

5. Conclusions

Although totora is not currently a crop of industrial importance, through the adequate management of the already existing sources, in addition to the potential material production that may result from other uses such as constructed or natural wetlands, it may be possible to create several sources for raw material supply that can become feedstock to other industrial developments.

The totora binderless boards produced using the parameters described in this study did not generate satisfactory outcomes in terms of water uptake and internal bonding strength properties. However, post treatments such as wax addition could improve the water resistance of these boards, and the study of different properties, such as their thermal and acoustic insulation capacity, could help identify potential applications in other fields. Further research is needed to study the influence of different hot-pressing parameters, and possible strategies to improve the boards' mechanical properties.

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Data statement

The raw data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study. The processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compstruct.2019.111572.

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