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Environmental assessment of bioproducts in development stage: The case of fiberboards made from coconut residues

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ABSTRACT

Fiberboards made from agro-industrial residues have been developed recently to add value to residues and decrease demand for wood and its byproducts. Nonetheless, new bioproducts made from residues are not inherently beneficial to the environment and bring no guarantee of improved efficiency in the use of resources, when compared to standard products. The impacts of these new bioproducts shall be compared to standard products to foster improvements and reduce potential harms to the environment from the development stage. This study assesses the environmental impacts of new coconut husk-based fiberboards, at development stage, aiming to prioritize those for future improvements and up-scaling. The following fiberboards are analyzed: i) MDF made exclusively of coir and fiber; ii) MDF UF made of coir and fiber bonded with urea-formaldehyde; and iii) HDF made only of coir and fiber. This assessment is performed considering different scenarios for allocation procedures (mass and economic, for current and future husk market value) and production scales (lab and pilot). The up-scaled husk-based fiberboards are compared to commercial wood-based panels to support decision about which products should be further improved. Short and long-term research agendas are proposed for reducing the potential impacts of these new products. This cradle to gate study is based on the ISO 14040 and 14044 standards for life cycle assessment, considering the production of fiberboards with $6.05{*}10^{-5}$ m^3, at laboratory scale, and 1 m^3, at pilot scale. The results show that husk-based MDF and HDF have high potential in terms of environmental performance. Nonetheless, they still require improvements to better compete with wood-based fiberboards when mass allocation is the criteria applied in the product modelling system. The hotspot analysis of MDF and HDF highlights the need to reduce impacts in husk transportation and processing, as well as in coconut farming. Two research agendas are proposed to improve MDF and HDF environmental performances: i) a short-term agenda, focused on reducing transportation distances and reusing nutrient rich effluents from husk processing in crop irrigation; and ii) a long-term agenda, focused on reducing the dependence of coconut farming in commercial fertilizers and improving the efficiency of irrigation. From this environmental assessment, the importance of applying both mass and economic allocation in the study of new bio-based products is shown. Furthermore, the need to design and evaluate up-scaled processes, at laboratory stage, in order to make meaningful choices among products is also highlighted. The methodological framework adopted in this study may support research teams searching to improve the environmental performance of products from laboratory stage.

1. Introduction

Fiberboards are usually manufactured from lignocellulose materials and a synthetic binding resin, which are pressed at high temperatures (Rivela et al., 2007). The fiberboard market has been on the rise in recent years, in particular, reconstituted wooden

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medium-density fiberboard (MDF). Between 2009 and 2013, the global market for fiberboards increased by 35%, with Brazil ranking fifth in terms of production. Brazilian production rose from 7 million cubic meters in 2009 to 10 million cubic meters in 2013 (FAO, 2016).

Wood-based fiberboards have been produced worldwide due to governmental incentives and industry compliance with waste reduction initiatives in the timber industry and other forest activities (Caraschi et al., 2009). These fiberboards are usually manufactured from wood fibers or particles from pine and eucalyptus trees, which are used for MDF, with density between 450 and 800 kg/m^3, or for high-density fiberboard (HDF), with density over 800 kg/m^3 (ABNT, 2006). However, recent research has demonstrated the potential to produce fiberboards with vegetal fibers from agro-industrial residues and byproducts, such as sugarcane bagasse (Santos et al., 2014) and banana tree fiber (Rashid et al., 2014).

Unripe green coconut (Cocos nucifera) is produced for water extraction and generates great amount of a fibrous waste: the unripe green coconut husks. These husks may amount to as much as 80% of total coconut mass (Mattos et al., 2011). It is estimated that the coconut industry globally generated as much as 408,216,000 tons of husk in 2013, primarily in tropical areas where coconuts are produced (FAO, 2016).

Although regarded as wastes, unripe green coconut husks can be used for the production of fibers and coir (Mattos et al., 2011). These materials have many applications, such as for use in substrates, pottery and fiberboards. The production of fiberboards from unripe green coconut coir and fibers adds value to these materials and may reduce the environmental burden related to husks disposal.

The manufacture of fiberboards from coconut husks was first investigated by Van Dam et al. (2004). According to these authors, coconut coir and fiber have a high percentage of lignin, which gains high thermo-durability at temperatures over 140 °C and may be employed in the manufacture of fiberboards without any chemical binders. In this context, two processes were developed at the Embrapa Tropical Agorindustry, at the Biomass Technology Laboratory, for producing HDP and MDF fiberboards exclusively from coir and fiber, using the lignin naturally present in these materials as the bonding agent. As fiberboards are usually produced at industrial scale by adding synthetic resins as binders, mainly urea-formaldehyde (UF), at a lower pressing temperature (Santos et al., 2014), the research team also developed a MDF that uses urea-formaldehyde as the bonding agent to produce MDF fiberboard (MDF UF).

At this point of the product development stage, two questions were formulated by the research team regarding the environmental performance of these new products: i) Which fiberboards should be the focus for further improvements and up-scaling? ii) What could be done at laboratory stage to improve the performance of these fiberboards?

The present study aims to answer these questions. The three new coconut-based fiberboards evaluated are: i) MDF made exclusively of coir and fiber; ii) MDF UF made of coir and fiber bonded with urea-formaldehyde; and iii) HDF made only of coir and fiber. Each fiberboard is evaluated considering different scenarios for allocation procedures and production scales. The up-scaled fiberboards are compared to commercial wood-based MDF and HDF to support the decision about which products should be further improved. Contribution analysis is performed to identify environmental hotspots and a short and long-term agendas are proposed to reduce the environmental impacts of these new products.

To our knowledge, no previous study has answered these questions or assessed the life cycle and environmental impacts of fiberboards made out of coconut husks. Environmental assessments are available primarily for fiberboards made from wood (Garcia-Gonzáles et al., 2009; Wilson, 2010; ATHENA, 2013; Piekarski et al., 2014; Santos et al., 2014; Silva et al. 2014), with two studies focusing on alternative biomass sources. Santos et al. (2014) evaluated the impacts of sugarcane bagasse particleboards bonded with urea-formaldehyde considering only the processes related to particleboard production at the laboratory scale. Silva et al. (2014) analyzed the impacts of particleboards made with a mixture of raw wood and sugarcane bagasse, bonded with urea-formaldehyde at the industrial scale. These two studies demonstrated the enhanced performance of sugarcane bagasse particleboard in comparison with conventional wood particleboard.

2. Fiberboards made out of unripe green coconut husks

The developed fiberboards have smooth surfaces, with a light to dark brown color. The physical and mechanical specifications of these fiberboards are presented in Table 1. For HDF and MDF, the same ratio of coir and fiber found in the coconut husk (70:30 w/w) was applied to define the amount of coir and fiber used to make these fiberboards.

Tests on water absorption, swelling thickness, elasticity modulus and rupture modulus revealed that HDF fiberboard is more resistant than MDF and MDF UF. HDF may be employed in parts of furniture carrying considerable weight, such as the bottom of drawers. On the other hand, MDF and MDF UF are lighter and may be used for the sides of furniture or as acoustic isolators. MDF UF is more appropriate for furniture that may have contact with water, because its water absorbance is lower than that of MDF.

3. Material and methods

The present study followed the life cycle assessment stages recommended by ISO 14040 (2006a) and 14044 (2006b).

Table 1
Physical and mechanical specifications of evaluated fiberboards.

Fiberboard	Composition (w/w)	Pressing Temperature (°C)	Thickness (mm)	Density kg/m^3	Water Absorption (%) 24 h	Swelling Thickness (%) 24 h	Elasticity modulus (MOE) MPa	Rupture modulus (MOR) MPa
HDF	70% coir 30% fiber	220	5	1297	27	20	2323	16.6
MDF	70% coir 30% fiber	210	5	793	86	40	236.9	3.44
MDF UF	82.54% (coir and fiber 70:30), 15% resin FU, 1.5% paraffin emulsion, 0.2% ammonia sulfate, 0.76% water	160	4	792	47	6	411.2	4.14

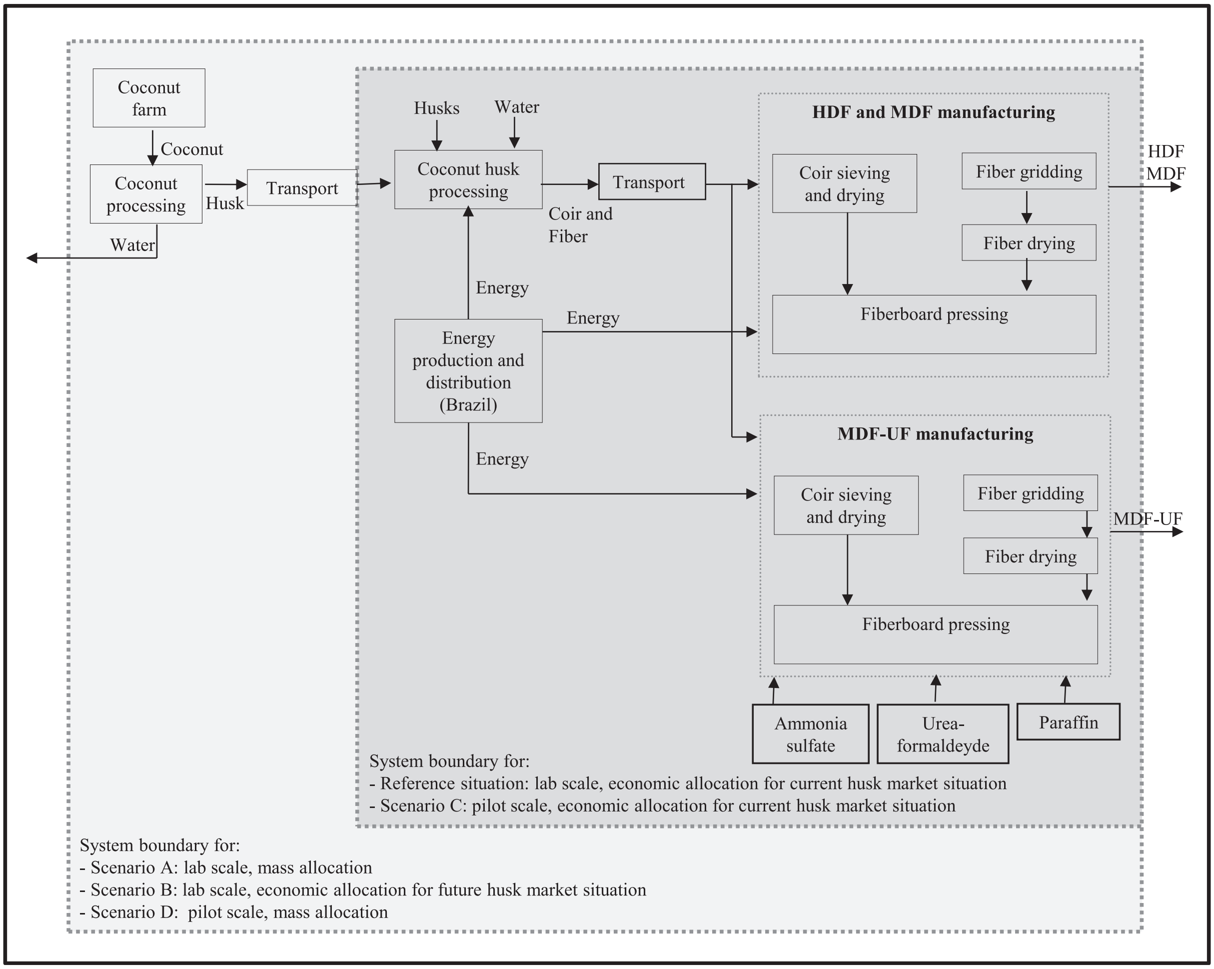


Fig. 1. System boundaries for the reference situation and scenarios analyzed.

3.1. Functional unit

The functional Unit adopted is a coconut husk fiberboard of $6.05*10^{-5}$ $m^{3,}$ for the analysis performed at laboratory scale, and with one cubic meter (1 m^3), for analysis at pilot scale.

At laboratory scale, each type of studied fiberboard has different dimension and mass, due to differences in density. HDF and MDF have 60.5 cm^3 (11 × 11 × 0.5 cm), while MDF UF has 48.4 cm^3 (11 × 11 × 0.4 cm). In terms of mass, HDF has 71 g, MDF, 46 g, and MDF UF, 37 g.

At pilot scale, all fiberboards are expected to have the same dimension of one cubic meter, but different mass. In this scale, MDF is expected to weight 764 kg, and MDF UF, 614 kg, and HDF, 1174 kg.

3.2. System boundary and allocation

The system boundary in this study comprises: inputs and energy production, transport of inputs and coconuts, coconut farming, coconut water processing, husk processing, and fiberboard manufacturing (Fig. 1). However, the consideration of all or some of these processes in impact assessment depends on the allocation procedure used for inventorying data in those processes that may result in more than one product.

Mass and economic allocations are both applied in this study, for two unit processes: coconut water processing, producing in water and husk, and husk processing, producing coir and fiber. When applying mass allocation, the system boundary encompasses all processes, from coconut farming to fiberboard production.

Nonetheless, when economic allocation is adopted, two marketing situations may occur and are evaluated: i) prices of materials based on their current market values, and ii) prices of materials according to estimations of market trends. In the current market situation (situation i), husks are not sold, but rather given to processing units that extract coir and fiber. As husks have no value, coconut water processing and, consequently, coconut farming are not accounted in the impact assessment of fiberboards.

In the future market situation, new husk processing units are expected to be installed, increasing the demand for husks and, consequently, their market value. Consulted experts in the coconut market estimated that 1 kg of coconut husks will cost around US$ 0.04. The prices of coconut water, coir and fiber in the near future are considered to be the same as nowadays. In this case, all processes in the system boundary are considered in the impact assessment of coconut husk-based fiberboards.

The applied mass and economic allocation percentages of coconut water, husk, coir and fiber are presented in Table 2.

3.3. Inventory: data collection

Primary data were collected for the following foreground processes:

Table 2
Mass allocation of coconut products.

Product	Mass (kg)	Mass allocation (%)	Current market situation		Future market situation	
			Value (US$)	Economic allocation (%)	Value (US$)	Economic allocation (%)
Extraction of coconut water						
Water from coconut	0.4	27	0.11	100	0.11	70
Husk from coconut	1.1	73	0.00	0	0.04	30
Processing of coconut husk						
Coir	0.55	85	0.21	90	0.21	90
Fiber	0.17	15	0.074	10	0.074	10

- unripe coconut farming;
- coconut processing for water extraction;
- husk processing;
- fiberboard manufacture.

Information on the production of unripe green coconuts was collected in 2014 on a coconut farm in Paraipaba, State of Ceará, Brazil. Regarding the coconut processing for water extraction, and the husk processing for extraction of coir and fiber, interviews were conducted in 2013 at a manufacturing plant in Fortaleza, State of Ceará, Brazil. Data on fiberboard manufacture were collected at the Laboratory of Biomass Technology (LBT) of Embrapa Tropical Agroindustry, where the fiberboards are manufactured at laboratorial scale.

Secondary data on electricity, chemical and diesel production (background processes) are from the ecoinvent version 3.0 database (Weidema et al., 2013). The Brazilian electricity mix, according to The Brazilian Energy Balance - BEB (2015) is used to account for the following sources of energy: 68% from hydropower plants, 14% from natural gas, 8% from biomass burned in thermal plants, 3% from coal burned in thermal plants, 3% from diesel burned in thermal plants, 3% from nuclear plants, and 2% from windmills.

The data of effluent volume and pollutant load generated in husk processing (liquid from coconut husk and coir washing) are from Figueirêdo et al. (2010).

The following sections describe the unit processes in which primary data were collected.

3.3.1. *Unripe green coconut crop production*

Unripe green coconut is produced from coconut palm trees of the dwarf or hybrid varieties. The environmental inventory of unripe green coconut production considered that each hectare contains 148 trees, averaging 220 fruits/plant/year. The soil type at the plantation is Quartzarenic Neosol, a sandy quartz soil characteristic of coconut-producing areas in Northeastern Brazil.

The following production stages for a 17-year span orchard were inventoried: seedlings production, plantation establishment (first year), growth (second and third years) and production (fourth to seventeenth year). Coconut farming in Brazilian Northeast is assumed to be sited in areas occupied with Caatinga (xeric shrublands) 20 years ago (the worst case for land transformation).

Regarding seedling production, fruits are harvested at maturity (after 12 months) and stored for 15 days to allow for total maturation. Seeds are placed vertically in a greenhouse, in parallel rows with 60 cm between rows. Seedlings are daily irrigated for 1 h over the duration of the three-month production cycle.

After germination, coconut plantlets are planted directly in holes and with 7.5 × 9.0 m spacing for each plant. Plantlets are fertilized with micro-granulated FTE, organic compounds and simple superphosphate. During the first year, plantlets are microsprinkled daily for 1 h, with an application of 55 L of water/plant/day for 240 days in the first year. Fertilization in the first year consists of 30 g of urea/plant/week and 30 kg cattle manure/plant/year. During the second year, irrigation comprises 110 L of water/plant/day for 2 h a day over the course of 240 days. In the third year, irrigation consists of 200 L of water/plant/day for 4 h/day from June to September and 4.5 h/day from October to January, for a total of 240 days. The coconut trees starts to produce fruit in the third year. Irrigation equipment is assumed to have a lifespan of 20 years. Although the tree may still be producing fruits, the orchard lifespan is considered to be 17 years as the hybrid coconut tree rises high above the ground, making difficult harvest and pest and disease control.

The emissions from coconut farming are calculated according to IPCC (2006) and Nemecek and Schnetzer (2012).

3.3.2. *Transport and coconut processing for water extraction*

Fruits are transported from farm to coconut water processing plants by a model 23220 Volkswagen (VW) diesel-run truck, with a carrying capacity of 10 tons. Coconut water plants are considered to be close (500 m) from farms.

Coconut processing for water extraction encompasses many unit processes with only one related to husks and reported in the present study: the opening of coconuts. This process is done manually with a sharp stainless steel instrument. The extracted coconut water is then processed and packed, while the husks from the opening process are collected by hand and sent to a coconut husk processing plant.

3.3.3. *Husk processing and transport of coir and fibers to the fiberboard plant*

Coconut husk processing plants are considered to be located 40 km from coconut water processing plants. Husks are transported on the 10 ton-capacity VW truck, unloaded and weighed prior to processing.

Equipment for coir and fiber extraction from husks is produced by the Fortalmag metal works. The present study does not consider the inventory of this equipment but only the processing of coconut husks. A lift takes the husks to a crusher, which processes the husks with a fixed knife roller. After crushing, the husks are pressed with horizontal rollers, reducing humidity. The coconut husk liquid, rich in nutrients and organic matter, is removed and treated in an anaerobic digester. After removing liquid by pressing, the coir and fibers are selected in the classification machine equipped with a roller of fixed knives and perforated plate. The material is separated by eddying or swirling throughout the axis of the machine. The coir passes through the perforated plate and the fiber emerges from the machine. The coir is washed to remove salts, producing a liquid effluent.

A 10-ton capacity VW truck is used again for transporting coir and fibers (332 km) to the fiberboard plant. For the calculation of transport distance, it is assumed that these materials are transported to a plant located at Marco, State of Ceará, Brazil. It is assumed that when the technological routes described in the present study are finalized at research level, furniture plants located in the industrial complex of Marco will probably start producing coconut fiberboards.

3.3.4. Manufacture of fiberboards

3.3.4.1. Manufacture of fiberboards at laboratory scale. Coir and fiber are each prepared in a different manner. The coir is sieved to remove foreign materials and then dried in an air-circulation buffer at 100° C for 1 h to decrease humidity to 8%.

The fiber is ground in a Wiley mill (Fritsch Pulverisett 25) to a granulometry of 4 mm. The ground fiber is also dried in an air circulation buffer for 1 h at 100° C to achieve 8% humidity.

The resin-less fiberboards (HDF and MDF) are manufactured with a mixture of coir and fiber at a ratio of 70:30 (w/w). MDF UF fiberboard is manufactured with coir and fiber at a ratio of 70:30 (w/w), to which the urea-formaldehyde resin, ammonium sulfate and paraffin-water emulsion are added (Table 1). The mixture of fiber and coir is left to rest for 24–48 h, distributed uniformly on an 11 × 11 cm stainless steel mold and pressed under a hydraulic MARCONI press, model MA 09850A1. The pressing process has the following time, temperature and pressing specifications: i) for the HDF fiberboard, 220 °C and 320 kgf/cm^2 for 4 min; ii) for the MDF fiberboard, 210 °C and 320 kgf/cm^2 for 4 min; iii) and for the MDF UF fiberboard, 160 °C and 100 kgf/cm^2 for 10 min.

Electricity consumption in this process was measured *in situ* while manufacturing equipment was actively running. A digital multimeter clamp True-RMS Fluke 324 was used to calculate electric tension and current and equipment power and electricity consumption in kWh were obtained.

Formaldehyde emissions (FE) in this process are estimated according to Wilson (2010).

3.3.4.2. Manufacture of fiberboards at pilot scale. To build the inventories of MDF, MDF UF and HDF production at pilot scale (scenarios D and E), a pilot plant producing 300,000 m^3 of fiberboard was conceived. This plant was defined considering the equipment and energy requirements described by Piekarski et al. (2014) that inventoried a wood-based MDF industrial plant in South Brazil. To develop the inventory of coconut-based fiberboards at pilot scale, the following assumptions are made:

- The mass of all inputs, except energy consumption, and all outputs grows linearly with the increase in production;
- The energy use for producing coconut husk-based MDF UF is similar to that required for the Brazilian MDF production from wood. Piekarski et al. (2014) acknowledge the use of electric and thermal power in MDF Brazilian companies (burning of natural gas and biomass). Thus, the inventory built for MDF UF considers that 23% of the energy comes from electric power, 16% from the burning of natural gas in a thermal plant, and 61%, from the burning of regionally available biomass. Coconut fiber and coir, instead of wood sawdust, are the biomass assumed to burn in thermal plants because of their great availability and low price on the Brazilian coast areas. According to Esteves et al. (2015), the heating value of unripe coconut coir and fiber is 18.48 and 19.47 MJ/kg, respectively (1 kg of coir and fiber is composed of 0.7 kg of coir and 0.3 kg of fiber, and corresponds to 0.007 m^3);
- The ratio between the total energy demand, at laboratory scale, for MDF and MDF UF (0.61), and HDF and MDF UF (0.95) stands at industrial scale. Thus, the total energy required for MDF production at pilot scale is equal to 0.61 multiplied by the amount of energy used for producing MDF UF at pilot scale, and the energy required for HDF, to 0.95 multiplied by the amount used for producing MDF UF.

3.4. Impact assessment

Environmental impacts are analyzed by the characterization models indicated by the European Joint Research Center (JRC) in the International Life Cycle Data System (ILCD) Handbook (JRC, 2011). The following categories are considered: water resource depletion, land use, mineral resource depletion, acidification, terrestrial, freshwater and marine eutrophication, global warming, depletion of the ozone layer, photochemical ozone formation, particulate matter, ionizing radiation, human toxicity, and freshwater ecotoxicity.

3.4.1. Scenario analysis

The aim of building scenarios is to analyze if results change if different allocation and production scales are adopted when modelling husk-based fiberboards. To perform this analysis, a reference situation and four scenarios are considered for assessing the impacts of coconut husk-based fiberboards (MDF, MDF UF and HDF), being described in Table 3. The reference situation, and the scenarios A and B are at laboratory scale, differing in terms of allocation criteria applied (mass or economic in current and future husk market situations). Scenarios C and D are at the pilot scale, considering mass and economic allocation in current husk market situation. Scenarios C and D are used to compare the impacts of coconut husk-based fiberboards to commercial ones, obtained from ecoinvent v.3 database (Weidema et al., 2013): i) the coconut husk-based MDF and MDF UF are compared with the inventory “Medium density fibreboard {GLO}| production, from virgin wood | Alloc Def, U”, and ii) the coconut husk-based HDF with “Fibreboard, hard {GLO}| production, from virgin wood | Alloc Def, U”.

3.4.2. Uncertainty analysis

The Monte Carlo simulation method is employed, using the software Simapro 8 (Goedkoop et al., 2013), in the comparative impact assessment of up-scaled coconut husk-based fiberboards and commercial wood-based MDF and HDF to evaluate uncertainties in results. Comparisons are performed for two products at a time: coconut MDF and commercial MDF, coconut MDF UF and commercial MDF and coconut HDF and commercial HDF. Scenarios D and E (Table 3) are considered in these comparisons.

The Monte Carlo method requires that the mean, type of statistical distribution, and standard deviation be defined for each

Table 3
Scenarios considered in the present study for the environmental impact assessment of coconut husk-based fiberboards.

Scenario	Production scale of fiberboards	Allocation criteria	System boundary
Reference	laboratory	economic, current husk market situation	Part of the processes[a]
A	laboratory	mass	All processes[b]
B	laboratory	economic, future husk market situation	All processes[b]
C	pilot	mass	All processes[b]
D	pilot	economic, current husk market situation	Part of the processes[a]

[a] Unit processes: transport of materials, production of inputs, husk processing and fiberboard production.
[b] Unit processes: unripe green coconut production, extraction of coconut water, transport of materials, production of inputs, husk processing and fiberboard production.

parameter. The mean value adopted for each parameter was the mean obtained from the three measurements performed for the foreground processes. The type of statistical distribution adopted in the present study was the lognormal, following the Weidema et al. (2013) indication that environmental parameters in LCA studies are independent and usually follow the lognormal distribution as do the impact results. The ecoinvent database also considers that most parameters have lognormal distributions because this distribution is frequently observed in real-life populations. The geometric standard deviation of each parameter was calculated as the sum of basic and additional uncertainties, according to Weidema et al. (2013).

According to Goedkoop et al. (2013) and Heijungs and Lenzen (2014), when comparing two products (or processes) using Monte Carlo simulation (the multiple-sample case), the same simulation run shall be used to generate values for those processes that are common to both products (e.g., electricity). Otherwise, the final uncertainty of the comparison would be overestimated, due to the uncertainties of common processes been calculated more than once.

Thus, comparative studies shall avoid performing separate simulations for each product and presenting the average results with an error bar. Instead, the uncertainty can be evaluated by comparing the results of each simulation run and counting the number of times that product a new fiberboard (e.g. coconut husk-based MDF, HDF or MDF UF) achieved better performance than a commercial board. To do this, for each simulation run and impact category, the value achieved by a new fiberboard is diminished by the value of a comparable commercial board (e.g.: husk-based MDF UF − MDF from ecoinvent). If the result of "MDF UF − MDF" is equal to or greater than zero, the impact of MDF UF is considered equal or greater than the impact of MDF (MDF UF $\geq$ MDF). In the inverse situation (MDF UF < MDF), the impact of MDF UF is considered less than the impact of MDF. In this study, for each impact category, the uncertainty analysis is performed considering that a significant difference between compared fiberboards exist when in 95% of 1000 simulation runs a fiberboard causes less impact than another (Goedkoop et al., 2013).

4. Results

4.1. Inventory analysis of foreground processes

The inventories of foreground unit processes are presented in Table 4. Inputs and outputs in this Table are presented for each unit process.

Coconut crop production results in many environmental aspects, including the use of large volumes of water for irrigation, land use transformation, and fertilizer use. A total of 760 m^3 of water is needed to irrigate one plant over the 17-year course of its productive life, throughout which the plant produces an average of 4950 kg of coconuts. Emissions from crop production occur primarily because of land transformation, which results in greenhouse gases, and fertilizers use, which results in the emission of nitrogen compounds and heavy metals.

At husk processing units, energy is the major input for coir and fiber extraction from husks. Husk processing generates effluents with high organic loads after treated in biodigestors. These effluents result from husk pressing and coir washing.

Fiberboard manufacture, at laboratory scale, requires also a significant input of electricity. Among the three fiberboard types considered in the current study, MDF UF has the highest energy demand, because the time necessary for pressing the fiberboard is long (10 min), despite the relatively low temperature applied (160 °C). Nonetheless, at pilot scale, energy comes from both electric and thermal power plants and consumption does not increase linearly when moving from lab to pilot scale (Table A1 in supplementary material).

An aspect of concern in MDF HDF and MDF UF manufacture is the substantial loss of materials that occurs throughout fiberboard production. Residues from coir sieving and fiber grinding account for between 75 and 79% of total mass of materials (coir and fiber) used to produce these fiberboards. At pilot scale, this residue is assumed to be used as fuel to the thermal plants that will generate energy for the fiberboard company.

Emissions of pollutants only occur during MDF UF manufacture (formaldehyde to air), due to the degradation of the binding resin.

4.2. Environmental impact assessment of coconut husk-based fiberboards

This section presents the impacts of husk-based MDF, MDF UF and HDF in different scenarios, showing trends in results when different allocation criteria are applied and when moving production from laboratory to pilot scale (Fig. 2). It is important to note that these fiberboards are expected to have different applications in the market and are not comparable.

When applying economic allocation for current husk market situation (reference situation and scenario C), the impacts of all fiberboards are lower than when economic allocation for future husk market situation (scenario B) or mass allocation are applied (Scenarios A and D). This happens because part of the impacts from coconut farming is allocated to husks only in scenarios A, B and C, and it boosts fiberboards impacts.

When moving from lab to pilot scale, using the same allocation criteria (reference situation and scenario C, or scenarios A and D), results in Fig. 2 show that the impacts of coconut husk-based fiberboards reduce. This is mainly due to the reduction in energy consumption per m^3 of fiberboard produced at pilot scale, and the use of thermal energy from biomass, partially substituting the need for electricity that is solely used at laboratory scale.

4.2.1. Comparison of up-scaled husk-based fiberboards to commercial wood-based fiberboards

The proposed fiberboards are compared to commercial wood-based MDF and HDF, considering the scenarios C and D for pilot scale. This analysis shows that husk-based MDF and HDF have better performance than MDF UF and should be prioritized by the research team (Fig. 3). Nonetheless, these fiberboards need further improvements since in one scenario their environmental performance is worse than the performance of commercial boards.

In scenario C, the results from comparisons show that coconut husk-based MDF and HDF are environmentally suitable products. The husk-based MDF is significantly better than the commercial wood-based MDF in four impact categories (climate change, acidification, land use and particulate matter) and worse in two (water depletion and freshwater eutrophication). The husk-based HDF is better than the commercial HDF for three categories (acidification, land use and particulate matter) and worse for two (water depletion and freshwater eutrophication). MDF UF performs significantly better than the commercial MDF for the land use impact category, but worse for climate change, water depletion, and terrestrial and freshwater eutrophication. All proposed fiberboards perform worse than the commercial panels for water depletion and eutrophication in scenario C, because husk processing demands water and release nutrient rich effluents, while consumptive water and nutrients are not released in the production chain of wood-based commercial panels.

In scenario D, all coconut husk-based fiberboards perform significantly worse than the commercial ones (Fig. 3). This is mainly

Table 4
Inventories of foreground unit processes.

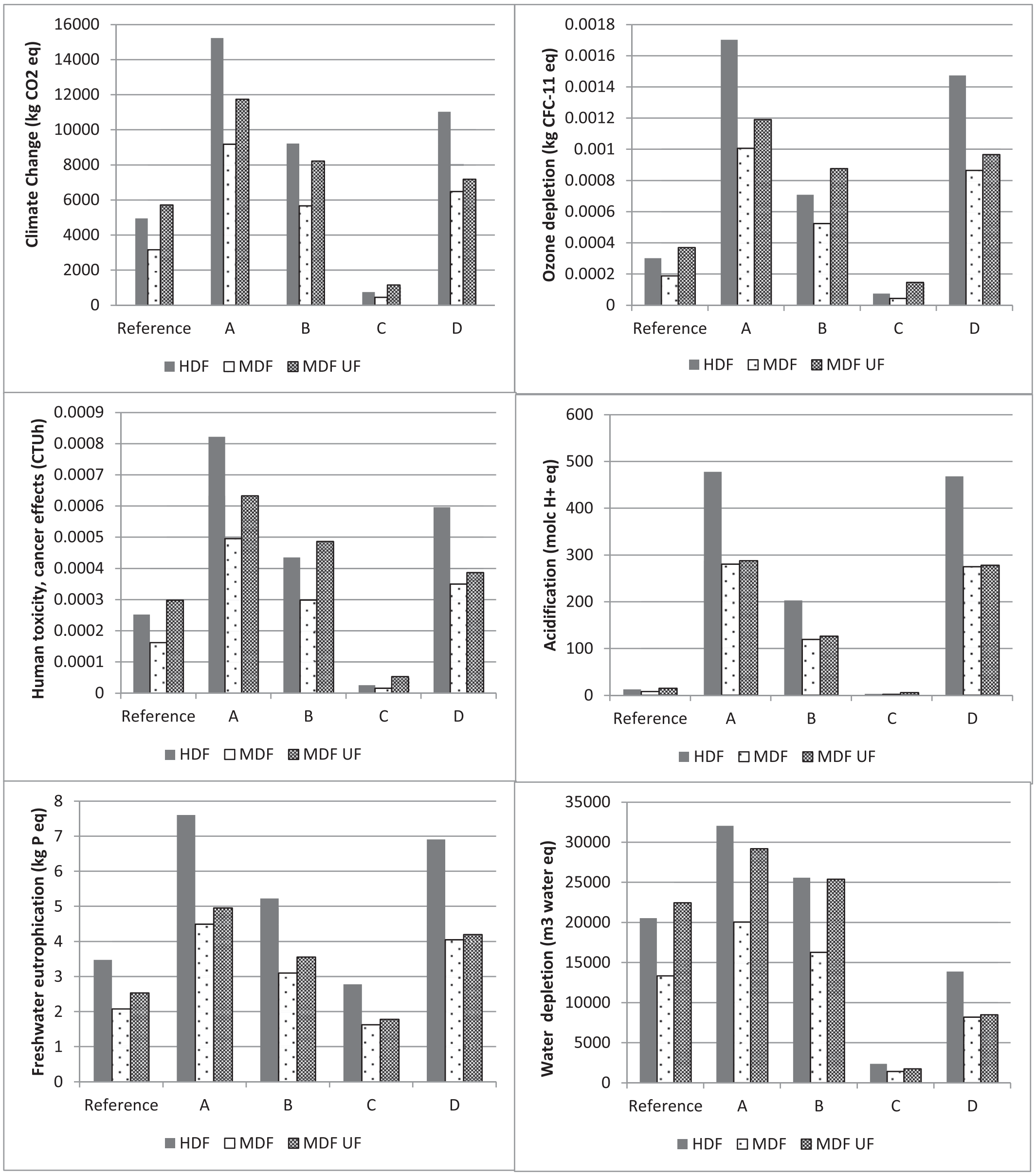
Inputs and outputs	Unripe green coconut crop production (one tree over 17 years)	Coconut opening for water extraction	Processing of coconut husks	Washing of coir	Production of HDF (lab scale)	Production of MDF (lab scale)	Production of MDF UF (lab scale)
Materials and Energy							
Area (ha)	0.00676						
Water (m^3)	759.69			0.719			1.05E-05
Energy (kWh)	132.7		0.18		0.71	0.46	0.75
Diesel (kg)	15.53						
Urea (kg)	61.44						
Poultry manure (kg)	540						
Potassium chloride (kg)	60						
Single superphosphate (kg)	32						
Boric oxide (g)	2.5						
Copper oxide (g)	7.5						
Manganese oxide (g)	12						
Zinc oxide (g)	5						
Iron (g)	6						
FU Resin (g)							10.78
Paraffin emulsion (g)							1.725
Ammonia Sulfate (g)							0.014
Coconut (kg)		8.92					
Coconut husk (kg)			6.54				
Coir from coconut husk (kg)				3.30	0.31	0.18	0.14
Fiber from the coconut husk (kg)					0.06	0.33	0.02
Products							
Coconut (kg)	4950						
Coconut water (kg)		2.38					
Coconut husk (kg)		6.54					
Coir from the coconut husk (kg)			3.30				
Fiber from the coconut husk (kg)			0.056				
Washed coir (kg)				4.48			
HDF (g)					71.02		
MDF (g)						46.22	
MDF UF (g)							37.16
Emissions							
Carbon dioxide – air (kg)	45.31						
Nitrous oxide - air (kg)	0.78						
Methane - air (kg)	0.07						
Ammonia - air (kg)	5.67						
Nitrous oxide - air (kg)	0.16						
Nitrate - water (kg)	38.15						
Phosphorous - water (kg)	0.02						
Cadmium - soil (mg)	0.002						
Cupper - soil (mg)	0.005						
Zinc - soil (mg)	0.038						
Lead - soil (mg)	0.019						
Nickel - soil (mg)	0.004						
Chrome - soil (mg)	0.011						
Oil and Grease - water (mg)			0.39	0.029			
Total Suspended Solids - water (mg)			5.11	3.97			
Total Kjeldahl Nitrogen - water (mg)			0.10	0.05			
Oxygen Chemical Demand- water (mg)			45.71	37.26			
Oxygen Biochemical Demand- water (mg)			26.07	30.71			
Total phosphorus - water (mg)			0.03	0.20			
Water vapor - air (g)					45.91	31.23	29.94
Formaldehyde - air (g)							0.02

due to the higher amount of energy and agrochemicals used in coconut farming when compared to wood forestry, according to ecoinvent (Weidema et al., 2013).

4.2.2. Constribution analysis

Husk-based MDF and HDF are now evaluated to identify the main environmental hotspots in their production chains. Results from this analysis show that, when moving from laboratory to pilot scale, some processes lose importance as hotspots and new processes become important (Table 5). This also happens when different allocation procedures are applied.

At laboratory scale, when economic allocation for current husk market situation (reference situation) is applied, the main hotspots are the pressing of fiberboards that requires electricity production



* Reference: lab scale, economic allocation for current husk market situation; Scenario A: lab scale, mass allocation; Scenario B: lab scale, economic allocation for future husk market situation; Scenario C: pilot scale, economic allocation for current husk market situation; Scenario D: pilot scale, economic allocation for future husk market situation.

Fig. 2. Environmental impacts of coconut husk-based fiberboards in the reference situation and in different scenarios.

and distribution, and the transportation of husks that emits nitrogen and sulfur pollutants. If mass (scenario A) or economic allocation for future husk market situation are adopted (scenario B), coconut farming and the pressing of fiberboards appears as the main sources of impacts.

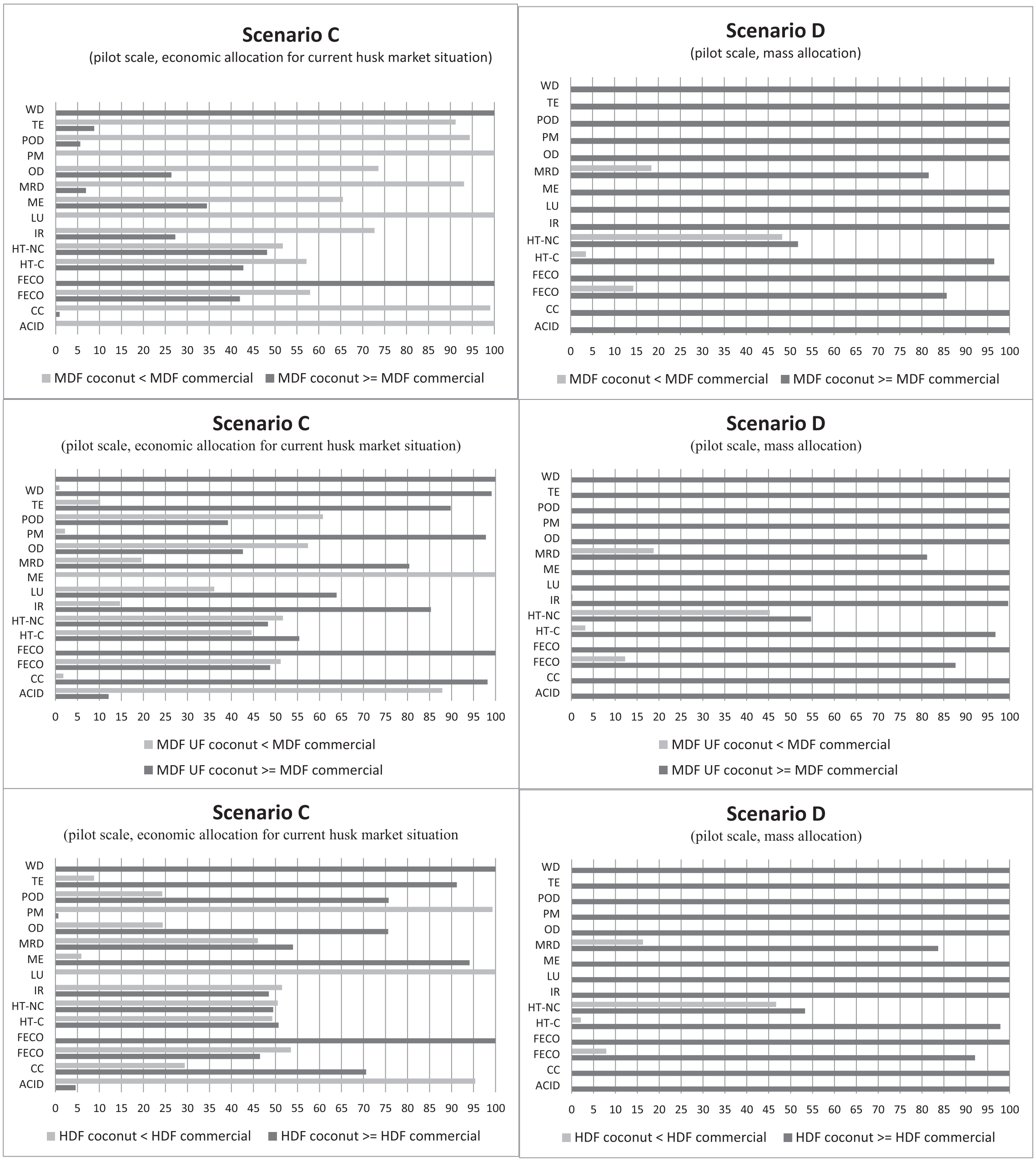
At pilot scale, when mass allocation is used (scenario D), the main hotspots are husk transportation and processing. However, when economic allocation for current husk market situation (scenarios C) is applied, coconut farming and husk processing are the main contributors for all impacts.

To define a research agenda for reducing the environmental impacts of husk-based fiberboards, it seems reasonable to prioritize hotspots from the assessments of pilot scale scenarios. Furthermore, it is important to consider results from mass and economic allocation, since both criteria can be applied by future consumers of husk-based fiberboards.

5. Discussion

5.1. Improving the environmental performance of coconut husk-based fiberboards

Considering the results from this study, two agendas are proposed, for the short and long run, to improve the environmental performance of husk-based MDF and HDF. The short-term agenda is defined considering scenario C (economic allocation for current



* CC - Climate change; OD - Ozone depletion; HT-C - Human toxicity, cancer effects; HT -NC - Human toxicity, non-cancer effects; PM - Particulate matter; IR - Ionizing radiation; POF - Photochemical ozone formation; ACID – Acidification; TE - Terrestrial eutrophication; FE - Freshwater eutrophication; ME - Marine eutrophication; FECO - Freshwater ecotoxicity; LU - Land use; WD - Water depletion; MRD - Mineral resource depletion.

Fig. 3. Uncertainty analysis of the comparative environmental impacts of coconut husk-based fiberboards and commercial wood-based fiberboards, in scenarios C and D.

husk market situation), while a long-term agenda is proposed considering scenarios D (mass allocation).

In this context, the proposed short-term agenda focus attention on husk transportation and processing. Regarding the impacts of husk transportation, it seems reasonable to suggest that future husk processing units should be located close to coconut water plants. Currently, there is no awareness among entrepreneurs to do so, as no previous study showed the importance the transportation of husks may have in the environmental performance of coconut husk-based products.

The impacts of husk processing are mainly related to the release of nutrient rich effluents with potential to cause freshwater eutrophication. Nonetheless, studies have shown the potential to reuse agro-industrial effluents in the irrigation of crops (Miranda et al., 2008; Gatta et al., 2015). Research should focus on developing technology for using this effluent in the fertirrigation of coconut or other crops to supply their demand for phosphorous and water. According to Rosa et al. (2011), the dwarf coconut palm tree

Table 5
Results of hotspot analysis of coconut husk-based fiberboards.

Scenario[a]	Product	Fiberboard production	Husk processing	Transport	Coconut farming	Electricity production	Thermal power production	Other inputs
Reference	MDF			X		X		
	HDF			X		X		
A	MDF				X	X		
	HDF				X	X		
B	MDF				X	X		
	HDF				X	X		
C	MDF		X	X				
	HDF		X	X				
D	MDF		X		X			
	HDF		X		X			

[a] Reference: lab scale, husk is a residue, mass allocation; scenario A: lab scale, husk is a residue, economic allocation; scenario B: lab scale, husk is a coproduct, mass allocation; scenario C: lab scale, husk is a coproduct, economic allocation; scenario D: pilot scale, husk is a residue, mass allocation; scenario E: pilot scale, husk is a coproduct, mass allocation.

(produces coconut for water extraction) may require as much as 309 g of phosphorous per plant, and some farms already incorporate unprocessed husks for increasing macronutrients in soils.

Regarding the long-term agenda, it is proposed to focus attention on reducing agrochemicals and irrigation in coconut farming. Decreasing the impacts of coconut farming may be achieved through efficient fertirrigation, avoiding nutrient and water losses to the environment. A reduction in mineral fertilizers may be achieved using nutrient rich effluents from husk processing, as previously suggested, and/or adopting green fertilization, cultivating leguminous plants, such as guandu bean, to coconut orchards (Balock et al., 2014). According to Carr (2011), irrigation with hydric deficit and also the use of soil covering are also feasible alternatives to improve efficiency in the use of water in coconut tree irrigation. Field experimental evaluations should be developed by crop system researchers to identify irrigation practices and consortium-based cultivation systems that are more efficient in terms of water and fertilizer use.

Action to minimize the impacts of coconut farming is of great importance, not only to improve the environmental performance of fiberboards, but of any products derived from coconuts. In addition to the commercialization of coconut water, companies in this sector are currently expanding production to encompass byproducts from husks, such as substrates, erosion control mats, and car seat fillers (Mattos et al., 2011). These products are usually considered environmentally friendly when they are derived from wastes such as unripe green coconut husks. However, the present study shows that environmental impacts exist in the life cycle of unripe coconuts that should be targets for reduction to mitigate the environmental footprint of coconut-derived products.

Although energy use is expected to decrease when moving fiberboard production from laboratory to pilot scale, improvements in energy efficiency is always a goal for cleaner production. In this sense, a review in the literature of wood-based fiberboard production was performed to identify alternatives for reducing energy consumption in husk-based MDF and HDF production. This review showed that thermal pre-treatment of raw material may reduce energy consumption at the pressing process, as it eliminates the factors that increase water absorption by the fiberboard that are normally removed by heat. According to Torquato (2008), thermal pre-treatment softens the fibers or wood particles and facilitates the de-fiber process, with a possible decrease in energy consumption during pressing. Castro et al. (2014) suggest thermal pre-treatment with hot water or steam. Pelaez-Samaniego et al. (2013) also underscore that thermal pre-treatment is a good alternative for the removal of hemicellulose without the use of chemical products. Zhang et al. (2015) state that thermal treatment with steam explosion is the most effective method to improve the dimensional stability of binderless fiberboards, since it liberates lignin from inside of cells to the fibers surface. Thus, two investigations are recommended for the research team developing husk-based fiberboards: i) to verify the effectiveness of applying thermal pretreatement to husk fibers, and ii) to compare the environmental impacts of HDF and MDF produced with and without thermal pretreatment.

5.2. The importance of applying mass and economic allocation in the environmental assessment of products obtained from biowastes

The analysis of different allocation procedures in this study revealed that for products based on residues as raw material, such as coconut husks, farming processes may become the most important process for improving the product life cycle environmental performance when residues start to gain market value. Cropping processes may even transform environmentally competitive biobased products in uncompetitive ones, as happened in the study of coconut husk-based fiberboards. Currently, many crop systems still rely on monoculture, use of commercial agrochemicals, and irrigation, this combination leading to important impacts in many categories.

In this regard, for research teams developing products from residues, it is of great importance to consider economic allocation for both current and foreseen market practices. The change in price of raw materials is expected especially for residues that currently have no value for society but sooner or later will start to have it.

Considering current and future scenarios for economic allocation is especially important when the raw material used in a new product (coconut husks in the present study) is the main mass of another commercial product (coconut water in the present study). This situation usually shifts environmental burdens between unit processes, when adopting different criteria for economic allocation, causing differences in results of contribution analysis. Comparisons between new and commercial products may also lead to different results in this case.

5.3. The importance of up-scaling scenarios for making decisions at laboratory stage

During product development, many design possibilities are tested at laboratory scale for the combination of inputs and materials, leading to distinct products with similar technical characteristics. At some point, the research team needs to decide which product to select for further improvements and production at pilot scale. To support this decision, it is important not only to compare new products at laboratory stage, but also to benchmark them with similar products available in the market.

If the new products represent an innovation without a substitute in the market, comparisons at laboratory stage are valuable to decide about materials or technological routes. This is the case of nanomaterials that are still starting to be up-scaled and have no similar product available in the market. Nonetheless, most of the time, new products are alternatives to similar products already being commercialized, being important to compare them in order to make decisions about future improvements. This is the case of coconut husk-based fiberboards that have similar characteristics as commercial wood-based fiberboards.

An important aspect regarding comparisons between products is that for a comparison to be meaningful the production processes of both products must be at the same scale. Thus, when deciding at laboratory scale about which product to prioritize for further improvements, it is necessary to design or simulate its production process at pilot scale in order to compare it with existing products. If results from this comparison show that a new product performs worse than its similar in the market, a research agenda needs to be defined to make improvements already at the laboratory stage, when the cost to implement change are lower.

A research agenda for improving a product environmental performance is built from the results of a contribution or hotspot analysis. Considering the analysis performed in this study, it is indicated that the hotspot analysis of new bio-based products focus on processes modeled at pilot scale, applying both mass and economic allocation.

6. Conclusions

The life cycle impact assessment of three new fiberboards obtained from coconut husks revealed that husk-based MDF and HDF have high potential in terms of environmental performance. Nonetheless, they still require improvements to better compete with wood-based fiberboards when mass allocation is the criteria applied in the product modelling system.

The contribution analysis revealed that the main environmental hotspots requiring research attention differ when moving from lab to pilot scale and when applying mass or economic allocation. The analysis of MDF and HDF at pilot scale, applying both mass and economic allocation, highlights the need to reduce impacts in husk transportation and processing, as well as in coconut farming.

Two research agendas for the short and long-terms are proposed to improve MDF and HDF environmental performances. For the short-term, activities should focus on: i) fostering the establishment of new husk processing units close to coconut water units to reduce the impacts of husk transportation between sites, and ii) investigating the feasibility and assessing the environmental impacts of reusing the nutrient rich effluent generated in husk processing units in the fertirrigation of crops, specially coconut trees. The long-term agenda should focus on reducing the dependence of coconut farming in commercial fertilizers and improving the efficiency of irrigation.

From this environmental assessment, the importance of applying both mass and economic allocation in the study of new bio-based products is shown. Furthermore, the need to design and evaluate up-scaled processes, at laboratory stage, to make meaningful choices among products and decide about future improvements is also highlighted. The methodological framework adopted in this study may support research teams searching to improve the environmental performance of products from laboratory stage.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.03.100.

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