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Effect of the retting process on the life cycle performance of hemp fibre composites

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Abstract

Our study investigates how different retting processes affect the life cycle performance of a hemp fibre composite by carrying out a Life Cycle Assessment (LCA). LCA is applied to compare traditional field retting with enzymatic retting. Enzymatic retting has been proposed as an innovative retting method capable of producing fibres with higher mechanical properties and lower porosity in the resulting composite. Improved fibre properties allow producing lighter composite materials, which at the same time still fulfil the mechanical design constraints.

The LCA results show higher impacts for the enzymatic retting (due to increased energy and material consumption for this process) which are not counterbalanced by reductions in other life cycle stages, if the composite is used in static application. Instead, for dynamic application, when lightweighting also implies fuel savings, the enzymatic process helps to reduce the overall environmental impact of the hemp fibre composite.

Keywords: LCA, biobased materials, natural fibre composites, enzymatic process, ecodesign

1. Introduction

The great interest for biomass utilization has boosted research and exploitation of biomass and waste for the production of fuels, feeds and products. Most of the biomass upgrading technologies are focused on chemical or/and biological conversion of biomass. Despite limited, efforts have also been made to mechanically upgrade biomass for the production of structural materials. One of the most studied biobased products, made from mechanical means, are natural fibres, which can replace conventional fibres (e.g. glass and carbon) in composite application (Pickering *et al*. 2016).

Nowadays, the use of natural fibres is gaining more and more interest. Natural fibres have mechanical properties similar to glass fibres but with a lower density and possibly a lower environmental footprint (Dittenber and Gangarao 2012). However, current production methods for natural fibres are not yet optimized for composite production. The production process is mainly derived from the textile industry and does not attempt to achieve the highest possible mechanical properties. Consequently, there is an ongoing effort on developing alternative production process, which can improve the mechanical properties of natural fibres for composite application.

Three different steps compose the production process of natural fibres: biomass cultivation, retting and extraction of the fibres. The retting process is intended to facilitate the removal of the non-cellulosic component from the biomass via degradation by naturally occurring bacteria and enzymes. This is a critical factor in the production process because the mechanical properties and the porosity of the resulting composite are greatly affected by the non-cellulosic components still present on the fibre surface.

Traditionally, the retting process has been performed directly in the field. During the field retting (FR), the stems are cut, spread on the ground and exposed to the action of fungi and aerobic bacteria for 2– 10 weeks. The microorganisms attack the pectin and other cementing compounds that holds together the micro-fibrils, which facilitate the subsequent fibre extraction process.

A promising process, alternative to field retting is enzymatic retting (ER). Selected enzymes can provide cleaner fibres with improved mechanical properties, because targeted degradation occurs in a controlled environment where only certain organism with specific degradative properties are used (Turunen and van der Werf 2006; Liu *et al*. 2016a).

LCA is a methodology which can quantify the environmental performance of products and services (ISO 2006). The methodology is capable of providing results across a broad range of environmental areas of concerns.

LCA studies focusing on material comparison must be carefully designed in order to take into account not only input needed and energy consumed to produce the material but also how the material properties affects the succeeding life cycle stages.

Different material properties may influence the use stage (e.g. if the material is used in dynamic application) or the disposal stage at the end of the product life cycle (e.g. reuse vs. recycling).

While life cycle assessment of other types of biobased products is widely applied (e.g. biofuels), biobased composites are covered sporadically and there are only a limited amount of publications available. Most of these publications apply mass-to-mass comparisons between biobased and conventional composites (mainly glass fibre composites). They typically provide results at the fibre production-gate or at the composite-gate without discussing how different material properties could affect the subsequent life cycle stages of the studied product (Joshi *et al*. 2004; González-García and Hospido 2007; Carus 2011; Duflou *et al*. 2012; Zampori *et al*. 2013; Barth and Carus 2015; Deng and Tian 2015).

Few published studies includes the evaluation of mechanical properties as part of the LCA scope definition thereby ensuring that environmental performance of comparable mechanical services are assessed (Duflou *et al*. 2014; Le Duigou and Baley 2014; Corona *et al*. 2016).

Our study applies LCA to assess the lifecycle performance of a stiffness-limited hemp/epoxy composite panel produced using two different fibre retting process: traditional field retting (FR) and enzymatic retting (ER), taking into account that FR and ER yields fibres with different (mechanical) properties.

2. Methods

a. Goal and scope definition

Our study seeks to assess the environmental burdens, related to two different retting processes both applied in relation to the production of hemp fibres for composite applications: traditional field retting and enzymatic retting. The methods differ in terms of energy consumption, yield of technical fibre, auxiliary material consumptions but also on the technical properties of the resulting fibres (see table 1).

b. System boundaries

The system boundaries of our study are cradle to gate. The study starts at the agricultural step, where hemp is grown, down the value chain until the use stage of the composites.

Disposal stage is excluded since this in our case actually is the same for both scenarios and because it has been reported to have a limited contribution to the total life cycle impacts (Boland *et al*. 2015) of natural fibres. Figure 1 shows the different scenarios and the process covered by the system boundaries.

The agricultural stage considers all relevant inputs and emissions related to the cultivation of hemp. Hemp (*Cannabis sativa L.*), variety USO-31, is in our case grown in France, the largest European hemp producer producing up to 45% of the total hemp fibres available on the market (EIHA 2015). The inventory for the agricultural stage is taken from (Barth and Carus 2015; Corona *et al*. 2016).

For the FR scenario, the hemp stalks, when mature, are cut and left in the field for 20 days to allow the stems to undergo biological degradation. The retted stems are cleaned in France from the shives by scouching and hackling. Subsequently, the fibres are transported to Denmark for succeeding production steps. Inventory of the field retting is taken from (Labouze *et al*. 2007).

For the ER scenario, the fibres are initially processed via hydrothermal treatment, to facilitate enzyme penetration essential in relation to enzymatic treatment of the solid substrate and to reduce enzyme consumption. The hydrothermal pretreatment is performed in an autoclave at 100kPa and 121°C for 30 minutes. The fibres are subsequently peeled to remove the coarse xylem parts (shives). The enzymatic treatment targets the non-cellulosic components removal and it is performed using *endo-polygalacturonase* and *pectin-lyase.* A dose of 0.2% of endo-*polygalacturonase* and 0.1% of *pectin-lyase* is applied in a reactor at 40°C and 6.0 pH. As buffer NaOH is applied at a rate of 11.4g NaOH/kg of input fibres (Liu *et al*. 2016b).

The fibres after the retting process are bond together in a 2D-oriented mat using an air-laid process. The mat is subsequently mixed with the epoxy resin to produce the final composite panel. The use stage includes two scenarios: the first where the composite is used in static application (e.g. indoor furniture) where no impact arise from this life cycle stage.

Table 1. Mechanical properties, used in the comparison model, of the hemp fibre produced using the two retting methods

Property	Unit	FR	ER
Fibre porosity factor (α_f)	[-]	0.16	0.08
Fibre stiffness (E_f)	GPa	51	74
Fibre strength (σ_f)	MPa	470	620

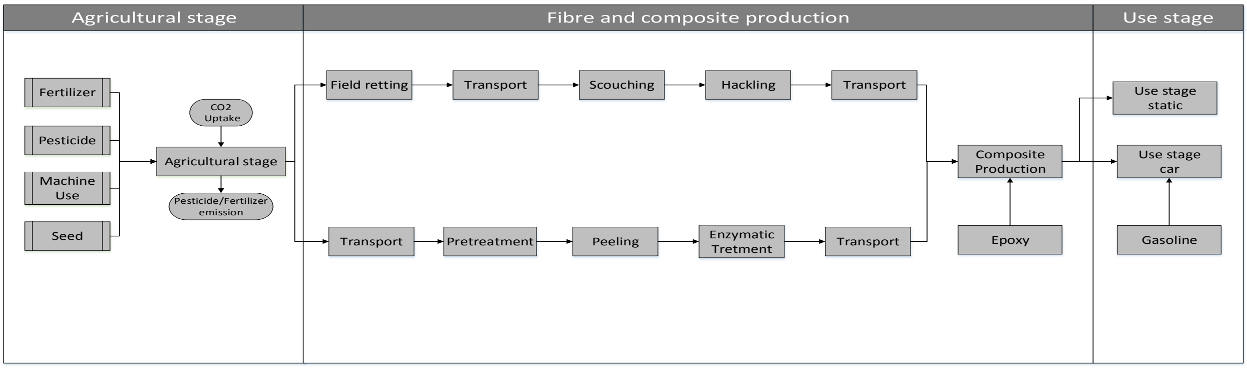

Figure 1. System boundaries of the LCA study. All the foreground process for the different scenarios are included.

Table 2. By-products amounts, prices and allocation keys of the fibre production process

Product	**Price**	**FR**		**ER**	
	€/kg	Mass (kg)	Allocation key	Mass (kg)	Allocation key
Fibres	0.60	1	0.55	1	0.61
Shives	0.25	1.96	0.45	1.55	0.39

The second scenario illustrates a dynamic application where the composite panel is used as a car door panel. It is assumed that the panel is used in a petrol engine car with a total lifetime of 200.000 km. To account for the fuel savings due to lightweighting of the car, the method presented in (Koffler and Rohde-Brandenburger 2010) is used.

c. *LCA modelling framework and LCIA method*

Data for the attributional LCA study are based on lab scale experiment, literature review and completed using the EcoInvent 3 database (Wernet *et al*. 2016).The fibre production process yields two by-product: the fibres itself and the shives (i.e. the woody core). The woody core is used in several applications: from bedding material to short reinforcement for low performance application. To distribute the environmental impacts between the two by-products from the fibre production economic allocation is applied. The allocation factors are based on the prices of the by-products. Prices are taken from (Zampori *et al*. 2013). Table 2 shows the amounts, prices and allocation keys for the two scenarios.

The LCIA methodology used is ReCiPe 2015 (Huijbregts *et al*. 2015). Results are presented as midpoint results in accordance with the Hierarchist (H) perspective. The study is performed using the GaBI 6 software (Bilanzierung 2007).

d. *Comparison method*

The fibres produced by the two retting methods differ in terms of mechanical properties and the minimum porosity achievable for the final composite. Such variations must be accounted when comparing the two scenarios because they affect the amount of composite material needed to fulfil the same design constraints. We used a comparison method developed by Corona (2016) to analyse the two scenarios. The method integrates the evaluation of different micromechanical properties and application types, when performing LCA studies on composite materials. In the present study, a stiffness-limited panel is used as reference application type along with a fixed fibre weight fraction of 0.5 for the two scenarios. Results are calculated using 1kg of FR composite as the reference scenario.

3. Results

Table 3 lists the impact potentials for the two retting scenarios and the two use stages. For static application, the ER performs worse than the FR across eight of twelve impact categories. While, for dynamic application, ER performs worse across only in three of twelve impact categories: freshwater eutrophication, human toxicity and water depletion. The higher impacts obtained for the ER scenario are associated with the retting process where, contrary to the FR scenario, larger inputs of materials and energy are required.

Figure 2 shows the hotspot analysis for the hemp panel used in dynamic application. The impact category selected for the hotspot analysis is climate change and the results are presented as the difference between the ER and the FR scenario (ΔLCA results). The trendline in figure 2 represent the cumulative difference between the two scenarios in each life cycle stage.

The figure reveals that considerable impacts arise in the fibre production step for the ER scenario due to consumption of electricity and auxiliary material.

Table 3. LCA midpoint results for the two applications and the two retting scenario (FR: Field retting; ER: Enzymatic retting)

Impact category	**Static Application**		**Dynamic Application**	
	FR	ER	FR	ER
Agricultural land occupation [m^2a]	1.18E+00	8.88E-01	1.24E+00	9.15E-01
Climate change, incl biogenic carbon [$kgCO_{2eq}$]	3.06E+00	3.86E+00	2.22E+01	2.09E+01
Fossil depletion [kg oil_{eq}]	1.42E+00	1.62E+00	7.96E+00	7.43E+00
Freshwater ecotoxicity [kg 1,4-DB_{eq}]	2.00E-04	4.60E-04	9.67E-04	1.13E-03
Human toxicity [kg 1,4-DB_{eq}]	4.37E-01	1.14E+00	2.20E+00	2.68E+00
Marine eutrophication [kg N_{eq}]	3.23E-03	2.44E-03	1.21E-02	1.03E-02
Metal depletion [kg Fe_{eq}]	2.26E-02	3.52E-02	7.54E-01	6.88E-01
Particulate matter formation [kg PM_{10eq}]	1.18E-02	1.15E-02	8.90E-02	8.03E-02
Photochemical oxidant formation [kg_{NMVOC}]	2.30E-02	2.25E-02	2.82E-01	2.54E-01
Terrestrial acidification [kg SO_{2eq}]	2.21E-02	2.27E-02	1.74E-01	1.58E-01
Terrestrial ecotoxicity [kg 1,4-DB_{eq}]	1.88E-04	2.38E-04	1.73E-03	1.61E-03
Water depletion [m^3]	2.41E+00	5.35E+00	9.18E+00	1.13E+01

At this stage, the trendline is above zero, meaning higher environmental burden for the ER scenario.

However, the ER fibres have higher mechanical properties, which implies savings in the subsequent life cycle stages. For the composite production stage, less material (fibre and epoxy) is needed to fulfil the same mechanical service. At this stage, the trendline is still above zero because the savings are not enough to counterbalance the larger impacts of the fibre production step (results from at this stage can also be used to represent the static application since no impact arise in the use stage for that scenario).

Only in the use stage, if the composite is used in dynamic application, the fuel saving compensates for the larger impacts associated with the fibre production process and the trendline thus becomes negative showing benefit for the ER scenario.

4. Conclusion

Our study presents how the retting process can affect the lifecycle performance of natural fibre composites. The two retting methods analysed in this study differs in terms of energy and auxiliary material inputs but also on the mechanical properties of the resulting composite.

Improving the fibres mechanical properties can help to reduce the composite's environmental impact only if the induced impact from the fibre production step are compensated by higher impact reduction in other life cycle stages.

In our case, this is achieved only when the composite is used in dynamic application where the fuel savings counterbalance the higher impact of the fibre production step. However, even if used for dynamic application, ER performs worse across a few impact categories. Further impact reduction could be achieved by process optimization and heat integration.

The study shows the importance of providing LCA results not only at the production gate level but also by including all relevant subsequent life cycle stages since the application contexts where of composites are used can greatly affect the outcome of the environmental performance assessment.

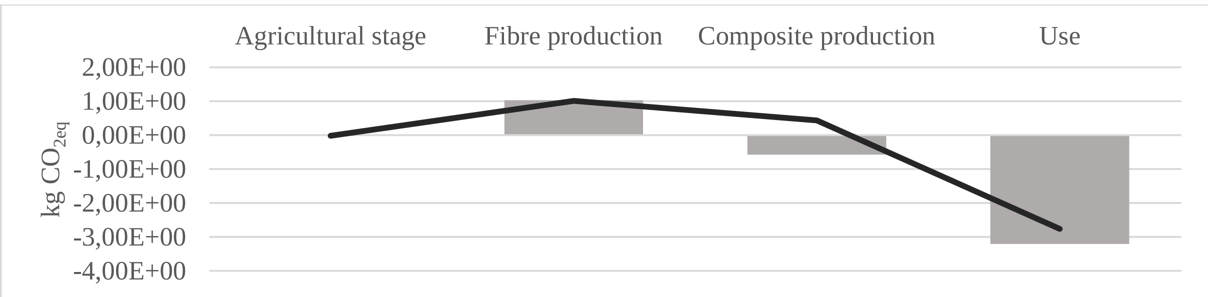

Figure 2. ΔLCA results for climate change. The column shows the relative difference between field retting and enzymatic retting for each life cycle stage. The trend-line shows the cumulative differences for the two retting scenarios at each life cycle stage.

Furthermore, the study demonstrates the need for including specific micromechanical properties along with the exact application type when defining the scope and hence the comparison basis of composites. Providing results on a mass-to-mass basis for comparison at the fibre or at the composite gate level can lead to incorrect assessments because different mechanical properties and applications will determine the amounts of material needed to fulfil the design constraints.

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