# Fiberboards Made from Corn Stalk Thermomechanical Pulp and Kraft Lignin as a Green Adhesive

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The feasibility of incorporating purified kraft lignin, at different concentrations ranging from 5 to 29%, into fiberboards made from corn residues was studied. The lignin was obtained from black liquor, which is a residue of the paper industry. Corn stalk raw material and its thermomechanically produced fiber were characterized in terms of their chemical composition. The physical and mechanical properties of the resulting fiberboards were evaluated. The fiberboards produced following a wet process had good mechanical and water resistance properties that satisfied the requirements of the relevant standards. In addition, a Life Cycle Thinking (LCT) approach suggested that lignin-based fiberboards are environmentally preferable than those based on thermosetting resins.

*Keywords: Corn residues; Thermomechanical pulp; Kraft lignin; Green adhesive; Mechanical properties; Life cycle thinking*

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## INTRODUCTION

Corn (*Zea mays*, Poaceae family) is a cereal crop, grown in various agro-ecological regions. Corn is an important food for many people in Africa, Asia, and Latin America (Yaning *et al.* 2012) and is also used in livestock feed (poultry, pigs, cattle) in the form of grains, feed milling, or as fodder (Escalante-Ten Hoopen and Maïga 2012). The global corn production increased from 729 to 1038 million tonnes (42.38% improvement) during the decade 2004 – 2014, which is higher than the relative increase of world population 12.89% (6.44 to 7.27 billion) for the same period (FAOSTAT 2016).

Cobs, leaves, and stalks are important residues of corn processing and consumption, remaining after corn grains are collected. Among these, corn stalks give an important proportion, amounting to 0.50 kg for every kg of dry corn grain produced (Sokhansanj *et al.* 2002). Among all agricultural wastes, corn stalk is an important lignocellulosic crop in terms of annual global production (Table 1). Currently, these residues have a number of limited application, *e.g.* (a) use of stalks as livestock feed and biofertilizer (Chen *et al.* 2010; Li *et al.* 2007; Duffy and Marchand 2013), as lignocellulosic fibers for pulp and paper making (Flandez *et al.* 2010) and ethanol production (Hong *et al.* 2015), (b) use of corn cobs as building materials and activated carbon (Cao *et al.* 2006; Pinto *et al.* 2012), (c) use of corn leaves as a feedstock for fermentable sugars and supplemental fiber for paper pulp (Donghai *et al.* 2006; Shinners and Binversie 2007). However, these residues are not efficiently managed; they are mainly burned in the field, particularly in developing parts of the world

(Pang *et al*. 2012). Since there is a lack of waste management, there is a need for applications of such residues.

**Table 1.** Annual Production of Agricultural Lignocellulosic Residues in 2014*

| Lignocellulosic Residue | $10^6$ Tm/year |
|---|---|
| Cereals** | 1,537 |
| Corn | 1,237 |
| Rice | 1,139 |
| Soybean | 481 |
| Sorghum stalk*** | 252 |
| Sugarcane | 203 |
| Rapeseed | 123 |
| Cotton Stalk*** | 68 |
| Total: | 5,040 |

*Elaborated from Smil 1999, (Smil 1999; Kim and Dale 2004; FAOSTAT 2016, and Leal *et al*. 2013)
**Includes wheat, barley, triticale, oat, and rye
***Cotton stalk and sorghum stalk production values were published in Hurter (2015)

Kraft lignin is a by-product of pulp mills generated during the kraft pulping of wood chips, which is the most common chemical pulping method. Currently, approximately 2% of the produced lignin is utilized in value-added and commercial products (paper industries, medical, agriculture, fuel, chemical, concrete and cement, carbon fibers/nanotubes, board binder, dust controller, battery, cosmetics, foams, plastics, and heat), while the rest is burned to generate energy and recover chemicals (Khitrin *et al.* 2012). However, this trend is changing due to the increasing interest in developing lignin-based products. Some of these high-value products include: green substitutes for fossil fuel, carbon fibers, surfactants, polymer blends, and composites; phenol replacement in phenol-formaldehyde resin; and green binders. For these two last applications, Anglès *et al*. (2001), Mancera *et al*. (2012); and Mejía *et al*. (2014) have reported several strategies to develop natural lignin-based adhesives for their use in panel products. Moreover, many recent patents have described the replacement of formaldehyde-based resins with industrial lignin but, for various reasons, they have not been implemented (Vishtal and Kraslawski 2011). It must be noticed that previous published references used the dry process to produce fiberboard, but there has been a lack of publications on the topic of the wet process at the laboratory scale, which has great interest at the industrial scale, as there are industries that follows this process.

Waste production has been an issue of concern within the European Union for many years, with a first Directive published in 1975 (EC 1975). The first adopted policies were “end-of-pipe” oriented, *i.e.*, introducing technologies to minimize the impact of waste after it was produced. Subsequent policies have improved on the preceding ones in terms of environmental impact and economic cost. In early 1997, the Council of the European Union confirmed the so-called waste management hierarchy in which waste prevention is the first priority of waste management, followed by re-use and material recycling; only after verifying those options are not feasible, waste is used for energy recovery (EC 1997). Burning without energy recovery and landfilling are the very last options of waste management. The life cycle approach is commonly used to verify that a given waste management option is better environmentally speaking than another one or to confirm the hierarchy for a specific case (Finnveden *et al.* 2005; Moberg *et al.* 2005; Hauschild and Barlaz 2009). To standardize the “green” product categorization, the European Commission has initiated the “Single Market for Green Products” (Klüppel 2005), based on a harmonized methodology for the calculation of the so-called “Product Environmental Footprints”, which are, in fact, life cycle assessment studies. Waste should not only be considered a problem but rather a valuable resource for industry (Zamagni 2012). Recently, circular economy principles have been strongly pushed into the European market. Turning Europe into a more circular economy means enhancing product recyclability, reducing the use of new raw materials and demonstrating that a new economy based on the preservation of the environment can help to achieve a minimum-waste production (Zaman 2015). Based on a life cycle thinking approach, the environmental pros and cons of the boards with added lignin were examined.

The present study aims to (1) develop fiberboards made from corn stalk thermomechanical fibers with reinforcement of kraft lignin as a natural binder using the wet process to produce fiberboards and (2) discuss life cycle aspects of the composite preparation and subsequent processes. Corn biomass will be treated by steaming in a rotary digester reactor without any chemical agent addition, while kraft lignin will be extracted from black liquor (residues of pulp and paper production) and dried to be a powder form, and later mixed both materials together with additional of water using a disintegrator. The final goal is to produce binder-free composite from corn stalk having enhanced properties with respect to commercial fiberboards that rely upon the usage of synthetic resin, and lastly to discuss the shelf life of this product based on pros and cons impact on environment.

## EXPERIMENTAL

### Materials

The basic materials used in the research were corn biomass and spent black liquor pulp. Corn residues (moisture content of 12%) were collected from a field at La Tallada d'Empordà, Girona, Spain, and stored at room temperature. The commercial spent black liquor pulp was supplied by Torraspapel S. A. Pulp and Paper Factory (Zaragoza, Spain), and had a pH of about 12. Sulfuric acid ($H_2SO_4$) at 72% concentration and sodium hydroxide (NaOH) were purchased from Sigma-Aldrich (Barcelona, Spain) and used as received. Cationic starch and colloidal silica were provided by Torraspapel S. A. (Sarrià de Ter, Girona, Spain) and were used as retention agents during the dispersion of both the corn fibers and the powdered purified kraft lignin.

### Methods

*Thermo-mechanical corn stalk fiber production*

The preparation of thermomechanical fibers involves vaporization, followed by mechanical defibration. A suspension of corn stalks was submitted to steam-water treatment by keeping the suspension at 160 °C for 15 min in a reactor, at a water-to-solid ratio of 6:1 (liters of water per kg of solid). The obtained pulp was rinsed in cold water and then submitted to mechanical defibration in a Sprout-Waldron refiner (model 105-A, Andritz, Janesville, WI, USA), which was responsible for fiber individualization (Theng *et al*. 2015).

*Lignin preparation*

Purified kraft lignin powder was prepared from commercial black liquor, as described by Lin (1992). Commercial black liquor was first treated with hot water with stirring. The homogenized black liquor solution (pH 12) was acidified using 72% sulfuric acid with stirring. The solid lignin was recovered by precipitation after lowering the pH of the mixture to 2 and applying filtration. Solid lignin was washed with distilled water and filtered several times to remove residual sulfuric acid. To recover pure, powder-form lignin, the solution pH was increased to 6.0 by the addition of sodium hydroxide, and the lignin was subsequently dried in an oven at 60 °C (Mancera *et al*. 2012). After drying at room temperature, lignin samples were stored in plastic bags for use as a natural green adhesive in corn stalk fiberboards.

*Fiberboard production*

Corn stalk pulp was passed through a Sprout-Waldron machine and subjected to a vacuum until the moisture content reached 20%. Using a disintegrator at 80,000 revolutions to ensure good dispersion, the pulp was mixed with lignin in different proportions (0, 5, 9, 13, 17, 21, 25, and 29%), followed by addition of the retention agents 0.5% cationic starch and 0.8% colloidal silica, and water. With the obtained mixture, a web was made using a paper sheet former of 20 cm diameter, which was then cut carefully to the same size of the molding box (150 mm in length and 50 mm in width). Boards were prepared with a target thickness of 3.0 mm. After the material was placed in the mold, it was hot-pressed in a three-stage cycle (Angles *et al*. 1999) consisting of: (1) pressing at the desired temperature (230 °C) and pressure (0.23 MPa) for a given period of time (2 min); (2) a breathing period or pressure relaxation for 1 min; and (3) pressing at the desired temperature and pressure for a given period of time (230 °C, 0.23 MPa, and 5 min). The experimental procedure is shown in Fig. 1.

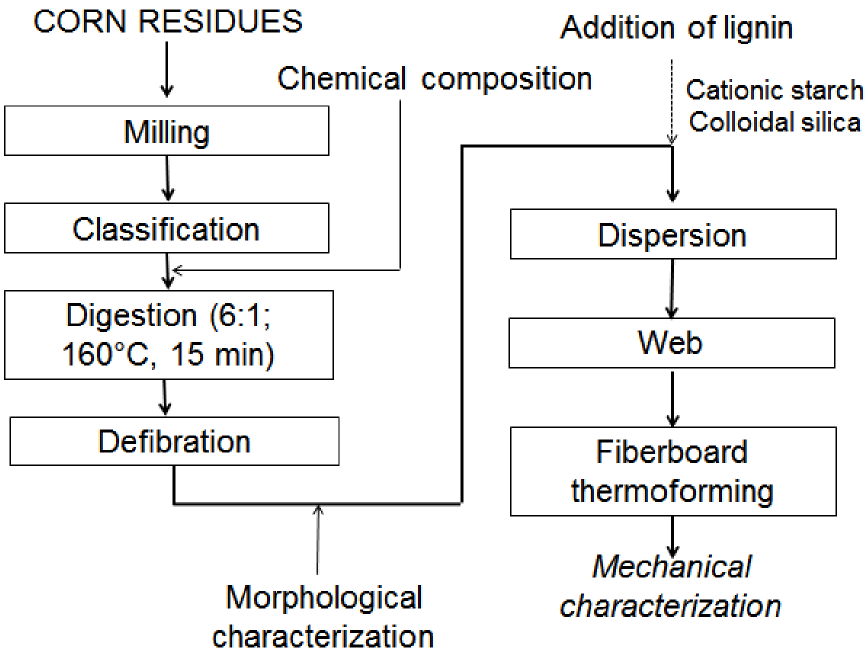


**Fig. 1.** Flow chart of the experimental procedure

*Physical and mechanical characterization*

The boards were characterized using European standards. The measured mechanical properties were impact strength (IS), modulus of elasticity (MOE), and modulus of rupture (MOR) (EN310 1993). Dimensional stability was characterized by thickness swelling (TS) (EN317 1993) and water absorption (WA) (EN382-1 1993). Additionally, the density of the boards was determined (BS-EN323 1993). Boards were conditioned at 20 °C and 65% relative humidity before any physical or mechanical tests were conducted, and the dimensions of the test pieces were determined by EN325 (1993).

*Characterization of corn stalk materials and lignin adhesive*

For corn stalk waste and corn stalk pulp, the ash contents were obtained gravimetrically after furnace calcinations for 3 h at 575 °C (ASTM D1102-84 2001). The corn stalk samples were milled and treated with 95% ethanol for 6 h in a Soxhlet apparatus to remove extractives. The Klason lignin was determined by the conventional method as the insoluble fraction after two-step acid hydrolysis (TAPPI T 222 Om-98 1985). Acid-soluble lignin was determined by applying the spectrophotometric method (TAPPI UM 250 1991). The cellulose and hemicellulose were determined as described by Wise *et al*. (1946) and TAPPI standard T223 cm-01 (2001), respectively.

Thermogravimetric analysis (TGA) of purified kraft lignin powder was measured using a TGA-50 series instrument (Shimadzu, Japan), with temperature up to 1000°C and maximum sample mass 1 g. The samples were heated from room temperature to 800 °C with a heating rate of 5 °C/min under an air atmosphere. Thermogravimetric analysis was conducted to measure if the temperature of the thermoforming would degrade lignin.

## RESULTS AND DISCUSSION

### Thermogravimetry of Purified Kraft Lignin

The TG curve of the lignin sample displayed the mass loss of polymeric materials *vs*. the temperature of thermal degradation (Fig. 2).

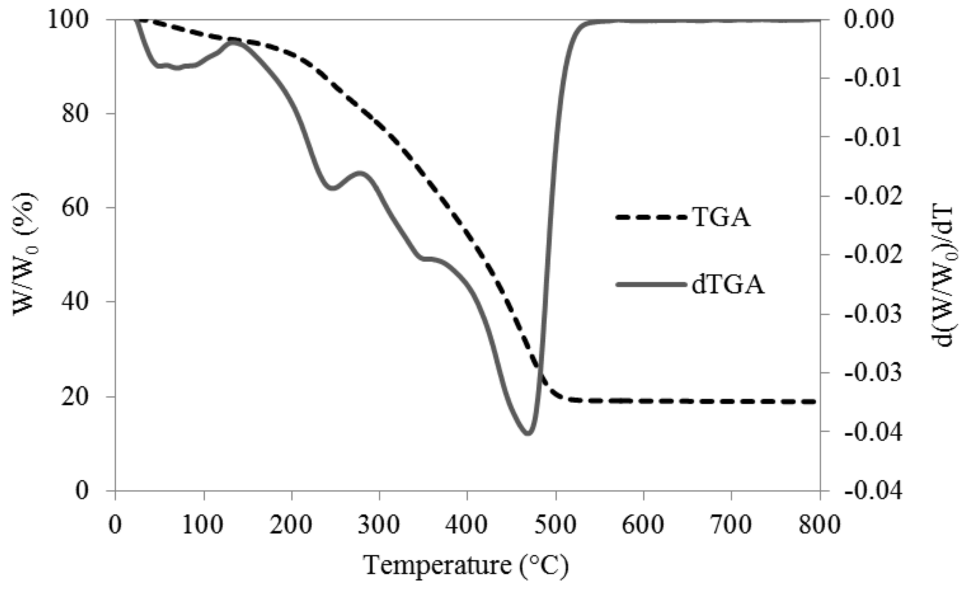


**Fig. 2.** Thermogravimetric analysis of kraft lignin

A first mass loss was observed at 100 ºC, concurring with water vaporization. Moisture content of the trial lignin powder was 3.73%, being of the same magnitude as the observed weight loss in the TGA curve at 100 ºC. Then, the thermal degradation of all lignin compounds took place at a stage between 200 ºC and 500 ºC (approximately 72% of mass loss). At this stage, all carbohydrate volatile components in the lignin sample were degraded. At higher temperature, there was no more weight loss, since the remaining mass corresponded to ash (about 19% of the total mass) by the end of the measurement. These results are in accordance with a previous report showing that the degradation temperature of lignin began at around 200 °C, depending on the lignin origin (El Mansouri *et al*. 2011).

Figure 2 also indicates the mass loss rate as a DTGA (derivative thermogravimetry) curve, which is shown as a square dot line. The peak of this curve can be expressed as a single thermal decay temperature and used to compare its polymeric materials in term of thermal characteristics. This analysis illustrated that when the lignin sample was heated at about 450 ºC, pyrolytic deprivation took place and the inter-unit linkage of the lignin structure became fragmented, with the release of monomeric phenols into vapor phase. The range of obtained maximum derivative thermogravimetric is in agreement with other previous findings (El-Saied and Nada 1993; Sun *et al.* 2000; Tejado *et al.* 2007; El Mansouri *et al.* 2011). The high temperature of lignin degradation allows applicable of blending it with other lignocellulosic materials and compress at quite high temperature to produce fiberboards without decomposed lignin.

### Chemical Composition of Corn Stalk Raw Material and Pulp

Table 2 shows the chemical composition of corn stalk raw material and pulp.

**Table 2.** Chemical Analysis of Corn Stalk Raw Material and Pulp

| Chemical Analysis | Corn Stalk | Corn Stalk Pulp |
|---|---|---|
| Ash Content (%) | 3.20 | 0.80 |
| Extractives (%) | 3.10 | 1.05 |
| Lignin Content (%) | 16.00 | 17.24 |
| Cellulose (%) | 50.57 | 55.17 |
| Hemicelluloses (%) | 27.03 | 25.75 |
| Holocelluloses (%) | 77.60 | 80.92 |

Corn stalk contains more cellulose but has relatively low lignin content compared to commonly used wood fibers from pine and eucalyptus (Mancera *et al*. 2012), which suggests its suitability as an alternative for industrially manufactured fiberboards and papers. The corn stalk raw material was submitted to thermomechanical processing at 160 °C for 15 min; this procedure determined the final morphology and chemical composition of the obtained fibers. In this case, the fiber yield was about 87.1 wt./wt.%. Theng *et al*. (2015) indicated that thermomechanically processed corn fibers contain almost all the initial lignin, with the exception of the waxes and extractives removed during the steam treatment. The obtained pulp exhibited higher cellulose and lignin contents with lower hemicelluloses content.

### Effects on Water Absorption and Thickness Swelling

Water absorption (WA) and thickness swelling (TS) are physical properties related to the dimensional stability of the fiberboards (Fig. 3). These properties demonstrate how the boards would behave if they were used under humid conditions, as physico-mechanical properties of lignocellulosic materials always are strongly related to the water content. Lower values of water absorption and thickness swelling mean higher dimensional stability, resulting in a better performance when fiberboards are submitted to any strain. Establishing a parallelism with papermaking, fiberboards with less relative bonded area (RBA) are more likely to retain water due to the availability of hydroxyl groups on the fiber surface. In addition, fiberboards with a higher RBA have more inter-fiber bonds per volume unit, leading to higher physico-mechanical properties (Page 1969).

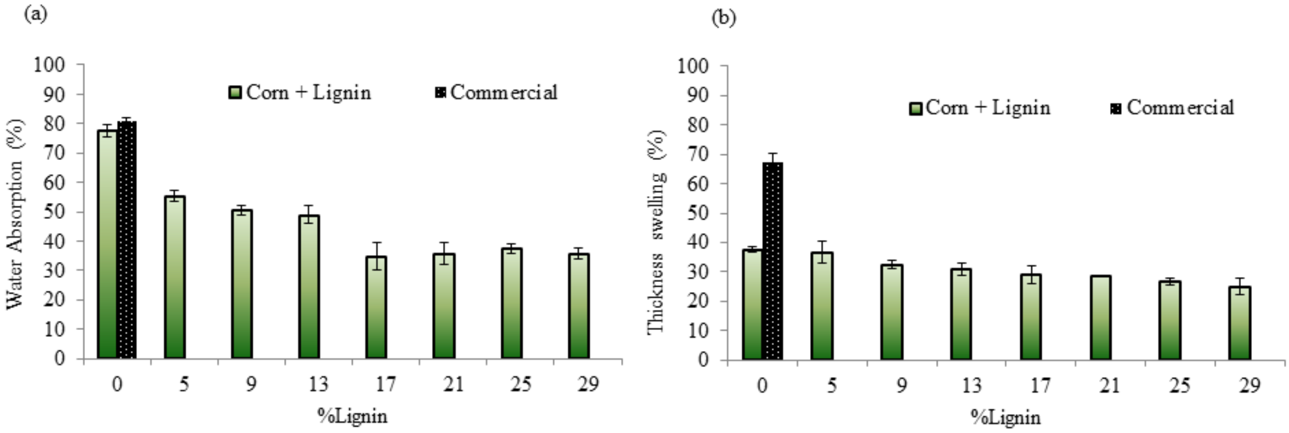


**Fig. 3.** (a) Mean water absorption (WA) and (b) thickness swelling (TS) of fiberboards

As shown in Fig. 3(a), increasing amounts of kraft lignin decreased the water absorption values of the fiberboards. Specifically, the addition of 29 wt./wt.% kraft lignin decreased WA by about 50.5% compared with the binderless fiberboard and 54.3% if the commercial fiberboard is taken as reference. Therefore, increasing lignin content notably decreased the water absorption and, thus, improved the water resistance and dimensional stability of the fiberboards. Rowell *et al.* (1976) reported that lignocellulosic materials absorb water by forming hydrogen bonds between water molecules and hydroxyl groups in cell wall components. However, the addition of kraft lignin during the preparation of fiberboards reduced their water absorption. This result can be explained by the presence of non-polar hydro-carbon chains and aromatic rings in the lignin molecule (Rozman *et al*. 2000).

Thickness swelling occurs in fiberboards when the cell wall is bulked by water. As shown in Fig. 3(b), the addition of kraft lignin reduced thickness swelling in all fiberboards made of corn. The addition of 29 wt./wt.% kraft lignin decreased TS by about 33.6% compared with the binderless fiberboard and 63% if the commercial fiberboard was taken as reference. These results clearly showed that the addition of kraft lignin reduced swelling in fiberboards. The same behavior was reported by Mancera *et al*. (2012) when studying the effects of adding alkali lignin to *Vitis vinifera* fiberboards.

## Effects on Modulus of Rupture and Modulus of Elasticity

The modulus of rupture (MOR) and the modulus of elasticity (MOE) are mechanical properties related to the bending strength of fiberboards. These values were analyzed together in the same bending assay (Figs. 4a and b, respectively).

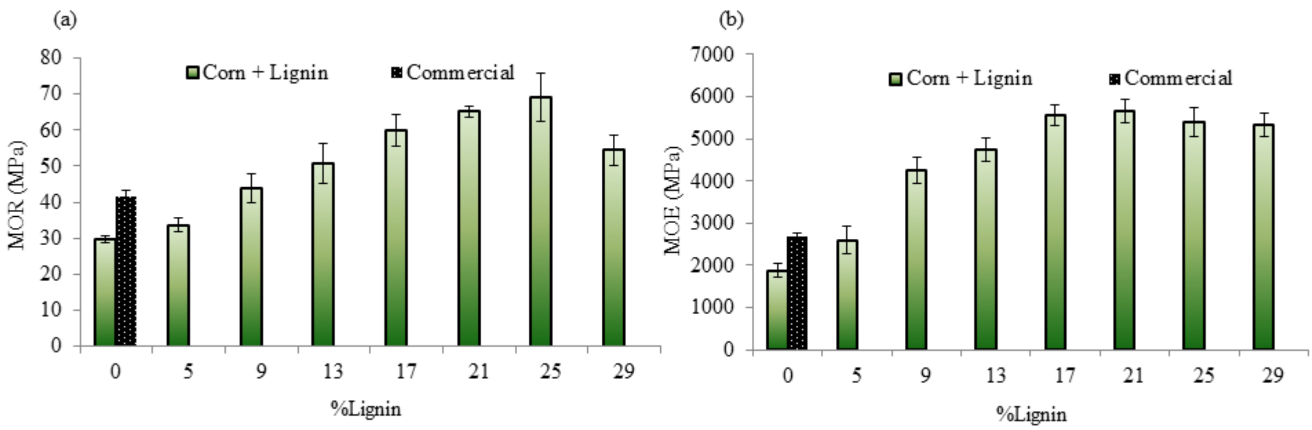


**Fig. 4.** (a) Mean modulus of rupture (MOR) and (b) modulus of elasticity (MOE) of fiberboards

Fiberboard MOR was enhanced by increasing amounts of added kraft lignin (Fig. 4a). Thus, kraft lignin was effective as a green adhesive. It is particularly interesting to note that the formulation made with just 9 wt./wt.% of kraft lignin showed MOR values higher than those of the standard specifications. More interesting are the results obtained for both formulations made with 17 and 25 wt./wt.%-added kraft lignin, in which the strength of the fiberboards was more than two times higher than that obtained for binderless fiberboards. This result indicated that the addition of kraft lignin improves the MOR of fiberboards made from corn stalk fibers. This improvement can be explained by the good adhesion between fibers produced by the addition of kraft lignin, which is able to overcome discontinuity in the fiber matrix. Recently, Theng *et al.* (2015) added cellulose nanofibres (CNF) to corn biomass to produce HDF, and their results showed that 2 wt.% CNF increased the MOR from 30 to 53 MPa, which is less than that obtained with 25% lignin and equivalent to those obtained with 13% lignin (Fig. 4a). Unlike lignin, an addition of more than 2% CNF did not increase the MOR of the board, suggesting that the surface of the TMP fibers was saturated by CNF nanofibers. Nasir *et al*. (2013) obtained a maximum MOR with a 10% addition of lignin, which was somewhat below the performance level of the commercial board. Figure 4b shows that the MOE of the fiberboards was notably increased as the lignin loading increased to 21%, with a value over 5500 MPa, which is slightly higher than that obtained by adding CNF to corn fibers (Theng *et al*. 2015) and notably higher than that of the commercial board. Thus, kraft lignin enhanced the stiffness of fiberboards, possibly through fiber compatibility. In this regard, other authors have shown that the addition of lignin increased the MOR and MOE more so than phenol-formaldehyde additions (Oluwasina *et al*. 2015).

## Effects on the Impact Strength

The impact strength describes the ability of a material to absorb shock and impact energy without breaking. The impact strength of fiberboards increased to 6.4 $KJ/m^2$ as the lignin content was increased from 0 to 29% (Table 3), which was mainly due to the high-interface bonding strength. It is interesting to note that the impact strength of fiberboards made with 29 wt./wt.% kraft lignin was doubled compared with that of binderless fiberboard. Thus, the results confirmed that lignin improves the impact strength of fiberboards made from corn stalk fibers. This effect was due to the good melting of the kraft lignin at the selected operation conditions, which was able to flow over the fiber surface and form strong inter-fiber bonds (Back 1987). Nevertheless, this value was still lower than the impact strength of commercial fiberboards because formaldehyde-based resins have higher interface bonding strength than lignin. These results were in agreement with previous reports (Castro *et al*. 2012; Silva *et al*. 2012; Theng *et al*. 2015). The lower impact resistance compared with commercial board is probably due to the higher interface bonding strength of formaldehyde-based resins.

## Specific Properties of Fiberboards

The physical and specific mechanical properties of the fiberboards are shown in Table 3. These properties were studied against the percentage of added kraft lignin, from 5 wt./wt.% to 29 wt./wt.%.

**Table 3.** Results of Mechanical Properties of Fiberboards

| Trials | $\rho$ (kg/m$^3$) | $f_m/\rho$ (MPa.m$^3$/kg) | $E_m/\rho$ (MPa.m$^3$/kg) | IB/$\rho$ (MPa.m$^3$/kg) | IS (kJ/m$^2$) |
|---|---|---|---|---|---|
| Commercial | 883 ± 19 | 0.047 | 3.02 | $5.32.10^{-4}$ | 10.81±0.20 |
| Corn TMP | 917 ± 48 | 0.032 | 2.04 | $2.12.10^{-4}$ | 2.92±0.11 |
| Corn + 5% Lignin | 1063 ± 47 | 0.032 | 2.45 | $3.24.10^{-4}$ | 3.45±0.36 |
| Corn + 9% Lignin | 1107 ± 38 | 0.040 | 3.84 | $2.95.10^{-4}$ | 4.62±0.39 |
| Corn + 13% Lignin | 1108 ± 54 | 0.046 | 4.29 | $4.29.10^{-4}$ | 5.37±0.35 |
| Corn + 17% Lignin | 1168 ± 54 | 0.051 | 4.76 | $4.12.10^{-4}$ | 6.35±0.28 |
| Corn + 21% Lignin | 1135 ± 45 | 0.057 | 4.99 | $4.32.10^{-4}$ | 6.33±0.34 |
| Corn + 25% Lignin | 1098 ± 28 | 0.063 | 4.92 | $4.53.10^{-4}$ | 4.95±0.32 |
| Corn + 29% Lignin | 1128 ± 14 | 0.048 | 4.72 | $3.11.10^{-4}$ | 5.47±0.55 |

Two results for no added kraft lignin were included, which corresponded to binderless corn stalk and commercial fiberboards. All fiberboards (both control samples and kraft lignin-containing fiberboards) had densities from 900 to 1100 kg m$^{-3}$ and were classified as high density fiberboard (HDF) based on European standard EN316 (1999). These results were similar to those in a previous work using nanofibrillated cellulose (NFC) as a reinforcement agent (Theng *et al*. 2015). The results of the trial work included density and specific mechanical properties (Table 3). The specimens of fiberboards with added lignin obtained higher specific strength and specific elasticity than commercial fiberboards, but they were lower in specific internal bonding strength and impact strength. Moreover, as the amount of lignin was increased, specific properties were enhanced as well. This indicates that, in the case of absolute properties, the properties improvement not only comes from the increase on the density, but also in the formation of stronger bonds (*i.e.* covalent) at high temperature.

## Discussion on the Green Properties of the Proposed Material

According to circular economy postulates, reintroducing wastes such as corn stalk and lignin into the economy reduces the need for net resources (Iqbal *et al.* 2013; Asim *et al.* 2015), as less synthetic adhesives and wood pulp are extracted from the environment to deliver a product with equal or better physical properties. In addition, substituting natural materials in place of potential carcinogenic agents such as formaldehyde compounds represents an improvement in another area of protection: human health. Finally, avoiding the practice of burning corn stalk decreases $CO_2$ emissions and, therefore, enhances the protection of the natural environment (Jegatheesan *et al*. 2009).

In the life-cycle thinking (LCT) approach, however, the optimal percentage of lignin needs to be determined in order to know if the proposed alternative is beneficial. In order to balance the ideal with practicality (Baitz *et al.* 2013; Bidstrup *et al*. 2015), a quantitative life cycle assessment (LCA) was not applied at this point, but may come in at a later stage. LCT and LCA are the scientific approaches behind modern environmental policies and business support related to Sustainable Consumption and Production (EC 2010). A complete LCA is not always needed to guide environmental innovation, but a LCT approach is essential. According to various authors (Lazarevic *et al*. 2012; Wolf *et al*. 2012), LCT is essential to the Thematic Strategy on the Sustainable Use of Natural Resources and the Thematic Strategy on the Prevention and Recycling of Waste (EC 2005) and is very important for the Waste Framework Directive. These strategic documents are relevant to the present study, as the main goal of a sustainable use of natural resources is based on waste prevention and recycling. A condition *sine qua non* identified by the Directorate for General Research and Innovation of the European Commission for the call on Sustainability Assessment of Technologies was that both the framework technology and its derived methods and tools had to be based on LCT approaches, *i.e*., adequately considering the three pillars of sustainability (economic, environmental, social). Other documents state that sometimes a fully-fledged LCA is not needed (see Bala *et al*. (2010) for a list of examples). Sometimes, the intermediate alternative of a simplified LCA may be used (Delgado-Aguilar *et al*. 2015), which is between a complete LCA and a qualitative life-cycle approach.

Corn stalk is a residue, but dumping it *in situ* gives the soil structural properties and organic matter that enhance the productivity of the soil. The decrease in productivity resulting from the removal of the stalk should be compensated for by the addition of other (synthetic) products, which have their own life cycle of resource needs and emissions. In contrast, if a burning scenario is in place, the emitted $CO_2$ would equal the absorbed $CO_2$ used by the corn plant to grow (Garcia and Freire 2014). In addition, processes to collect, pack, and transport the stalk are needed, with, again, evaluations with regard to life cycle impacts. If stalk became a commercial product, an end-of-waste situation might occur, and an allocation of the environmental impacts of corn growth may be needed between corn-related products (food or fuel) and stalk-related products (boards). Therefore, the proposed alternative could be better, for instance, in terms of human toxicity or climate change but worse in terms of eutrophication or acidification.

From a circular economy point of view, using lignin as an adhesive instead of burning the lignin liquor for energy recovery keeps the substance longer in the system; this clearly entails a down-cycling process, as further recovery from the board is not possible. Other less destructive recycling processes could maintain lignin longer in the system, but as long as lignin waste is available in sufficient quantities, this discussion may be postponed.

Parameters such as the lignin extraction efficiency, the needs of energy and water within the thermomechanical processes, the importance of the added chemicals within the lignin production processes, the differential quantity of energy and chemicals needed for fiberboard production, the life expectancy of the boards, the amount of board material required to fulfill the needed function, and the recyclability of the final product have important effects on the total environmental impact of the stated alternatives.

To go beyond life-cycle thinking, a life-cycle management perspective (Fullana i Palmer *et al*. 2011) indicates that to put this system in place, a new value chain is needed, requiring the different actors to agree on the new market conditions and the development of new logistics. Social barriers such as historical practices by corn farmers would have to be overcome.

The proper percentage of lignin may vary from one application to another, and depending on function, the board may require different degrees of strength (structural uses), water resistance (humid environments), or other physical properties. Therefore, the compared environmental impact may vary as well among the foreseen applications.

In sum, with the information gathered from investigating the life-cycle consequences, it is believed that using waste corn stalk in fiberboards is environmentally beneficial and that waste lignin may be called a green adhesive when substituting it for formaldehyde-based adhesives.

## CONCLUSIONS

1. The chemical composition of corn stalk revealed high cellulose and moderate lignin content, which supported its suitability as an alternative source for wood fibers used in fiberboards manufacturing.
2. Corn stalk fiberboards made without green adhesive had weaker mechanical properties than commercial ones. However, fiberboards containing more than 20% purified kraft lignin added in fiberboards produced by the wet process had good mechanical and water resistance properties that fully satisfied the relevant standard specifications.
3. Lignin provided fiberboards with benefits such as increased MOR, MOE, and impact strength. However, fiberboards made from corn stalk thermo-mechanical pulp showed lower performance in terms of this last property than commercial fiberboards.
4. Life-cycle thinking has been essential to finding the environmental pros and cons of proposed technologies. Although sometimes a simplified approach is adequate, this work recommends a thorough but practical life cycle assessment study for specific board applications to quantify the environmental impacts of competing alternatives.

## ACKNOWLEDGMENTS

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