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Totora (*Schoenoplectus californicus* (C.A. Mey.) Soják) and its potential as a construction material

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ABSTRACT

Totora is an emergent macrophyte with properties and historical uses supporting its potential use in contemporary construction and for reducing pressure on conventional forest plantations by diversifying the sources of biomass-based materials. Recent advances in the wood construction field have demonstrated the feasibility and advantages of using wood-based materials in tall building structures and other massive constructive uses, which could lead to a net reduction in CO_2eq emissions from the construction sector by replacing high-energy consuming materials such as concrete or steel with wood and biomass-based materials. Among these biomass-based materials are non-timber forest products. This category includes plants that can provide important contributions to the construction sector by diversifying the sources of biomass-based materials. One of these plants is totora (*Schoenoplectus californicus* (C.A. Mey.) Soják). Totora is a bulrush that grows in lakes and marshes in the Americas, from California to Chile, and some of the Pacific islands. This bulrush has been used by many cultures as medicine, food, forage, and material for building houses, boats, and different handicrafts. Although several people still use totora to make their handicrafts and rafts, the most important current examples of the use of totora are the floating islands of the Uros in Lake Titicaca. The Uros people have developed traditional techniques for building their homes, boats, and even the artificial islands where they live, with methods based almost exclusively on the totora culms. The studies and experimentation conducted on this plant have underscored its fast growth capacity, high yield values, anatomical and physical properties, and potential environmental benefits. This review aims to analyze the available data on this material regarding its potential for construction, which is intended to foster its research and development as an alternative source of a biomass-based building material.

1. Introduction

The increasing number of massive wood building projects has raised discussions on how environmentally friendly and how feasible is to replace materials such as concrete or steel with engineered wood and wood-based materials in the long term (Green and Karsh, 2012; Intergovernmental Panel on Climate Change, 2014). Studies have shown that some engineered wood elements can perform as well as concrete or steel in tall buildings (Podesto and Breneman, 2014; Popovski and Gavric, 2016; Ramage et al., 2017). Although wood construction has been demonstrated to be environmentally beneficial in comparison with concrete or steel, the demand for wood products is expected to rise threefold by 2050, which is expected to increase pressure on land and water resources that must concurrently provide the growing human population with food, urban area and other resources (FAO, 2015; García-Navarro et al., 2013; Intergovernmental Panel on Climate Change, 2014; World Wildlife Fund, 2012).

In this scenario, non-timber forest products, which include palms, herbaceous plants, bulrushes and reeds, among others, are an important source of biomass-based materials that can be studied to diversify the assortment of low-energy and biomass-based construction materials. Several studies have been conducted to examine these types of plants, assessing their feasibility for sue in the construction field and their environmental benefits (Bajwa et al., 2015; Flores et al., 2011; Hidalgo C., 2016; Wichmann and Köbbing, 2015). The non-timber-forest-products category includes totora (*Schoenoplectus californicus* (C.A. Mey.) Soják), which is a bulrush from the *Cyperaceae* family that grows in the Americas, from California (37°N, 120°W) to Tierra del Fuego (54°S, 70°W), and some of the Pacific islands such as the Cook Islands (21.23°S, 159.77°W), Eastern Island (27.11°S, 109.28°W), New Zealand (37.39°S, 174.72°E), and Hawaii (19.77°N, 155.57°W) (de Lange et al., 2008; Heiser, 1978; López et al., 2016). The taxonomy of totora has

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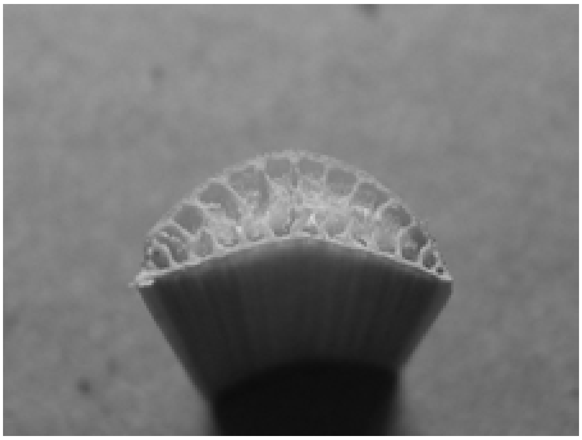

Fig. 1. *Typha latifolia* leaf section (Hidalgo-Cordero).

been studied to define if there are differences between individuals from different locations. The observations of different chromosome numbers and physical differences may support the existence of subspecies or varieties (Barros, 1942; Beetle, 1941; Heiser, 1974; Koyama, 1963). In the available literature, totora has been identified under different taxa names, e.g., *Scirpus californicus var. tatora* (Kunth) Barros, *S. californicus subsp. Tatora* (Kunth) T. Koyama, and *Schoenoplectus tatora* (Kunth) Palla. However, in the database of the Word Checklist of Selected Plant Families (WCSP), to date, these other names are considered synonymous to *Schoenoplectus californicus* (C.A. Mey.) Soják, (Heiser, 1978; WCSP, 2017). In some cases, the term totora has been used to designate some plants of the *Typha* species, another emergent macrophyte species with similar leaves to the culms of *Schoenoplectus californicus* (C.A. Mey.) Soják (Heiser, 1978; Heredia, 2014). Although in some cases, these two species have been used in similar ways, the differences are notorious. *Typha* leaves are thinner, and their sections are semi-circular (Fig. 1).

In contrast, *Schoenoplectus californicus* (C.A. Mey.) Soják is bigger, stronger, and has a round-to-triangular-shaped culm (Fig. 2). Different local names are used to refer to this plant, such as the term “tule” in California, Mexico, and some parts of Central America; or the term “piri” in Brazil (Dick et al., 2016; Heiser, 1978). In this review, the term “totora” will refer to the *Schoenoplectus californicus* (C.A. Mey.) Soják species.

In Lake Titicaca, where totora is an important part of the ecosystem, besides its social and economic importance for the local communities, institutions of Peru and Bolivia, the Autoridad Binacional del Lago Titicaca (ALT), and the United Nations Program for Development (PNUD) have worked on the development of projects aimed to research and improve the local management of this resource. The most relevant projects and institutions in this sense are the Proyecto Especial Binacional del Lago Titicaca (PELT), Fundación Medio Ambiente, Minería e Industria (MEDMIN), Asociación para el Desarrollo Sustentable (ADESU), Asociación Boliviana de Teledetección para el Medio Ambiente (ABTEMA), and Unidad Operativa Boliviana (UOB).

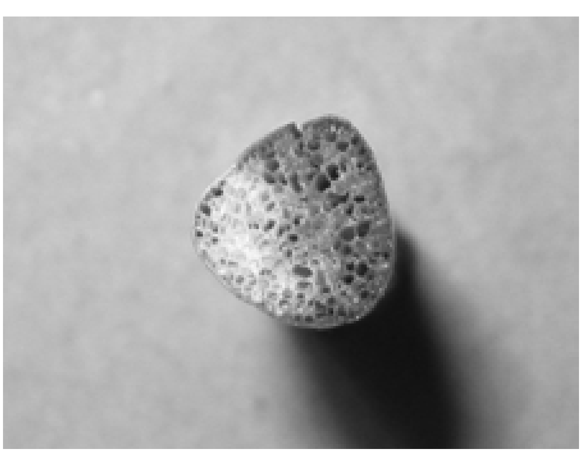

Fig. 2. *Schoenoplectus californicus* (C.A. Mey.) Soják culm section (Hidalgo-Cordero).

Typha species, which are broadly distributed worldwide, have been more extensively researched and studied for applications in the construction field (Kim et al., 2016; Wuzella et al., 2011). The procedures used in these studies could be a guide to develop and evaluate methodology that is applicable to totora and extend the results to other similar species.

Totora grows in lakes and marshes and achieves its best development in depths of 30–70 cm. However, in Lake Titicaca, it can grow in water depths up to 5 m (Collot, 1980; Gilson, 1937; Iltis and Dejoux, 1991). It can yield up to 57.90 t/ha/year of dry matter, depending on the substrate nutrients, location, and climate, as shown in Table 1 (Collot et al., 1983; de Lange et al., 2008; Heiser, 1978; Neill, 2007; Pratolongo et al., 2008).

This maximum yield capacity is high compared with the data obtained for the maximum over-bark yield of conventional planted forests from the Food and Agriculture Organization of the United Nations (FAO) report on Global Planted Forests (FAO, 2006), as shown in Fig. 3. Totora's fast growth makes it possible to harvest it twice a year for use in construction, guaranteeing a constant source of material supply from a relatively small plantation area (ABTEMA and UOB, 2000; Collot et al., 1983; Mardorf, 1985; PELT, 2000a; PELT and ADESU, 2003; Rodriguez, 2010). The sun-dried totora, when kept dry, is not prone to attack by biological agents, which can be observed on dry totora stalks or on traditional objects such as esteras that can last for decades when they are protected from extreme moisture (Hidalgo-Cordero and García-Navarro, 2017; PELT, 2000a; Simbaña, 2003).

These features stimulated several ancient cultures to use totora as food, forage, medicine, and for making a wide range of objects from rugs to huts (Hall, 2009; Heiser, 1978; Margolin, 1978). Nevertheless, the most important example of current use of totora is presented by the complex of the Uros Islands in Lake Titicaca (15.81°S, 69.96°W). The Uros’ constructive practices depend almost exclusively on the totora culms, which are virtually the only material available in abundance in the lake. Uros people use the totora bundled, weaved, or braided to build their houses, boats and artificial floating islands where they have lived for more than 500 years (Banack et al., 2004; Macía and Balslev, 2000). Despite the intensive use of totora by some communities, the available data on its constructive applications are still scarce and widely scattered. This review includes information obtained from books, primary sources, direct observation, peer-reviewed sources, gray literature, videos, and web sources.

This review is intended to provide a background for assessing the potential of totora as an alternative biomass-based source of material that could be used in the contemporary construction industry, and the potential environmental benefits or impacts of its usage in each context.

2. Anatomy

Totora is an emergent wetland macrophyte that has roughly three identifiable parts with different characteristics as follows: the roots, submerged culm and aerial culm (Corsino et al., 2013).

The root system consists of rhizomes that grow parallel to the substrate. The rhizome has nodes every 2–6 cm, from which the culms grow vertically. The roots system develops as a net-like structure that stores nutrients and helps the plant survive during dry seasons and adverse conditions (Honaine et al., 2013; PELT and ADESU, 2003). This netlike structure can be 0.50–3-m thick depending on the plant age and is intended to provide the plant with a stable support for growth (PELT and ADESU, 2003). When the water level of the lakes increases, these root blocks, which often contain air bubbles because of the aeration

Table 1
Yield of dry matter in tons per hectare per year of totora.

Location	Substrate	Yield t/ha/year	Reference
Parana River lower delta, Argentina 33.51°S, 59.85°W	natural	16.50	Baigún et al. (2008)
Port Waikato, New Zealand 37.39°S, 174.73°E	natural	21.00	de Lange et al. (2008)
Lake Titicaca, Peru and Bolivia 15.92°S, 69.33°W	natural	37.66	PELT (2000a)
San Pablo Lake, Imbabura, Ecuador 1.50°N, 78.20°W	natural	15.22	Simbaña (2003)
Parana River, Argentina "Bajos del Temor" 34.15°S, 58.15°W	natural	19.99	Pratolongo et al. (2008)
Lake Titicaca, Peru and Bolivia 15.92°S, 69.33°W	natural	15.22	Collot (1980)
Sacramento − San Joaquin delta, California, USA 38.30°N, 121.69°W	natural	26.50	Hester et al. (2016)
Hualqui, Biobío, Chile 36.98°S, 72.96°W	wastewater	17.82	López et al. (2016)
Aiken and Barnwel, South Carolina, USA 33.33°N, 81.73°W	wastewater	10.45	Murray-Gulde et al. (2005)
Hautapu, Waikato, New Zealand 37.86°S, 175.45°E	wastewater	57.90	de Lange et al. (2008)
The Pahu, Waikato, New Zealand 37.87°S, 175.44°E	wastewater	54.40	de Lange et al. (2008)

functions of the plant, float and separate from the bottom of the lake. In this way, the plant can float until the water level recovers or be relocated to shallower waters (PELT, 2000a). In Lake Titicaca, these blocks are collected in the rainy season by the Uros peoples, who tie them together to make their floating islands (PELT and ADESU, 2001). These blocks have not been reported as having any uses other than the island floating structure for these people.

The second part of the plant is the submerged culm, which has a group of small leaf-like organs at its base. These small leaves lack any photosynthetic function (Gonzalez, 2002). The culm has a round to triangular shape, an internal structure composed of the aerenchyma tissue and an external epidermis (Gonzalez, 2002; Simbaña, 2006). The aerenchyma tissue consists mostly of air chambers arranged vertically along the culm and divided approximately every 2.50 mm by perpendicular diaphragms. This internal structure is thought to be used by the plant to facilitate gas exchange between the organs (Apóstolo, 2005; Corsino et al., 2013; Simbaña, 2006). Some nutrients of the plant are transported through xylem vessels located between the air chambers (Apóstolo, 2005; Barrientos et al., 2014). The internal aerenchyma is known to form part of several macrophytes because of its low energetic cost to the plant and the aeriation function it supports. The air chambers comprise approximately 65% of the total transversal area of the culm, with slight differences between the base, mid and apical regions of the culm (Corsino et al., 2013). On the sub-epidermis layer, a major number of structural and nutrient-transporting tissues of the plant are concentrated, and on the external epidermis, a waxy substance makes up the mucilage of the plant and acts as protection (Apóstolo, 2005; Barrientos et al., 2014). Although the submerged part of the culm has some chloroplasts that give the plant its green color, this part of the culm lacks photosynthetic tissues and contains a few stomata, which can be used by the plant for water absorption or during severe water level changes (Corsino et al., 2013; Gonzalez, 2002; Simbaña, 2003).

The aerial part of the culm also has an internal structure consisting of aerenchyma and an aerial epidermis where photosynthetic functions and gas exchange occur. Therefore, the apical part of the culm has a greater concentration of stomata and a thicker palisade parenchyma than the middle and lower part of the aerial culm due to its greater exposition to light and air (Barrientos et al., 2014; Corsino et al., 2013).

The culm architecture of totora has been studied by Corsino et al. (2013) to determine the anatomical structures used by the plant to efficiently support a slender and long stem (3-m long and 1.50-cm in diameter on average). This study analyzed the anatomical differences between the basal, mean and apical part of the culm and determined that the anatomical characteristics that allow this plant to maintain its verticality are its triangular-pyramidal shape, the internal aerenchyma, and the concentration of most vessels and fibers in the sub-epidermal layer. Additionally, Honaine et al. (2013) have studied the silica biomineralization that occurs on the plant tissues, which is also thought to be used as a structural support.

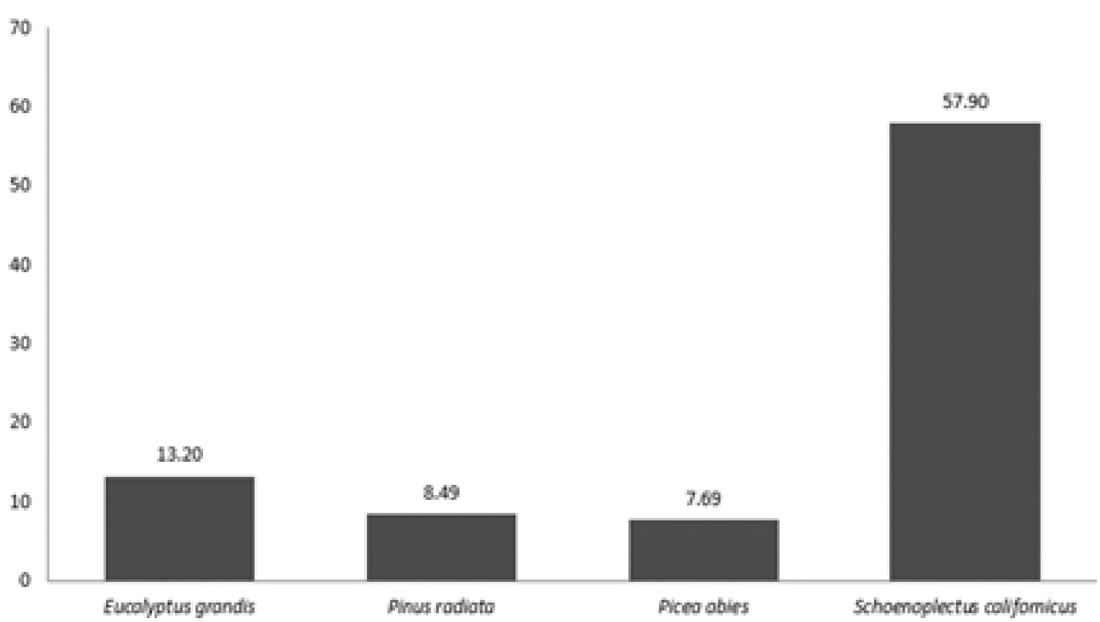

Fig. 3. Maximum reported aboveground over-bark yield of dry matter expressed in tons per hectare per year of some conventional fast-growing planted forests compared with totora. Figure made with data obtained from (de Lange et al., 2008; FAO, 2006).

3. Planting methods and harvesting of totora

Totora is regarded as a valuable resource for some communities, and it has also been used in phytoremediation and marsh restoration throughout America (Hester et al., 2016; Watson and Byrne, 2012). It has been reported that totora promotes a greater biodiversity than other emergent macrophytes and, when properly managed, can supply an important income source for the people that harvest it with a low impact or even a benefit to the environment (Hall, 2009; Lima Silveira et al., 2011; Sepúlveda-Mardones et al., 2017). Hence, some studies have assessed its management, planting methods, harvesting and potential economical returns (PELT, 2000b; Stevens and Hoag, 2003).

In the case of Lake Titicaca, studies and pilot projects to evaluate and validate techniques for planting and managing totora have been coordinated by ALT and PNUD from 2000 to 2005. In Lake Titicaca, the area covered by totora has decreased from 69,010 ha in 1986 to 38,629 ha in 2000, which is a reduction of 44% in 14 years (PELT, 2002). This phenomenon has been caused by its intensive use by the peoples on the shores of the lake, the increasing population density in the zone, lack of management, and, in some cases, the cessation of harvesting activities that would otherwise stimulate the regrowth of new totora shots. For this reason, both institutions (ALT and PNUD) coordinated a series of projects aimed to evaluate and protect the totora resource in Lake Titicaca and to encourage its proper use and management by the people. These projects included the planting of 60 ha of totora distributed between Peru and Bolivia and the evaluation of the economical returns it could generate to the indigenous people (PELT and ADESU, 2003).

Rhizomes containing 2–5 living culms were used for all the planting methods. The two main groups of planting techniques utilized were shore planting for a water depth < 1 m, where the plant was buried in the substrate and then compacted by stepping around it, and deep water planting for a water depth > 1 m, where plants were tied to a stone or a block of earth to sink them to the bottom of the lake. Of these techniques, the best results were obtained using the shore technique due to its high efficiency and because compacting the substrate provided a better support, reducing the possibility of plants being swept away by the currents (PELT and ADESU, 2001). Totora plants were separated 2 m from each other in both directions. Thus, a total of 2500 plants were used per hectare. The plantation was evaluated the subsequent year. At this stage, the productivity was 25 culms/m^2, which was still low compared with the high density of naturally grown totora, which has approximately 250 culms/m^2. Once established, totora can be harvested twice a year, and its cutting stimulates the growth of new culms and keeps the plants clean and free of litter from senescent plants (ADESU, 2001). The economic revenue that planting totora can generate has been assessed, in this case considering the production of 100 tons of green matter per hectare per year. The planting costs per hectare were US$240 using shore techniques and US$432 using deep water techniques, and the expected revenue from selling totora bundles at the local market in 2001 was approximately US$2450 and US$2270 per year for each technique, respectively (PELT and ADESU, 2001). Considering that in subsequent years there will not be a repeated need to plant totora and the culm density will increase, it is possible to add value to the totora by processing it, which could constitute a suitable livelihood for the local people based on their own resources.

Totora planting methods have also been studied for marsh restoration mainly in the southern United States, where it has been reported to improve the biodiversity of wetlands through the recovery of their ecological and environmental characteristics (Denson and Langford, 1982; Hester et al., 2016; Sloey et al., 2015). With the aim of defining the best planting strategies for this plant, Mallison and Thompson (2010) conducted a study in Lake Tohopekaliga, Florida, to analyze a series of variables that influenced plant survival. In that study, 15 plots (3×3 m) were planted using 5 different methods, which varied depending on the length of the rhizomes (2–4 cm and 6–8 cm), below and above water level with cut and uncut single culms, and one with a longer rhizome of 12–15 cm with 2–7 uncut living culms. The water depth at the planting location was 60–65 cm. The plants were evaluated after 4 months for retention rate, survival rate, and condition. This study showed that totora must be planted in an emergent manner because the survival rate of the plants that were cut under the water level was lower than the survival rate of those that were cut above it or uncut. The rhizome length did not influence the survival rate. However, the condition of the plants with a longer rhizome with more uncut living culms was superior at the time of the evaluation. Hence, if the objective is to establish a single robust plant, the best option is to plant a larger rhizome with several emergent living culms. If the objective is to achieve a broader distribution, then it is possible to divide the rhizome into smaller pieces and plant them with emergent living culms.

The management of totora has also been studied as a means to prevent other emergent macrophytes to displace indigenous plants and fauna (Hall, 2009; Mudge and Netherland, 2014). However, de Lange et al. (2008) has stated in a case study in New Zealand, where totora is an introduced species, it should be controlled until the weed potential is properly assessed.

As the harvesting of totora promotes re-growth and development of the plant (ABTEMA and UOB, 2000; PELT and ADESU, 2003), its use by the people could result in a symbiotic relationship by maintaining a desirable ecological equilibrium and generating income sources for the harvesters (Lima Silveira et al., 2011).

4. Water treatments

Cyperaceae is one of the macrophyte families that has been used for the construction of wetlands for water treatment. The species *Schoenoplectus californicus* has been widely used in constructed wetlands for phytoremediation and phytoextraction (Scholz and Lee, 2005; Vymazal, 2013). Several studies have been conducted to examine totora performance in removing common nutrients and contaminants (Araya et al., 2016; Daniels et al., 2010; Duchicela and Toledo, 2013; Kadlec et al., 2010; López et al., 2016; MEDMIN, 2003; Neubauer et al., 2012; Rojas et al., 2013), metals (Arreghini et al., 2017; Knox et al., 2010; Murray-Gulde et al., 2005; Rearte et al., 2013; Villamar et al., 2014), pesticides (Miglioranza et al., 2004), industrially produced water (Kanagy et al., 2008), combined treatments (Malecki-Brown et al., 2010), and other contaminants (Sundberg-Jones and Hassan, 2007; Thullen et al., 2008). Additionally, the greenhouse gas emissions, and energy consumption of a constructed wetland with a 700-person equivalent capacity planted with totora and *Phragmites australis* have been reported to be approximately 3 times lower than those of a conventional wastewater treatment plant (Casas Ledón et al., 2017). Although water treatment with totora presents several benefits, adequate management of the plants is of importance because some contaminants accumulate on the internal tissues of the culms, which are not recommended for use as forage (MEDMIN, 2003), allowing the plants to undergo decomposition in the system and thus increasing midge production (Costantini et al., 2004; Thullen et al., 2008). Additionally, part of the absorbed contaminants, if not in considerable quantities, could return to the water flow (Murray-Gulde et al., 2005). The capacity of totora to capture CO_2 has been evaluated in coastal marshes, where it absorbed a total of 73.70 t of CO_2/ha. In this scenario, the collection of totora culms for use in industry could serve as a CO_2 storage reservoir and prevent other pollutants absorbed by the plant to return to the biotic cycle.

5. Uses of totora as material

Several handicrafts are made with totora, such as rugs, baskets, blowers, jewelry, and souvenirs. The versatility of the plant has allowed many communities and artist developed a wide range of techniques based both on tradition and innovation (Centro Interamericano de Artes

Populares, 2015; Heiser, 1978; Mardorf, 1985; Universidad del Pacífico, 2015). Concerning constructive applications, the most developed techniques and uses are currently found in the indigenous communities of Lake Titicaca. Some other communities have been reported to have constructive traditions using this plant, but they have been lost and left little information concerning the details of the techniques used (Hall, 2009; Heyerdahl, 1971; Mardorf, 1985; Prieto, 2016). Herein, the main techniques currently employed for making constructive elements with totora are described.

5.1. Quesana

The quesana is a traditional thick rug made in the highlands of Peru and Bolivia that is locally used as a floor mat, roof, and wall covering (ABTEMA and UOB, 2000; Gilson, 1937; Heiser, 1978; Ninaquispe et al., 2012). It is made by twining totora culms with a rope at intervals of approximately 30 cm. The quesana thickness is approximately 5 cm, its width is approximately 2 m depending on the length of the totora culms, and its length is usually between 3 and 10 m. Nevertheless, its final dimensions depend on the size of the framework for weaving it and its final use. Herein, the process of making a quesana of 2.40-m wide and 9-m long is described (Fig. 4).

The reported quesana manufacturing process was observed on the Uros Islands in 2006. A plastic layer was laid on the ground to avoid mixing the culms on the ground with those of the quesana. Two 5-cm in diameter round logs of eucalyptus were placed 9 m from each other on the island ground and secured with planks. Nylon thread with a diameter of approximately 3 mm was tied to the eucalyptus logs at intervals of 30 cm and tightened. These threads were the guides for the twinning process. Then, bundles of dry totora of approximately 5-cm in diameter were placed perpendicularly over the thread guides, and the bundles were twined together and tightened with another nylon thread. Once the quesana was ready, the ends of the threads were cut and knotted. The final product was a 5-cm thick textile that could be used as a wall, roof or rug. House structures were made of slim eucalyptus joists

Fig. 4. Quesana manufacturing process (Hidalgo-Cordero).

Fig. 5. Huts on the Uros islands (Hidalgo-Cordero).

of approximately 4 cm × 5 cm, to which the quesanas were nailed or tied to form the walls and roofs (Gilson, 1937; Hidalgo-Cordero, 2007) (Fig. 5).

Ninaquispe et al. (2012) conducted a study to analyze the insulation capacity of the quesana and its suitability for use as insulating material in the Puno highlands of Peru. The tests were conducted in a laboratory at the University of Minnesota in accordance with the standard "ASTM C1155-95:2013, Standard practice for determining thermal resistance of building envelope components from the in-situ data" (ASTM, 2013). The conductivity reported from these tests was 0.083 W/mK. It was stated that 5 cm of quesana had the same conductivity value of 30 cm of adobe walls. Therefore, the use of quesanas was a suitable solution for improving the thermal conditions in that case, and it included additional environmental and social benefits derived from its local production using a widely available local material.

Other works have examined the use of quesanas in construction, such as the study by Eduardo Palominio and Zegarra Lazo (2015) at the Universidad Nacional del Altiplano in Puno investigating panels made of quesanas covered with gypsum and cement mortar. These panels were assessed mainly with respect to their impact resistance, fire resistance, acoustic insulation and thermal insulation. Another researcher, Banderas (2015) at the Universidad Politécnica de Madrid, analyzed the use of quesanas as a thermal insulating layer incorporated into a prefabricated mud and reed panel for applications in low-cost housing projects in Ecuador.

Additionally, the research group Centro Tierra from the Pontificia Universidad Católica del Perú, PUCP, has been working since 2014 on research involving the implementation of quesanas as insulating material on roofs and walls in a series of houses in the Puno highlands to improve their thermal performance (Rodríguez Larraín and Meli, 2015). Although that study has yet not issued official data regarding the improvement of internal conditions of the houses, it is important to note that totora is being studied and tested in practical cases studies, which will provide valuable insights on its thermal performance, durability, construction techniques and other issues that will be evaluated by studying these practical examples. The availability of the material in the zone and the observation that the construction elements are locally produced by indigenous peoples are elements of interest that represent further environmental and social benefits.

5.2. Single-culm totora sheet

The single-culm totora sheet is mainly used on the Uros Islands for roofing. These single-culm sheets were observed on the Uros Islands in 2006. They are normally 2-m wide and could range from 2 to 10-m long. They are made by perforating the totora culms with a needle and 2-mm in diameter nylon thread that joins them together to form a single

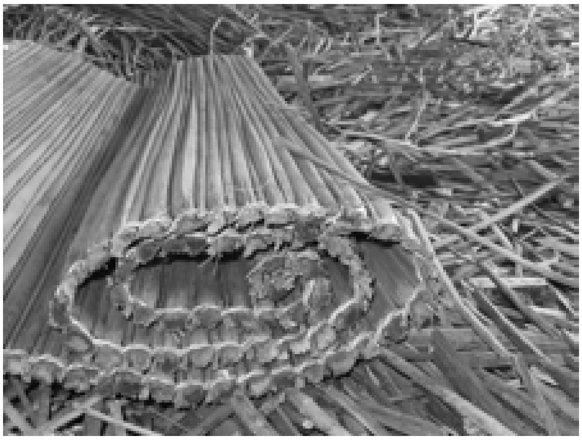

Fig. 6. Single-culm sheet (Hidalgo-Cordero).

layer. The reported single-culm totora sheets were observed on the Uros Islands in 2006. The reported sheets had threads every 30 cm, and the totora culms were woven at the ends with nylon or totora threads to keep the culms together (Fig. 6).

These sheets are used in roofs because their knots-free surface allows the water to flow freely and avoids leaks. For the Uros huts, two to three layers of these mats are used to make one roof (Fig. 7). The outer layer should be replaced every 6 months, but the internal ones can last longer periods (Hidalgo-Cordero, 2007).

5.3. Totora culms tied directly to the structure

This technique was observed on the Uros Islands in 2006, mainly for building small huts (Fig. 8). The huts observed had a square structure of approximately 2.40 by 2.40 m consisting of rough round logs of eucalyptus. The main rafters were approximately 7-cm in diameter, and the battens were approximately 4-cm in diameter. The structure had a pyramidal shape with a slope of approximately 60°. First, a nylon thread of approximately 3-mm in diameter was tied to the structure at intervals of approximately 40 cm to form parallel guides to create a

Fig. 7. Roof layers (Hidalgo-Cordero).

Fig. 8. Uros' huts (Hidalgo-Cordero).

Fig. 9. Uros hut construction details, thread guide (Hidalgo-Cordero).

framework similar to the one used for the quesanas. These horizontal thread guides were tied to the wooden rafters (Fig. 9). To this framework, totora bundles of approximately 10-cm in diameter were placed perpendicularly to the guides and tied with another thread that lashed the culm bundles to the guide and to the previously tied bundle to form an approximately 5-cm thick layer. Once the lower layer of the totora culms had been completed, the next layer was placed on the previous one with a displacement of 40 cm from the bottom of the previous layer. In this way, the roof was built from the bottom to the top and from the interior to the exterior. The final thickness of the hut roof was approximately 8 cm. In some cases, the guide threads were replaced with small eucalyptus logs of approximately 3-cm in diameter, to which the totora culms were tied (Fig. 10).

A similar technique has been reported to be used in Ohlone hut constructions in North America. In this case, thin willow logs were curved and fastened together to form a dome-shaped framework. The structure was then covered by totora bundles that were tied to the framework. Ohlone huts range from 2 to 6-m in diameter, and the larger ones can house two families (Margolin, 1978).

5.4. Esteras

Esteras, also known as petates, are made by interlacing totora culms to form a flexible and spongy sheet that has multiple applications from mats and rugs to wall coverings and architectural ceilings. Esteras are available in various sizes, although they do not normally exceed the useful length of culms, which is approximately 2.40 m. Nevertheless, it

Fig. 10. Uros hut construction details, log guide (Hidalgo-Cordero).

Fig. 11. Rolled esteras (Hidalgo-Cordero).

Fig. 12. Estera weaving process (Hidalgo-Cordero).

is possible to find larger esteras made with alternated culms (Heiser, 1978; Mardorf, 1985). In the case of Lake San Pablo in Ecuador, esteras weaving is an important income source for several families that have organized in a sort of productive cooperative. Just in this community the production of esteras was of 2392 units per week in 2013, and the whole productive cycle involved more than 3000 families from harvesters to weavers in the northern Andean parts of Ecuador (Simbaña, 2003). The following description of the esteras manufacturing process was observed in the traditional handicrafts market of the Plaza Rotary in Cuenca-Ecuador (Fig. 11). The manufacturing process of esteras was started by moistening the totora culms with some water and leaving them in the shade for approximately one hour to allow time for water absorption to soften the culms and make them more flexible and suitable for weaving. Once the totora culms had been softened, a stone was used to strike the culms to flatten them, decreasing their volume and increasing their density, which makes the fibers more resistant and flexible for weaving (Fig. 12). Additionally, as explained by the weaver, this process helps to achieve a stiffer tissue because once the mat is finished; the culms recover some of their volume by swelling and stiffening the entire tissue. Esteras are the most widespread object among totora-working communities, with uses tracing back to thousands of years, and they are still used in many parts of the world (Bautista and Sánchez, 2015; Hall, 2009; Hidalgo C., 2015; Lima Silveira et al., 2011). Some studies have indicated that totora esteras seemed to be very valuable objects during the Inca empire, for there are records suggesting they were accepted as payment for tributes to the Inca due to their utility (Mardorf, 1985). One interesting modern example of the use of esteras is "La Petatera", in Colima-México, where a temporary bullring for approximately 5000 people is constructed every year using wood logs as the structure and esteras as the building envelope (Mendoza Pérez, 2008).

5.5. Bound totora bundles

Bound totora bundles represent a construction technique for building the traditional rafts and boats used by several totora working people for harvesting and fishing both in lakes and the sea (Carpenter, 2007; Collot, 1980; Heiser, 1978). Although totora culms are individually relatively weak, when they are tightly bound together, they form compact bodies with considerable strength (Rodriguez, 2010; Rondón et al., 2003). The process of making totora balsa hull reported herein was observed on the Uros Islands in 2006. The balsa was a small one approximately 3-m long. The hull building process was started by generating three totora bundles, two of approximately 60-cm in diameter and 3-m long and one of approximately 30-cm in diameter and 3-m long. In this case, two totora culms were overlapped to create the 3-m long bundles. The overlap was approximately 1 m and the culms were 2-m long. The overlap was made in a manner in which the apical part of the previous culms overlapped with the base of the subsequent ones. The three bundles were placed parallel on the ground, leaving the small one in the middle between the larger ones. Subsequently, a continuous thread for each big bundle was wrapped in spiral intervals of 10 cm by lashing each big bundle with the central one. Once the thread was positioned, the three bundles had to be tightened to form the hull. The culms were lashed as tightly as possible to achieve a compact body. The tension of the rope was gradually increased using a wooden tool to pull the rope and stiffen the whole bundle (Figs. 13 and 14). These totora balsas are used on Lake Titicaca for fishing, transportation, and as a tourist attraction. The average durability of small totora balsas (3–5-m long) in Lake Titicaca is approximately 6 months, and of bigger balsas (6–8-m long) (Fig. 15) is approximately 12 months (PELT and ADESU, 2003, 2001; Prieto, 2016).

Similar techniques have been employed by several cultures in America to make totora balsas (Rondón et al., 2003; Simbaña, 2003). Additionally, similar construction techniques have been reported for many other reed balsas for thousands of years worldwide using plants such as papyrus, typha or common reed for fishing, transportation, and seagoing vessels (Broadbent, 2008; Heyerdahl, 1971; Pearson, 1938). Some interesting experiments concerning totora balsas have been conducted according to the initial studies and expeditions performed by Thor Heyerdahl in the late 1940s. Among his expeditions, of particular interest is the Ra II expedition of 1960, which succeeded in crossing the Atlantic Ocean from Morocco to Barbados in 51 days on a balsa made with papyrus reeds, which, like totora, is a plant from the *Cyperaceae* family and has culms with a very similar structure to those of totora. After the first expedition, Ra I (1959) built by African reed boat builders from Lake Chad in Africa, had failed to reach the Caribbean due to

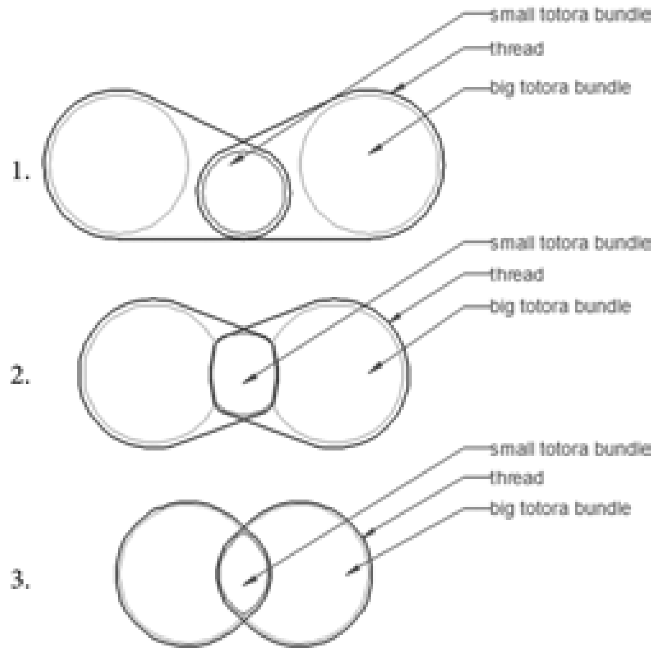

Fig. 13. Totora balsa hull making process.

Fig. 14. Thread tightening process for a small totora balsa (Hidalgo-Cordero).

Fig. 15. Large totora balsas next to a floating island on Lake Titicaca (Hidalgo-Cordero).

building deficiencies attributed to the loss of the building tradition of these kinds of vessels in Africa, Heyerdahl decided to hire a team of Aymara boat builders from Bolivia consisting of the Limanchi brothers José, Juan, and Demetrio, as well as Paulino Esteban, who had maintained their long tradition of making totora boats in Lake Titicaca. These men were taken to Africa to build the Ra II vessel using papyrus culms. This vessel succeeded in reaching the Caribbean in 51 days, confirming its seaworthiness (Díaz et al., n.d.; Heyerdahl, 1971; Portugal Alvizuri, 2017). After the experiences of Thor Heyerdahl, other explorers launched a series of expeditions across oceans using totora vessels to demonstrate theories about possible contacts between ancient cultures and the settlement of remote islands such as the Eastern Island. The explorers and their main expeditions using totora vessels are listed herein to illustrate the number of investigations concerning this subject. Kitín Muñoz (Uru expedition, 1988), a German Crew (Chimok expedition, 1988), Kitín Muñoz (Mata Rangi 1, 2 and 3 expeditions, 1996, 1999 and 2001, respectively), Paul Harmon and Alexei Vranich (QalaYampu expedition, 2009), Dominique Goerlitz (Abora 2 and 3 expeditions, 2002 and 2012 respectively), Phil Buck (Viracocha 1 and 2 expeditions, 2000 and 2003, respectively) (Allen, n.d.; Buck, 2017; Tangen, 2007), and recently Phil Buck have set up the Viracocha 3 expedition, which is expected to travel from Chile to Australia and thus cover more than 10,000 M, which would be the longest sea trip made on a reed ship (Buck, 2017). Most of these experimental journeys have lasted more than 2 months, which is important evidence of the strength of bound totora bundles considering the great strain of the constant shock of sea waves and the crew loads during these journeys.

Another interesting experience concerning the constructive possibilities of totora bundles was the "Totora Project" created by the Professor George Teodorescu as part of the International Master Program of Integral Innovation developed in collaboration between the SAdBK-Germany, and the PUCP-Peru during the course 2009–2010. The totora-bound bundle technique was used to create a series of experimental constructions that addressed the possibilities of using totora to build structures that could house some cultural and communitarian activities of the Uros people (PUCP, 2010). The structures consisted of lashed totora bundles of different dimensions and shapes, some of which more than 60-cm in diameter, to make approximately 4-m high arches (Figs. 16 and 17) (PUCP and SAdBK, 2010). Although information on the mechanical strength of these structures was not documented, they demonstrated that using this technique allowed the construction of complicated structural shapes that were able to support themselves and the eventual extra loads during the building process, such as the workers. More extensive research on this subject could be of interest to evaluate the structural behavior of totora bundles and its potential applications.

Another example of the use of bound totora bundles is presented by the work of Ricardo Geldres, who designed the "Silla Totora" chair made with a metallic framework to which round-shaped totora bundles were tied to form the seat and the backrest (Geldres, 2008).

6. Treatments and processes applied to totora

6.1. Experimentation using new techniques

Hidalgo-Cordero (2007), in his research conducted at the Universidad de Cuenca-Ecuador, experimented with several possible uses of totora as contemporary architectural finishes. The main purpose of this research was to potentiate the social and environmental benefits the use of totora could generate for its communities by proposing the diversification of the possible uses of this material in the contemporary architecture and industrial design field (Hidalgo-Cordero, 2008). In this research, tests to define some physical properties of totora culms were conducted. These tests showed that the dry weight of totora culms increased four times at the date of saturation. The initial absorption

Fig. 16. The biggest arches made out of totora being placed together. Totora Project, by Prof. George Teodorescu. (2009–2010) Master Program of Integral Innovation – SAdBK and PUCP, Lima-Peru. Photo: Rosemary Teodorescu.

capacity showed a 7% increase in the weight per minute during the first 20 min of immersion. This absorption capacity was considered to be of interest because it could save energy during the treatment application of the culms. The axial compressive strength of a single culm was 1.47 N/mm^2, and the axial compressive strength of a lashed bundle was 3.90 N/mm^2. The tension strength of a single culm was 3.70 N/mm^2. Hidalgo-Cordero developed several techniques for treating and using this material in the industrial design field and produced some design objects illustrating the wide variety of treatments of totora (Telerama, 2013). Among the innovative productive processes studied in his work was the "totora textile", a sheet made of short totora culms with a length of approximately 1.50 cm that is glued on one side to a natural rubber sheet. This totora sheet behaved as a flexible textile when bent outwards and as a stiff surface when bent inwards. The spongy tissue of the aerenchyma plays an important role in this case because it allows the achievement of almost perfect interlacing of the totora shapes, minimizing the air space between the culms and thus conferring, in the one case, textile rigidity. The combination of the stiffness and flexibility properties of this totora textile has been used in some furniture such as the totora flexible lounger (Fig. 18), the shape and rigidity of which can be changed to obtain different forms.

Other experimental designs of interest are the malleable totora surfaces consisting of a wooden mesh that holds totora culms placed perpendicularly to the mesh plane. The internal spongy tissue of totora

Fig. 17. The inauguration ceremony starts. Totora Project, by Prof. George Teodorescu. (2009–2010) Master Program of Integral Innovation – SAdBK and PUCP, Lima-Peru. Photo: Rosemary Teodorescu.

Fig. 18. Totora flexible lounger (Hidalgo-Cordero).

exerts a certain pressure among the culms, but their waxy rind simultaneously allows them to move independently in the longitudinal direction, rendering the effect of a malleable surface made of small movable particles. This malleable surface concept has been used for the malleable totora table, the boards of which are able to change shape to hold different objects (Fig. 19).

Another study examining the applications of totora in the industrial design sector analyzed the use of Polyvinyl acetate (PVA) glues to form agglomerated blocks, which were then sanded and modeled into bowls or furniture parts (Culcay, 2014). Strength tests conducted by Culcay showed a higher flexural strength for the agglomerated board sample made with cross laminated culms compared with the board made with parallel-oriented culms. The results of these tests provided values of 0.81 N/mm^2 and 0.16 N/mm^2, respectively.

6.2. Insulation capacity of totora

Aza-Medina (2016), in her research investigating the thermal insulating capacity of totora in the Universidad Politécnica de Catalunya-Spain, studied several totora samples using crushed and whole culms agglomerated with natural glues. The thermal conductivity was analyzed using the thermal analyzer Quickline TM-30. However, the samples that were made with crushed totora culms showed the best thermal conductivity values, with an average of 0.055 W/mK compared with the ones made with whole culms with an average of 0.066 W/mK. Conductivity values of the different totora elements are shown Table 2.

The samples were also tested for fire resistance according to the "UNE 23723:1990 Tests for determining the reaction to fire of building materials…" (AENOR (Asociación Española de Normalización y Certificación), 1990). This test revealed that crushed totora samples had ignitions that lasted 2.50 s and a mass loss of 31.60% on average. The samples consisting of full culms had ignitions that lasted 5.13 s and a mass loss of 23% on average. However, the samples consisting of ground and full culms that received a treatment based on potassium alum and borax salts showed no durable ignitions and were considered null. The mass loss of the treated ground totora samples was 27% on average, and the mass loss of the full culms samples was of 28% on average. The hygrothermal performance of the samples was also tested according to the standard "UNE-EN ISO 12572: 2016 Hygrothermic properties of construction products and materials, and water vapor transmission" (AENOR (Asociación Española de Normalización y Certificación), 2016). This test showed that the samples made with ground totora had a vapor resistance factor of $\mu = 4.35$ on average, which was similar to other insulating materials such as wool or wood fiber. The flexural resistance of the samples was tested using Zwick Roell equipment. In this case, the average dimensions were 150-mm long, 37-mm wide and 12-mm thick. The support distance was 100 mm, and the load was applied at the center of the samples. The results showed that the ground totora sample MoR was 0.48 ± 0.16 N/mm^2. The complete culm samples showed resistances of 7.46 ± 1.07 N/mm^2. In conclusion, this study is of interest because it demonstrates that totora boards can achieve a good balance between thermal conductivity and mechanical resistance in one layer, which is an interesting feature for materials in the contemporary construction sector (Krus et al., 2014). The mechanical strenght values of the different totora elements are reported in Table 3.

Table 2
Conductivity values of totora elements.

Material	Thickness cm	Conductivity W/mK	Reference
Quesana	5.00	0.083	Ninaquispe et al. (2012)
Ground totora	1.60	0.055	Aza-Medina (2016)
Agglomerated culms	1.50	0.066	Aza-Medina (2016)

6.3. Innovative applications of traditional weaving techniques

The Anti-Kiosk project developed by the Ecuadorian architecture firm odD+ architects is an interesting example of the use of woven

Fig. 19. Totora malleable table board holding a glass cup (Hidalgo-Cordero).

Table 3
Mechanical strength of different totora elements.

Material description	Thickness mm	Binder	Flexural strength N/mm^2	Compressive strength N/mm^2	Type	Reference
Cross laminated totora culm board	50	Polyvinyl Acetate	0.81		perpendicular to the fibers	Culcay (2014)
Parallel oriented totora culm board	112	Polyvinyl Acetate	0.16		parallel to the fibers	Culcay (2014)
Ground totora board	13 ± 2	natural adhesives	0.48 ± 0.16			Aza-Medina (2016)
Cross laminated totora culm board	13 ± 2	natural adhesives	7.46 ± 1.07		perpendicular to the fibers	Aza-Medina (2016)
Parallel oriented totora culm board	125	Polyvinyl Acetate		0.60	compression parallel to the culms	Culcay (2014)
Single culm	50	–		1.47	compression parallel to the culm	Hidalgo-Cordero (2007)
Lashed totora bundle	100	Mid tension thread		3.70	compression parallel to the culms	Hidalgo-Cordero (2007)

totora in contemporary architecture and design. The project consists of a round-shaped kiosk made of different wedges that can open like a puzzle to configure different spaces. Each wedge has a metallic framework to which the totora culms were woven by local artisans from Ecuador to create the external skin (odD+ architects, 2015).

The Totora Cube-Archqid developed by Lerner F., Fuentes A., Jara O, and Jones V. in Imbabura-Ecuador in 2016 is another interesting project that uses traditional weaving techniques from the local community of San Rafael de la Laguna, developed in collaboration with the community-enterprise Totora Sisa, to make a series of mats that are used as envelopes for an architectonic cubic structure. This cubic structure is made of wood panels that are hinged and can be opened to use the space in different ways (Franco, 2016). As stated by the authors, this is an experimental project with a main objective of cataloguing traditional weaving techniques for the community and providing incentive for the creation of new ways of thinking about this material and the possibilities it can offer to the contemporary architecture and construction field.

7. Pulp potential of totora

Although few studies have addressed the pulp potential of totora, the available data has reported an amount of holo-cellulose of approximately 40–60%, which could be of interest to the pulp production industry and the cyclability of totora construction materials (Condori, 2010; Dick et al., 2017; Simbaña, 2006).

The NaOH, sulfite and Kraft processes for producing totora cellulose pulp have been analyzed and reported by Simbaña (2003). The pulp yield percentages of totora culms from the San Pablo Lake in Imbabura-Ecuador were 26.10%, 38.20%, and 31.80%, and the bursting strength was 0.30 kg/cm^2, 0.85 kg/cm^2, and 0.99 kg/cm^2, respectively (Simbaña, 2003). This study did not report the concentration of the solutions used and indicated that the totora had a low pulp yield and that the obtained paper was of lower quality than those obtained from other natural fibers.

Another study on this subject was conducted in Puno by Condori (2010) using totora from Lake Titicaca to evaluate its suitability for producing glassine paper. In this case, a solution with a concentration of 8% NaOH provided a higher yield (44.20%) than the experiment mentioned above, which should presumably have been higher than 8%, potentially dissolving part of the useful cellulose and hemicellulose of the pulp and causing the lower pulp yield. The tensile index of the glassine paper produced was 0.11 Nm/g. This study also analyzed the average lignin content of the plants at different phenological stages: before flowering (3-month-old), during flowering (6-month-old), and after flowering (12-month-old). The lignin content of the plants collected before, during, and after flowering were 34.99%, 25.30%, and 23.57%, respectively (Condori, 2010).

Another study conducted by Dick et al. (2017) in Rio Grande, Brazil, analyzed the chemical characteristics of totora culms, its kraft pulp yield, and the physical properties of its fibers. This study reported holocellulose contents of 55.89%, lignin contents of 22.19%, total extract contents of 11.98%, acetone extracts of 3.60%, solubility in acid of 2.70%, uronic acid content of 1.85%, ash content of 7.67% and silica content of 4.80%. Based on the physical analysis of the totora fibers, it was stated that although their length was similar to eucalyptus fibers, their width was smaller, which could reduce the final resistance of the totora paper. This study stated that the high level of total extracts, silica content, and hexuronic acid content, and the smaller width of the totora fibers could be unfavorable during the cellulose production process. The cellulosic pulp of the short fiber was produced with the Kraft method and provided a Kappa number of 45.74 and purified yield of 45.85%. (Table 4).

Some artisanal projects have been performed to assess totora paper production, e.g., the case of Bertha Soto from Bolivia, or the community-enterprise Totora Sisa from Ecuador are two current examples of

Table 4
Chemical analysis and pulp yield of totora culms.

Material description	Holo-cellulose %	Lignin%	Pulp yield %	Kappa no.	Strength	Method	Reference
Totora culms	55.89	–	–	–	–	HPLC-PAD[a] according to (Wallis et al., 1996)	Dick et al. (2017)
Totora culms	–	22.19	–	–	–	TAPPI T 222 om-98-adapted	Dick et al., (2017)
Totora culms	–	–	45.85	–	–	Kraft. AA[b] = 7% Na_2O, sulfide 25%, liquor/reed = 5/1, max. temp.[c] = 170 °C, time to max. temp.[c] = 90 min.	Dick et al. (2017)
Totora cellulose pulp	–	–	–	45.75	–	TAPPI T 236 om-85	Dick et al. (2017)
3-month-old totora culms	–	34.99		–	–	Acid Detergent Lignin. (Van Soest, 1963)	Condori (2010)
6-month-old totora culms	–	25.30	–	–	–	Acid Detergent Lignin. (Van Soest, 1963)	Condori (2010)
12-month-old totora culms	–	23.57	–	–	–	Acid Detergent Lignin. (Van Soest, 1963)	Condori (2010)
Totora culms	–	–	44.20	–	–	8% NaOH for 24 h	Condori (2010)
Totora-based glassine paper	–	–	–	–	0.11	Tear strength according to (Casey, 1990). Nm/g	Condori (2010)
Totora culms	66.79	27.80	–	–	–	–	Simbaña (2006)
Totora culms	–	–	26.10	–	0.30	NaOH pulp yield bursting strength kg/cm^2	Simbaña, (2003)
Totora culms	–	–	38.20	–	0.85	Sulfite pulp yield bursting strength kg/cm^2	Simbaña (2003)
Totora culms	–	–	31.80	–	0.99	Sulfate pulp yield bursting strength kg/cm^2	Simbaña (2003)

[a] HPLC-PAD. High-performance Liquid Chromatography with Pulsed Amperometric Detector.
[b] AA. Active alkali load.
[c] Max. temp. Maximum temperature reached during the process.

artisanal producers of paper and decorative envelopes made from totora culms (Álvarez, 2011; Bautista and Sánchez, 2015). Although production is at a very low scale, the ability to produce paper or cardboard from totora using relatively simple methods could be an indicator of the recyclability potential of the material, which could lead to a closed-loop system. Further research is needed in this field of study to accurately assess this subject.

8. Conclusions

The current demand for forest products from the building sector is increasing, which has led to a surge in research and developments that have made it possible to use a wider range of materials for the high demand of construction needs, e.g., fast-growing conifer wood in structures. These advances suggest that other forest products could be studied and improved to fulfill some of the needs of the current construction industry, which could lead to a reduction of pressure on conventional wood forests and plantations.

Totora is an emergent macrophyte with a habitat, anatomy, growth rate, phytodepuration capacity, physical properties, and traditional uses for which studies and recent experimentation support its potential for use in the industry to diversify sources of biomass-based materials. Since totora can grow in many climate zones, it would be possible to generate short-term local material sources in parts of the world where the climate is not suitable for growing wood forests, which could lead to a more balanced resource distribution. The traditional techniques and new experiments conducted using totora indicate that it is a versatile material that can be subjected to different procedures to improve its properties. Totora could be a reliable material source that is renewable and, when managed correctly, it can provide material for a long time with minimal potential environmental impacts, as demonstrated in the Uros Islands in Lake Titicaca.

Despite the long traditional use of totora by several communities, the available published data are scarce. The goal of this review was to organize and promote this information to foster further research on this material and identify potential advantages and possible limitations that must be solved to benefit from this material in the contemporary industrial field.

Conflict of interest

The authors declare there are no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.indcrop.2017.12.029.

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