Flax Fiber for Technical textile: a life cycle inventory

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ABSTRACT

Flax fiber appears as a suitable feedstock in the endeavor of deploying a sustainable biobased economy. Its environmental performance as reinforcement in composite materials has been studied in previous Life Cycle Assessments (LCAs). However, these studies only present a coarse Life cycle Inventory (LCI) and often fail to detail all processes of the supply chain or to represent the co-products. This paper aims to bridge this gap and provide data for future LCAs on flax fiber production and transformation.

The study focuses on the impacts of producing a bio-based reinforcement material (a fabric product for non-aesthetic purposes) with a system expansion perspective. The functional unit is defined as the production of 2400 m² flax-based technical textile per year, this corresponds to one hectare of cultivated land. The geographical scope considers that the production occurs in France and that some manufacturing process are outsourced in China. A Sensitivity Analysis was carried out to assess the influence of the electricity mix in the various countries involved in the manufacturing cycle.

A detailed life cycle inventory for flax fiber production and transformation was built and the environmental performance of a flax technical textile was assessed as a cradle-to-gate LCA. The fate of co-products was documented and was shown to contribute to the reduction of the generated environmental impacts.

Through a cradle-to-gate LCA, a broader understanding of the environmental performance of a flax-based technical textile was presented by including the valorization of co-products and a wider set of analyzed impact categories, going therefore beyond the existing state-of-the-art. Results show agricultural activities and electricity production to be the biggest contributors to the environmental impacts of flax technical textile; contributions due to land use changes were minor in comparison. Very specifically for this case study, a sensibility analysis showed the influence of an all-French production to be more efficient from an environmental point of view.

1. INTRODUCTION

The latest update of the European Commission's (EC) Bioeconomy Strategy (EC 2018) sheds light on the strategic role of bio-based products and services in the transition towards a post- fossil carbon economy, bringing both innovative and sustainable solutions to global challenges such as climate change, land- and ecosystem degradation. Because it allows decoupling the material and in particular, the chemical sector from the use of

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fossil carbon, bio-based materials is a growing and encouraged market throughout Europe (EC 2018). In France, for example, the national Bioeconomy Action Plan suggests to use bio-based materials for the construction of the Olympic Village 2024, among others (Ministère de l'Agriculture et de l'Alimentation 2018).

Flax (*Linum usitatissimum*) has been long used as a source of textile fibers. Lately, it has also been used to meet technical applications such as reinforcement for composite materials. In fact, natural-fiber reinforced materials are increasingly being used as a substitute for glass fiber reinforced composites, particularly in the automotive sector (Deng and Tian 2015; Yan et al. 2014), since it allows a weight reduction of parts of ca. 5% (Le Duigou and Baley 2014), among other benefits. Amongst the different natural fibers being used, flax represented 50% of the market share for composites in 2012 (Barth and Carus 2015).

Worldwide, Europe accounts for 70% of the world's flax production, with the French Normandy region responsible for ca. 85% of the European production (C.E.L.C. 2010a; FAOSTAT 2017), making France the world leader of flax fiber production. This reflects the suitable agronomic conditions provided in the North of France (humid climate and nutrient rich soils) for the cultivation of flax, combined with a long-established know-how for cultivating and supplying this crop for the flax seed and fiber market. At the European level, there are about 140 flax fiber-processing plants and France has the installed capacity to carry out all stages of the supply chain (C.E.L.C. 2010a) i.e. the cultivation stage up to the final weaving into technical or textile fabric.

C.E.L.C. (2010) states that the cultivation of one hectare of flax fiber contributes to stock 3.7 tonnes of CO_2 (below-ground carbon). Moreover, most co-products generated through the flax fiber transformation stages are re-circulated into the economy and valorized as new products (C.E.L.C. 2010b). The environmental performance of flax fiber reinforced composites has been assessed in previous Life Cycle Assessment (LCA) studies (Bachmann et al. 2017; Le Duigou et al. 2011; van der Werf and Turunen 2008; Bensadoun et al. 2016). However, these studies do not focus on the production of the flax fiber technical textile per se and, therefore, lack detailed information on the LCI. Additionally, co-products are handled by using economic allocation techniques and their fate is little discussed or specified.

Flax thus appears as a potentially important feedstock to a Europe aiming to deploy a sustainable bioeconomy. However, the full consequences induced by the use of flax as a source of fiber to replace glass fibers has been little studied.

To the authors' knowledge, current work on LCAs assessing the environmental impact of flax fibers as reinforcement on composite materials is limited and what is available either does not address the whole supply chain of flax fiber transformation (from cultivation to weaving into a technical textile) or lacks transparent information on the LCI used. Le Duigou et al. (2011) presented LCI data up until the *combing* process and used mass allocation to artificially attribute parts of the impacts to the studied product only. On the other hand, Deng and Tian (2015) did follow a consequential approach, but accounted only for seeds, short fibers, shives and flax tow as co-products; whereas in this work every co-product emerging in the supply chain were accounted for, along with consequences of demanding constrained resources (e.g. land use changes).

In an endeavor to bridge this gap, the purpose of this study is to assess the environmental performance associated to transforming flax fibers into a technical fabric used as reinforcement in a composite material, in the short-term horizon. It also aims to provide transparent, clear and precise inventory data for future LCAs to be carried out for flax fiber intended for the technical textile sector.

2. MATERIAL AND METHODS

2.1. LCA approach

The Life Cycle Assessment was carried out with the SimaPro LCA software, version 8.5.2. The impact assessment method ILCD 2001 Midpoint+ was used but slightly adapted based on the recommendations from the European Commission (EC) "product environmental footprint category rules" (PEFCR; EC 2017), themselves based upon the IPCC update published in their Fifth Assessment Report (AR5; IPCC 2013). This affects the GWP_{100} of i) biogenic methane (34 kg CO_2 eq); ii) non-biogenic methane (36.75 kg CO_2 eq) and iii) carbon monoxide, fossil and from land use changes (1.57 kg CO_2 eq).

From the 16 impact categories proposed by ILCD 2001 Midpoint+, the following were selected to be part of the assessment, being explicitly mentioned in the European Commission policy recommendation (EC 2013) for the methods to use for LCA, namely: *Climate change, Ozone depletion, Particulate matter, Photochemical ozone formation, Acidification, Freshwater eutrophication, Marine eutrophication* and *Mineral, fossil & renewable resource depletion*. Moreover, to include impacts related to the use of nuclear energy, the impact category *Ionizing radiation (Human Health)* was included as well.

Although no official guidelines exist about this specific issue, LCAs are often labeled as "attributional" or "consequential" (e.g. (Ekvall et al. 2016; Finnveden et al. 2009; Hamelin 2013; Weidema et al. 2018)), though other (e.g. advanced attributional) or additional (e.g. prospective, hybrid, etc.), labels are also used. The LCA performed herein could be referred as "consequential" (Brandão et al. 2017; Earles and Halog 2011), i.e. no co-products are left out from the system boundaries and all their exchanges from and to the environment, in terms of material and substance flows, are fully taken into account. This approach allows to gain insights of the environmental burdens associated to changes in demand and ultimately to foresee the environmental consequences of a decision being made (Sonnemann and Vigon 2011).

Accordingly, a system expansion approach was taken, and allocation techniques were avoided, as recommended in ISO 14040 and 14044 (ISO 14040 2006; ISO 14044 2006). Background data were extracted from two life cycle inventory databases, namely Ecoinvent v3.4 and Agribalyse v1.3 (a French specific agricultural database) from which "consequential processes" (Weidema et al. 2013; Wernet et al. 2016) or identified marginal processes were selected.

2.2. Goal

This study focuses on the impacts of producing a bio-based reinforcement material; from this point onwards, to be referred to as "technical textile", i.e. a fabric product manufactured for non-aesthetic purposes. In subsequent steps, this technical fabric is impregnated with a thermoplastic or thermosetting all-polymeric matrix (e.g. epoxy,

polyester, vinyl-ester resins, among others) to form a composite material. It is the long-term vision of the authors to address the consequences of the use of such bio-based technical textile for the aviation sector, though this full assessment is beyond the scope of the present study. The present study follows therefore a cradle-to-gate approach; it encompasses all steps of flax fiber production and transformation, from the fields up until (and including) the production stage, i.e. just prior to blend the fabric with the polymeric resin. The work carried out aims to provide a complete LCI for future LCA studies to be performed.

2.3. Functional Unit

The functional unit is defined as the production of 2330 m² flax-based technical textile per year, having the required properties for an eventual use in the aviation sector. This corresponds to one hectare of cultivated land, from which about 7000 kg of flax green stems (wet weight; ww) are harvested per year (mean yield value of the last ten years according to data from FAOSTAT, 2017). For tractability reasons, the results will be here expressed per ha of land used for the cultivation of flax.

2.4. Scope

Geographical scope. The geographical scope considers that the production stems from a company located in France; parts of the manufacturing process are however outsourced in China. In other words, the cultivation and initial stages of the flax fibers conversion takes place in France (the inventory data reflects the French bio-physical and legislative conditions), while the last steps of the process chain take place in China (under the applying Chinese context for the use of electricity and other inputs). Background systems affected outside these two countries (e.g. the production of fertilizers) are also included, in accordance with state-of-the-art LCA principles (ISO 14040 2006; ISO 14044 2006).

According to C.E.L.C (2010) the European flax fiber production market is represented by over 10 000 companies distributed in 14 European countries. Europe is responsible for 80% of the world's flax fibers (scutched fibers) production and over 60% of the registered suppliers of technical fabric are located in France. However, China is considered the world leader of textile-clothing production (IFM 2004) as it makes up for 22 and 24% of the world's installed capacities for *spinning* and *weaving*, respectively (BIOIntelligence Service 2007). Hence, these last steps of the production are considered to take place in China.

Temporal Scope. The temporal scope of the study considers the short-term horizon, i.e. data from "current" production practices were collected, assuming they can be representative of future production conditions. In other words, our data represent "today's" production and are judged valid to represent the production taking place within the next five to ten years.

3. LIFE CYCLE INVENTORY (LCI)

3.1. Overview

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The identified supply chain stages to obtain a flax fibers technical fabric are presented in Figure 1 along with the various co-products emerging from these, and their fate.
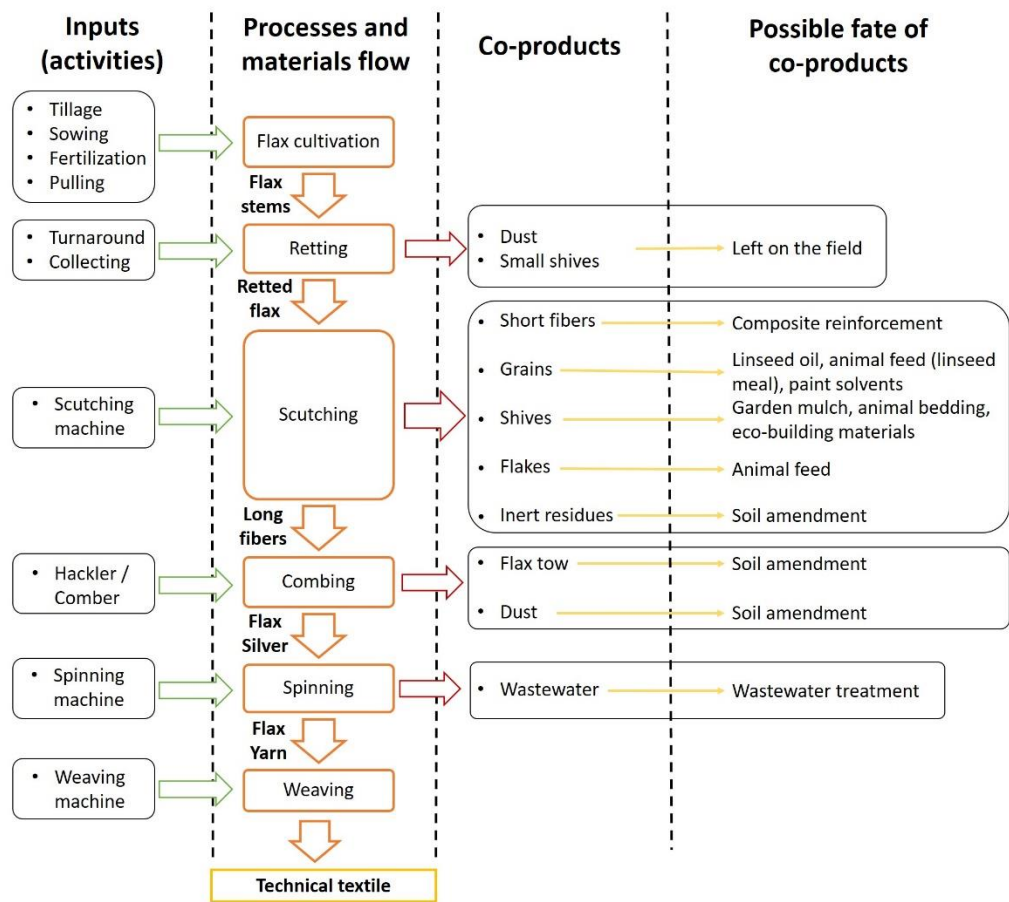

Figure 1. Process tree including input and output flows and the fate of co-products

The overall input and output flows to and from the system's boundaries in terms of materials and emissions are summarized in Table 1 (foreground data). These are represented per ha of cultivated land; values above one hectare in Table 1 mean that more than one passage of the agricultural machinery is required. For plowing, for example, machinery passes three times, each time covering the totality of the one-hectare field. This is the same for the application of fertilizers and plant protection products. As it can be seen from Table 1, the foreground inventory data considered for the *flax cultivation, scutching, combing, spinning* and *weaving* processes were essentially drawn from the work of Bensadoun et al. (2016), BIOIntelligence Service (2007) and Le Duigou et al. (2011); the only existing inventories documenting French flax production. The work behind these inventories was based on data from the industry, albeit indirectly (namely from the "Institute Technique du Lin", a French organization that manages the production and transformation of flax fiber) and the C.E.L.C.

The life cycle inventory for the *retting* stage as well as for the use of the co-products have not been documented before and are a novelty of this study. The hypothesis, calculations and data source behind these inventories are detailed in the Supporting Information (SI) Word document. All background processes (e.g. agricultural activities, production of fertilizers) involved were retrieved from the Ecoinvent v 3.4 database; the exact processes used are documented in the SI Excel document.

Table 1. Values of input and output flows from the technical textile supply chain. All units are per hectare of cultivated land per year.

FLAX CULTIVATION

Input		Value	Units
Tillage	Plowing	3	ha
Tillage	Rotary cultivator	1	ha
Tillage	Harrowing	1	ha
Sowing		1	ha
Fertilizing & zinc application by broadcaster		3	ha
Plant protection (Herbicides&Pesticides) by field sprayer		5.5	ha
Pulling		1	ha
Seeds		115	kg
Land Use		1	ha*a
Fertilizers	Potassium chloride	117	kg
Fertilizers	Ammonium nitrate phosphate	86	kg
Fertilizers	Triple superphosphate	146	kg
Pesticides	Carbendazime / Benzimidazole	150	g
Pesticides	Prochloraze	38	g
Pesticides	Flusilazole	300	g
Pesticides	Thirame	73	g
Herbicides	Triallate	144	g
Herbicides	Linuron	90	g
Herbicides	Bentazone	1584	g
Insecticides	Deltamethrin / Pyrethroid	15	g
Zinc	For seed's treatment	414	g
Zinc	For soil treatment after sowing	1000	g
Copper		9.53	g
Iron		3.48	kg
Calcium		30.24	kg
Carbon dioxide (captured from air)		10395	kg

Output		Value	Units
Flax stems		7000	kg
Induced Land Use Change		0.05	ha
Emissions to air	Ammonia	0.73	kg
	Dinitrogen monoxide	0.49	kg
	Nitrogen dioxide	0.1	kg
	Carbendazim	7.5	g
	Triallate	136.8	g
	Linuron	45	g
	Bentazone	237.6	g
	Deltamethrin (pyrethroid)	0.15	g
Emissions to water	Carbendazim	0.75	g
	Triallate (groundwater)	1.57	g
	Triallate (river)	0.86	g
	Linuron	0.45	g
	Bentazone	7.9	g
	Deltamethrin (pyrethroid)	0.075	g
	Nitrate	25	kg
	Phosphate	0.93	kg
	Nickel (river)	1.51	g
	Phosphorus (groundwater)	0.07	kg
	Phosphorus (river)	0.276	kg
	Cadmium (groundwater)	42.24	mg
	Cadmium (river)	18.68	mg
	Chromium (groundwater)	20.87	g
	Chromium (river)	2.18	g
	Lead (groundwater)	102.7	mg
	Lead (river)	307.3	mg
	Mercury (groundwater)	0.17	mg
	Mercury (river)	0.44	mg
	Zinc (groundwater)	10.4	g
	Zinc (river)	1.44	g
	Copper (groundwater)	2.73	g
	Copper (river)	1.4	g
Emissions to soil	Arsenic (As)	0.56	g
	Cadmium (Cd)	18	g
	Cobalt (Co)	1.5	g
	Chromium (Cr)	92	g
	Copper (Cu)	17	g
	Iron (Fe)	5965	g
	Mercury (Hg)	0.011	g
	Molybdenum (Mo)	1.2	g
	Nickel (Ni)	17	g
	Lead (Pb)	2.2	g
	Selenium (Se)	1	g
	Zinc (Zn)	116	g

RETTING

Input		Value	Units
Flax stems		7000	kg
Land Use		1	ha
Agricultural Machinery	Turnover	2	ha
Agricultural Machinery	Collecting	4.67	m³

Output*	Value	Units
Retted flax	6230	kg
CO_2 emissions	545	kg
CH_4 emissions	4.55	kg
CO emissions	1.21	kg
NH_3 emissions	0.42	kg
N_2O direct emissions	0.098	kg
N_2O indirect emissions	5.4E-05	kg

SCUTCHING

Input	Value	Units
Retted flax	6230	kg
Electricity	723	kWh
Transport from field	249	tkm

Output	Value	Units
Long fibers	1470	kg
Short fibres	770	kg
Grains	350	kg
Shives	2520	kg
Flakes	490	kg
Inert residues	630	kg

Co-products fate*		Value	Units
Production of glass fibre composites (Short fibres)		-693	kg DM
Marginal oil production (Linseed oil from Grains)		-99	kg
Marginal animal feed production (Linseed meal)	Marginal protein (soybean)	-177	kg FM
	Marginal carbohydrate (maize)	-149	kg
	Marginal fats (palm oil)	-3.83	kg
Avoided Land Use Change		-0.013	ha
Combustion of woody residues		41	MJ
Heat production from natural gas (Shives)		-33	GJ
Marginal animal feed production (Flakes)	Marginal protein (soybean)	-81	kg
	Marginal fibre (hay)	-666	kg
Use of inert residues as amendment		630	kg

COMBING

Input	Value	Units
Long fibers	1470	kg
Electricity	809	kWh

Output	Value	Units
Flax Sliver	980	kg
Flax tow	420	kg
Dust	70	kg

Co-products fate*	Value	Units
Use of inert residues as amendment	490	kg

SPINNING

Input	Value	Units
Flax Sliver	980	kg
Electricity	4414	KWh
Gas	24024	MJ
Water	12.74	m³
Lubricating oil	49	kg
Transport from Combing facility to port	147	tkm
Transport from port to port	19110	tkm
Transport from port to factory	196	tkm

Output	Value	Units
Flax Yarn	910	kg
Wastewater	12.74	m³

WEAVING

Input	Value	Units
Flax Yarn	910	kg
Electricity	11830	kWh
Starch	159	kg
Transport from factory to port	168	tkm
Transport from port to port	16380	tkm
Transport from port to distribution place	168	tkm

Output	Value	Units
Technical textile	840	kg

*Calculated data (specified in their respective sections and in the SI).

3.2. System boundaries

As previously discussed, system expansion was used to quantify the environmental impacts stemming from the co-products. Their inclusion into the system boundaries was done by identifying their most common use in the market, along with identifying the marginal (avoided) processes that would most likely be reacting to the demand change induced by their introduction to the market (Figure 2). These choices were validated by experts and professionals of the sector.
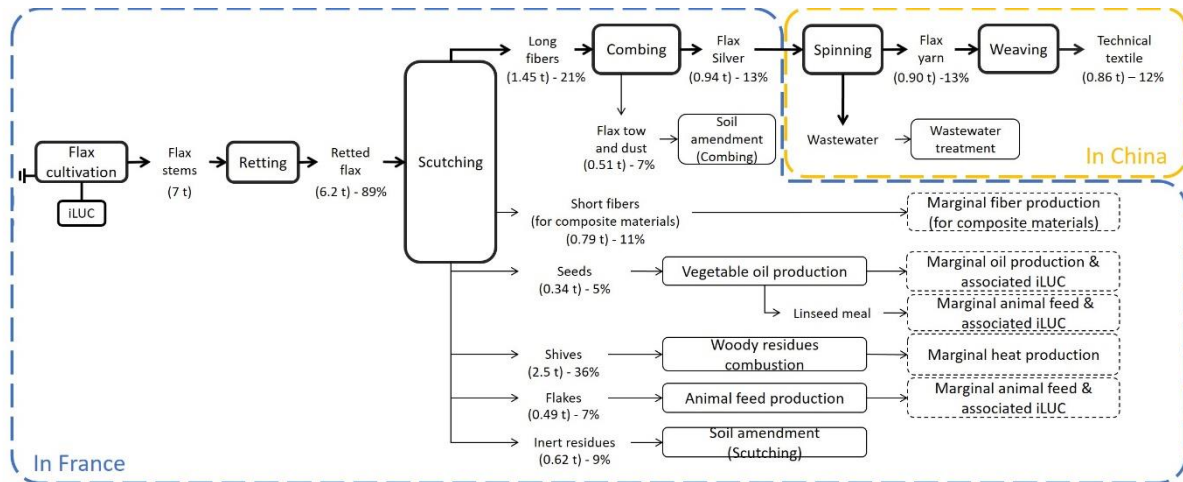

Figure 2. Process flow diagram illustrating the fate of the co-products from the production of a flax fiber technical textile. Boxes represent induced processes while dotted lines represent avoided processes

Other than agricultural machinery, infrastructure of foreground data is not taken into consideration. On the other hand, infrastructure related to background data is included in the already existing Ecoinvent processes.

Transportation requirements and corresponding transport distances are documented in the BioIntelligence Service report (2007) and these were considered herein. A 40 km distance between the cultivation location and the *scutching/combing* facilities is considered to be covered by a 32 t truck. The same transport goes for the distance between the *scutching* facility and the French port (150 km) from which flax fibers will be shipped by a transoceanic freight ship to the Nanjing port in China (19500 km). Fibers are then transported by land to a facility at 200 km where they will be spun and woven. The technical textile is afterwards sent back to France considering the same transportation route, except that once in France, a 200 km distance from the port to a selling point is covered by truck. In the model, transport processes are taken into consideration as part of the *spinning* and *weaving* processes; their influence is addressed in the discussion section.

3.3. Flax cultivation

For the cultivation of one hectare of flax fiber, about 115 kg of flax seeds are sowed. Sowing takes place between the months of March and April. After 100 days (blooming stage), the stems reach a height of one meter. As a result, by the month of July, 7000 kg ha^{-1} of flax stems (ww) are harvested by pulling (not reaping). This is done particularly for flax grown to be used as a fiber source for textile production; by pulling the whole stem, along with the roots, farmers ensure that fibers will be as long as possible.

Data for the planting and harvesting stages were collected from BioIntelligence Service (2007) and Le Duigou et al. (2011), as documented in the SI.

The impact of displacing land as additional arable land is demanded for *flax cultivation*, i.e. the so-called land use changes, was taken into account based on the approach described in a recently release study from the European Commission (EC 2019), itself updating the deterministic approach presented in Tonini et al. (2016). In a nutshell, this approach is based on an analysis of the global deforestation that occurred between 2000 − 2010, and considers two key reactions to an increased demand for arable land, namely arable land expansion (85% of the response) and agricultural intensification (15% of the response; here translated as an additional fertilizer demand only). All carbon (carbon dioxide; CO_2, methane; CH_4 and carbon monoxide; CO), nitrogen (ammonia; NH_3, dinitrogen monoxide; N_2O, nitrogen oxides; NO_x and nitrates; NO_3^-) and phosphorus flows occurring as a result of these two responses were taken into account. When translated into CO_2 eq, it results in an emission factor of 4.0 t CO_2 eq ha^{-1} y^{-1}. Which is in the same order of magnitude as the factor derived by Tonini et al. (2016) (4.1 t CO_2 eq ha^{-1} y^{-1}), but slightly above the factors derived by Schmidt and Muños (2014) (1.7 t CO_2 eq ha^{-1} y^{-1}); value for "world average arable land").

The iLUC value is obtained by considering the annualization of the use of 1 ha of land over 20 years, based on EU methods.

Removals of calcium, copper and iron from the ground were accounted for. The starting point for this was the composition of the flax plant (Heuzé et al. 2015). Here, it was considered that no external application of these micro-nutrients take place; therefore the whole quantities of these in the flax plant is assumed to stem from soil withdrawals. Biogenic CO_2 captured by the plant was calculated through Equation 1 (Boutin et al. 2005). In this equation, Q_{CO2} represents the amount of CO_2 required by the plant to make up its weight in dry matter (Q_{DM}); $\%_C$ corresponds to the carbon content of flax fibers (here 45%; (Sharma and van Sumere 1992)) and M_{CO2} and M_C represent the molar mass of CO_2 and C, respectively.

Equation 1 - $Q_{CO_2} = (Q_{DM} * \%_C) * \left(\frac{M_{CO_2}}{M_C}\right)$

Flax's nitrogen requirements are low and sensitive to the quality of the soil. According to ADEME and ITCF (1998), an input of 10-20 kg ha^{-1} suffices for a high quality soil, while 40 kg ha^{-1} are needed for soils with less humus content. Independently of the soil quality, potassium (K_2O) and phosphate (P_2O_5) requirements amount each to 70 kg ha^{-1}. For this study an average of 30 kg ha^{-1} was considered as nitrogen input. The specific fertilizers considered are based on the BioIntelligence Report (2007) and correspond to the marginal fertilizers identified by Hamelin (2013) for Europe, namely: ammonium nitrate (35% N content), potassium chloride (60% K_2O content) and triple superphosphate (48% P_2O_5 content). Similarly, the application of pesticides and herbicides was modelled based on the data from the BioIntelligence report (2007).

3.4. Retting

The first transformation step from plant to fiber is the *retting* process. Once the stems are pulled, they are laid over the field in windrows of approximately 1 meter long and left to "rot" by the enzymatic action of the

microorganisms present in the soil, being exposed to rain and other climate conditions particular to the region. Stems must be well aligned and not too tight to avoid mold (GNIS 2018b). To optimize the *retting* process, farmers will turn over the stems to obtain a homogeneous result. The quality of the fibers depends greatly on how well the *retting* was carried out by the farmers.

During the process, the pectins that bind the fibers to the woody part of the plant are depolymerized. This step can take from two to 12 weeks depending on the climate conditions and the industrial requirements for the fiber. At the end of the *retting* process, when the flax stems are sufficiently dry (less than 15% moisture content) they are stored rolled up in round or rectangular bales.

As confirmed by experts from the French organization "*Union Syndicale des Rouisseurs-Teilleurs de Lin*" (USRTL), no biomass is left on the field after collection of the retted stems. Possible dust and small shives produced from the *retting* process and their contribution to adverse health or as an input of carbon and macronutrients to soil are considered as negligible. Therefore, the mass loss is assumed to be emissions to air.

Consequently, carbon (CO_2, CO, CH_4) and nitrogen (N_2O, NO_x, NH_3) emission flows from the decomposition of biomass were estimated in order to model the overall environmental impact of the *retting* process. Carbon losses were calculated considering that 22% of the total mass loss happens in the form of carbon. This proxy is based upon ongoing research (Bleuze 2019) on the retting of hemp under industrial condition as no quantified data characterizing the degradation of flax during the *retting* process was available. By considering an overall mass loss of 11% (Table 1; specifications in SI) and a dry matter content of 90% for flax (Heuzé et al. 2015), the total carbon losses amount to about 150 kg C_{loss} ha^{-1}, being lost as of CO_2, CO and CH_4, as further detailed in the SI. Regarding nitrogen emissions, it was considered that losses correspond to 0.06% of the dry matter (DM), based on Hamelin et al. (2014); which translates into 0.42 kg N_{loss} ha^{-1}. These were considered to occur as N_2O and NH_3; details of the calculations can be found in the SI.

3.5. Scutching

Retted stems are baled and transferred to *scutching* facilities where the wood-like part of the stem is broken up for the fibers to be accessible. This is the first mechanical transformation of the fibers and a process in which numerous co-products are generated, namely long fibers that go from 60 to 90 cm (GNIS 2018a) (desired output), short fibers below 60 cm, grains, shives, flakes and plant residues that may include some dust and soil (Figure 1). The energy input related to this process was modelled according to BIOIntelligence Service (2007) and Le Duigou et al. (2011), as well as the mass percentages of the different co-products resulting from this step.

Bales are unrolled on carpets and, after having recovered the seeds by beating them, flax stems are spread out parallel as they pass through a machine composed of a set of metal toothed rollers that crush, beat and then comb them to eliminate the inside wood-like core. Drum carders spinning at 200 rpm, where long and short fibers are separated, then clean the fibers. Long fibers are kept while the different co-products fall to the floor of the machine. Small components such as flakes and plant residues in the form of dust, are extracted by an aspiration system.

Short fibers. As their name suggests, this co-product represent fibers of a reduced length. This co-product, also known as scutched tow, is essentially valorized as reinforcement in thermoplastic composite materials for leisure products (such as rackets, boards, skis, helmets, among others), automotive parts (e.g. dashboard, door panels), eco-building or composite furniture (C.E.L.C. Masters of Linen 2010). This application, i.e. reinforcement in composite materials, was therefore considered herein.

In some cases, short fibers undergo another cleaning process where high and low quality short fibers are distinguished. Low quality fibers are then used as insulation material for housing. Whether this additional step does take place or not is plant-dependent and was not considered in this life cycle assessment.

Here, the production of fiber-reinforced composites was considered to replace glass fiber reinforced composites in a 1 to 1 ratio. This assumption implies that markets are unconstrained, that supply is fully elastic (B. Weidema et al. 2013), and that both fibers deliver the same functionality per unit of mass. It was further considered that the type of fibers used (glass or flax) does not affect the quantity of resin needed to produce the composite material (resin was therefore left out of the system boundary). It was then considered that the 770 kg of short fibers produced per functional unit, avoid the production of 693 kg of glass fibers (considering a 90% DM content for the short fibers).

To represent the displaced glass fibers production (from the 770 kg of short fibers produced per functional unit), the process *avoided glass fiber production* was modelled, adapted from an existing process of the Ecoinvent v3.4 database, as further detailed in the SI Excel document.

Seeds. Linseeds are flat-shaped and have a bright, brown color. They are small and light, 2000 seeds weight around 10 g; which corresponds to the dose required to sow one m² of land (GNIS 2018a). They come inside a structure known as a capsule; each capsule is made up of two lobes that can contain 1-2 seeds. In total, 8-10 seeds can be obtained from one capsule.

Seeds are collected right at the beginning of the s*cutching* process and are typically used to extract oil (Deng and Tian 2015), to be sold on the vegetable oil market, thereby replacing the production of marginal oil. This is here considered to be palm oil, as identified by Schmidt and Weidema (2007). In the linseed oil extraction process, linseed meal is generated as a co-product. Linseed meal is considered to be further valorized as animal feed. It has a higher protein quality than other commonly used sources of protein (Newkirk 2015) and there is no other real economic market for it (Chandrasekaran 2013). The LCA model considers that the carbohydrate, lipid and protein content of the meal replaces marginal carbohydrate, lipid and protein sources in animal feed, respectively. The marginal carbohydrate was taken to be maize, as identified by Tonini et al. (2016), the marginal protein to be soybean meal (Dalgaard et al. 2008), and the marginal lipid as palm oil (Schmidt and Weidema 2007).

Substitution factors were derived based on the nutritional valued of linseed meal and those of the marginal displaced feed ingredients (detailed in Table 1 and the SI), an approach similar to that taken by e.g. Tonini et al. (2016). The life cycle inventory of the displaced ingredients was retrieved from the Ecoinvent v3.4 database

(consequential processes; exact processes documented in the SI). The so-called "oil loop" documented in Dalgaard et al. (2008), i.e. reflecting that the substituted palm oil is produced along with palm meal, whose displacement in turns affect other commodities, is taken into account through the use of these consequential processes of the Ecoinvent database.

Shives. Shives represent the inner core of the stem, a wood-like layer typically valorized as gardening mulch, animal litter and/or as eco-building materials in the form of chipboard panels (C.E.L.C. 2010a). For these three uses, an increased availability of shives involves a decrease in the use of wood residues. Wood waste (as wood chips for the case of gardening mulch and animal litter; and as a variety of streams for eco-building materials) is here considered as the marginal supplier for these uses. In other words, it is considered to be the least competitive supplier of these services, and thus the one to be displaced as a new alternative (here shives) becomes available. The fate considered for this increased availability of wood waste (no longer needed where shives are now used) is combustion in a 300 kW furnace with silo, supplying heat for district heating. This is based upon the findings of Projet AF Filières (2018), presenting a detailed material flow analysis of woody resources for the whole of France. The heat produced by these wood residues would then induce a decrease on the use of natural gas, the latter representing the marginal heat source for France.

The composition of flax shives and wood chips, in terms of DM, C and N, is very similar (C – 51% vs 50%; N – 0.6% vs 0.4%; expressed as % of the DM and retrieved from the Phyllis database). This involves that the emissions and impacts linked to their respective management (prior to their use) can be expected to be very similar to one another; these were thus neglected herein.

In a nutshell, the overall management of shives implies two key processes, namely:

- Induced *woody residues combustion*, to represent the emissions from generating district heating heat from the displaced wood residues and,
- *Avoided heat production from natural gas*, which would have otherwise been used to generate that heat.

Detailed information on the processes used as proxys to model this can be found in the SI Excel document.

Flakes. Flakes represent the fibrous tissue covering the flax grains and can be further valorized as animal feed (BIOIntelligence Service 2007). The mechanical force applied to the fibers during the *scutching* process, causes the outer tissue of the grains to detach and fall. The nutritional content of flakes is high on fiber, but also contains protein (SI). Just like the calculations done for the valorization of linseed meal as animal feed, the fiber content of hay (marginal fiber) and soybean meal (marginal protein) were compared to the nutritional composition of flakes in order to derive the displacement ratios. The processes *avoided soybean meal production (Flakes)* and a*voided hay production (Flakes)* were created, as detailed in the SI.

Inert residues. Inert residues include the dust from the plant itself, small plant residues and soil carried out from the field with the flax stems. Based on personal communications with the stakeholders of the flax supply chain, these few centimeters of dusty residues are typically returned to nearby farmers and mixed with the

amendments conventionally applied to soils. They are thus not used instead of fertilizers (or other amendments), but on top of these. Therefore, they do not replace marginal fertilizers. To model the emissions due to the application of this material on land (AoL), the algorithms detailed in Hamelin et al. (2014) for AoL were used, as further elaborated in Section 3 of the SI Word document.

3.6. Combing

Long fibers are combed for untangling and homogenization as well as removing small debris that may be left from the *scutching* process. Fibers are transformed into ribbons (flax sliver) and are ready to be spun into yarn. During this process, flax tow and plant residues are produced as inert materials. Similar to the inert residues produced during the *scutching* process, they are generally re-incorporated to nearby fields as amendment. The flows from and to the environment due to this were modelled using the same algorithms applied for the AoL of inert residues from the *scutching* process, as further detailed in the SI Excel document.

3.7. Spinning

Flax sliver is transported to China and spun into yarn by a process of untangling, regularizing, stretching and threating of the fibers. Wet spinning is a common practice to this end, and wastewater is generated as a result. This was represented in the model as *Wastewater treatment (from spinning)* as detailed in the SI.

3.8. Weaving

The last step is the *weaving* of the fabric. During this process, starch is usually used as a gluing agent. The result is a flax technical textile of 360 g/m². Detailed information on the input and exact processes used can be found in the SI Excel document.

4. SENSITIVITY ANALYSIS (SA)

The production process of flax-based technical textile takes place in different countries, namely France and China. **Erreur ! Source du renvoi introuvable.** highlights that China's marginal electricity mix mainly consists of coal (77%) and hydropower (20%), while France mainly relies on wind (84%) and solar power (44%) for their marginal electricity production (as modelled by the Ecoinvent v3.4 consequential processes for each country's electricity mix). Marginal sources of electricity represent the technologies that will be able to react to a surplus in demand.

Table 2. Marginal electricity mix for France and China (Source: Ecoinvent v3.4 processes)

Electricity mix (2016)	France	China
Coal	-	77%
Gas	-	<1%
Waste	13%	-
Nuclear	-	2%
Hydro	<1%	20%
Solar PV	44%	<1%
Wind	84%	<1%
Geothermal	2%	-

It has been shown several times (Ewertowska et al. 2016; Santoyo-Castelazo et al. 2011; Pehme et al. 2017) that electricity mixes involving less fossil supply (coal, natural gas, shale oil or gas) will yield an overall greater environmental performance, especially when it comes to climate change. To quantify the importance of the electricity mix for the present flax-based technical textile case, a virtual sensitivity analysis was made considering that all uses of electricity stems from the French electricity mix. This sensitivity analysis will thus reflect the impact of a hypothetical future wind and solar energy system.

5. RESULTS

5.1. LCA results

The main contributors to the overall environmental impact of the production of 2330 m² (considering a grammage of 360 g/m²) of technical textile issued from one hectare of cultivated flax, are the processes of *weaving*, *spinning*, *flax cultivation, retting,* the *avoided glass fiber production,* the *woody residues combustion* and, to a lower extent, the *induced land use change (iLUC)* (Figure 3).
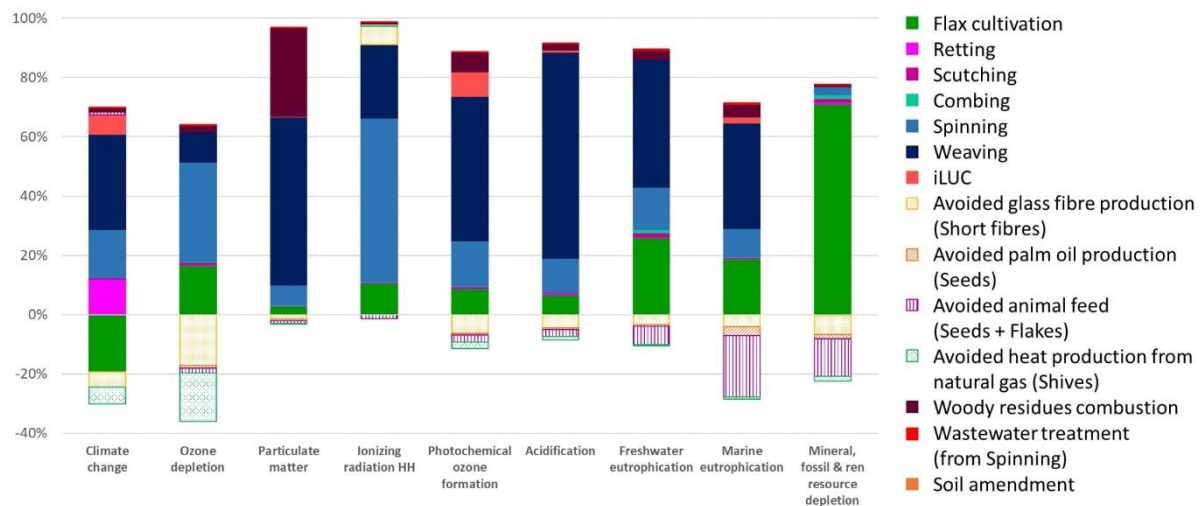
Figure 3. Processes contribution to generated (positive values) and avoided (negative values) environmental impacts in the production of a flax fiber technical textile from 1 ha of cultivated land

Moreover, Figure 3 illustrates the generated (positive values) as well as avoided (negative values) impacts, broken down at the process level. The absolute values behind Figure 3 are presented in Table 3.

Table 3. Results of the environmental impact of producing flax fiber technical textile issued from one ha of cultivated land

Impact category	Total/ha	Total/m² of technical textile	Unit
Climate change	18162	7.79	kg CO2 eq
Ozone depletion	3.6×10^{-4}	1.55×10^{-7}	kg CFC-11 eq
Particulate matter	52	0.02	kg PM2.5 eq
Ionizing radiation	1048	0.45	kBq U235 eq
Photochemical ozone formation	87	0.04	kg NMVOC eq
Acidification	194	0.08	molc H+ eq
Freshwater eutrophication	4.5	1.2×10^{-3}	kg P eq
Marine eutrophication	23	9.8×10^{-3}	kg N eq
Mineral, fossil & renewable resource depletion	0.48	2.1×10^{-4}	kg Sb eq

To better understand the causes and substances behind the environmental impacts (generated or avoided), each of the processes identified as main contributors were analyzed individually, as shown in Figure 4 to Figure 10.
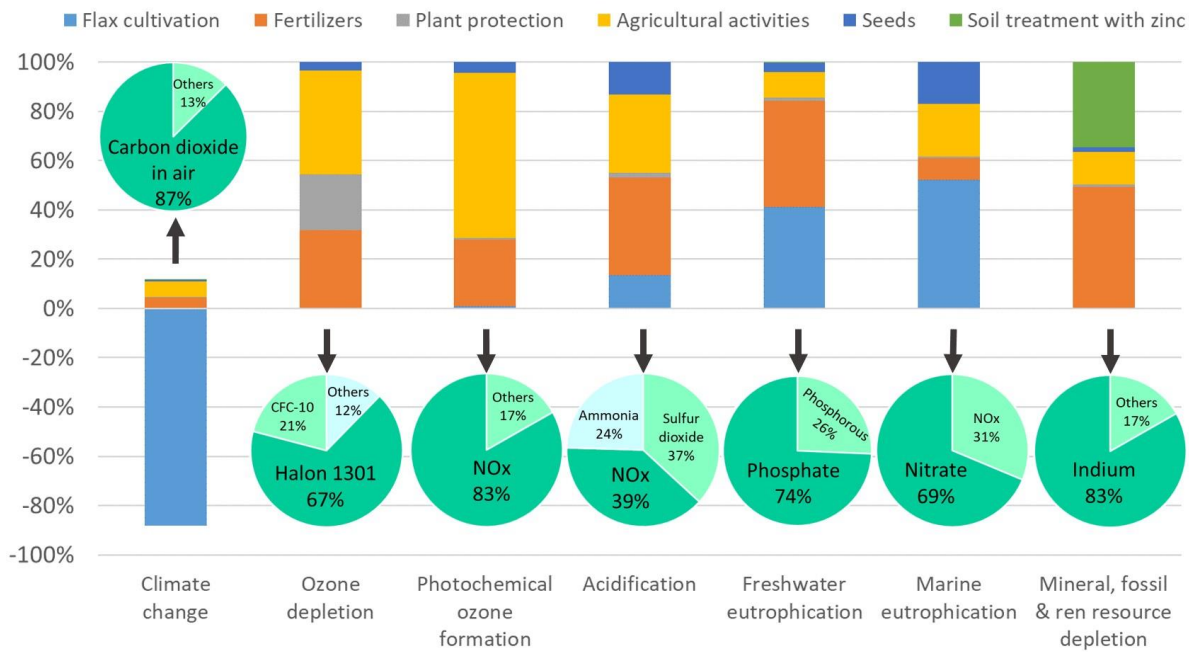
Figure 4. Flax cultivation - Individual analysis of the main induced and avoided environmental impacts and the substances responsible
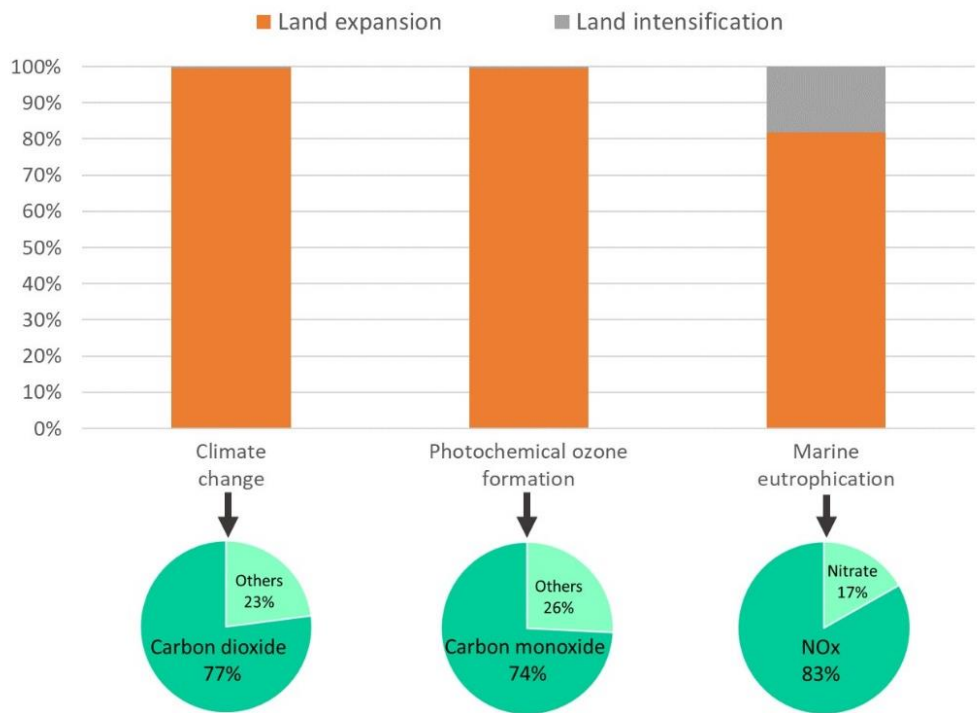
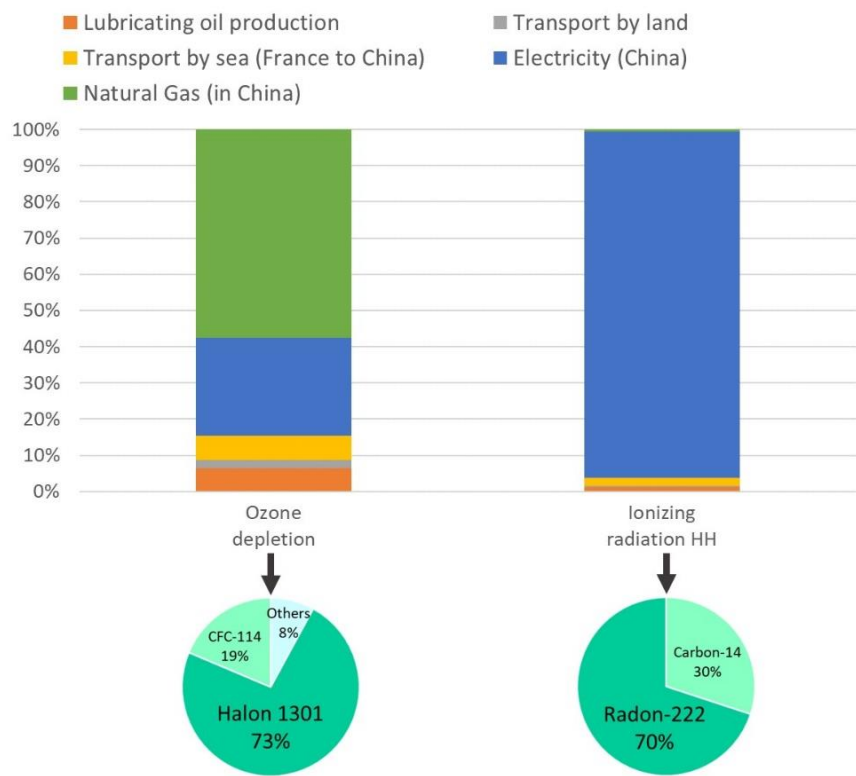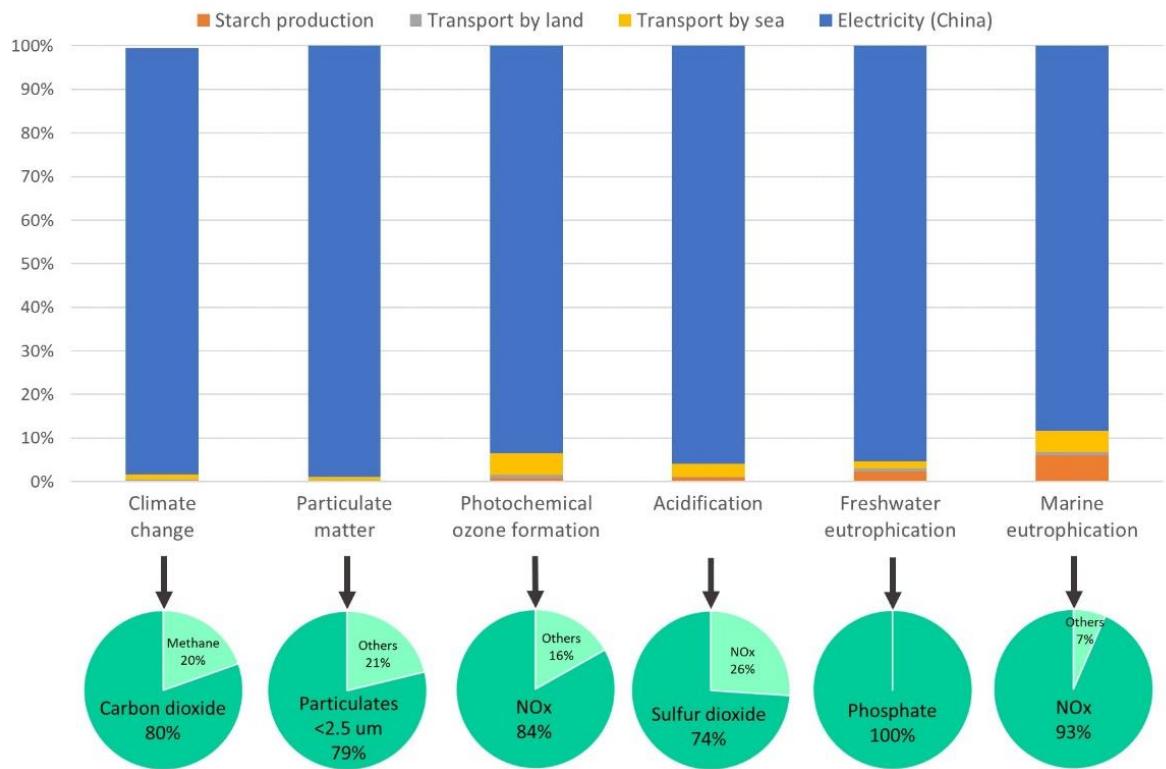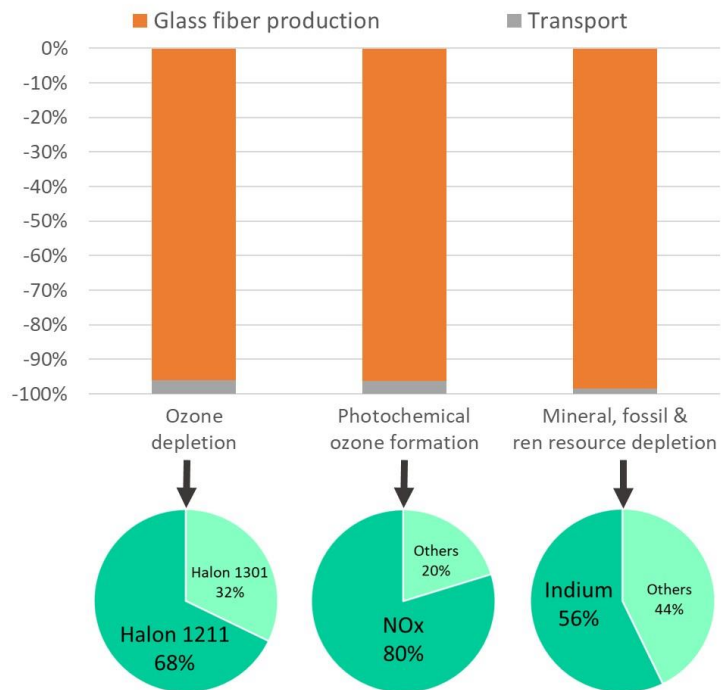**Figure 5.** iLUC- Individual analysis of the main environmental impacts and the substances responsible

Figure 6. Spinning - Individual analysis of the main induced environmental impacts and the substances responsible

Figure 7. Weaving - Individual analysis of the main environmental impacts and the substances responsible

Figure 8. Avoided production of glass fiber - Individual analysis of the main avoided environmental impacts and the substances responsible
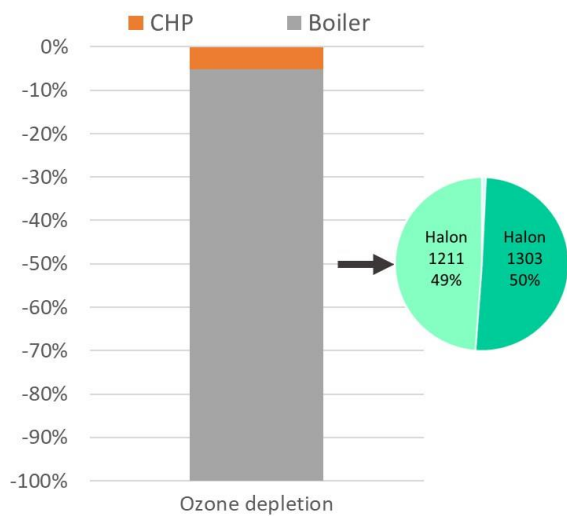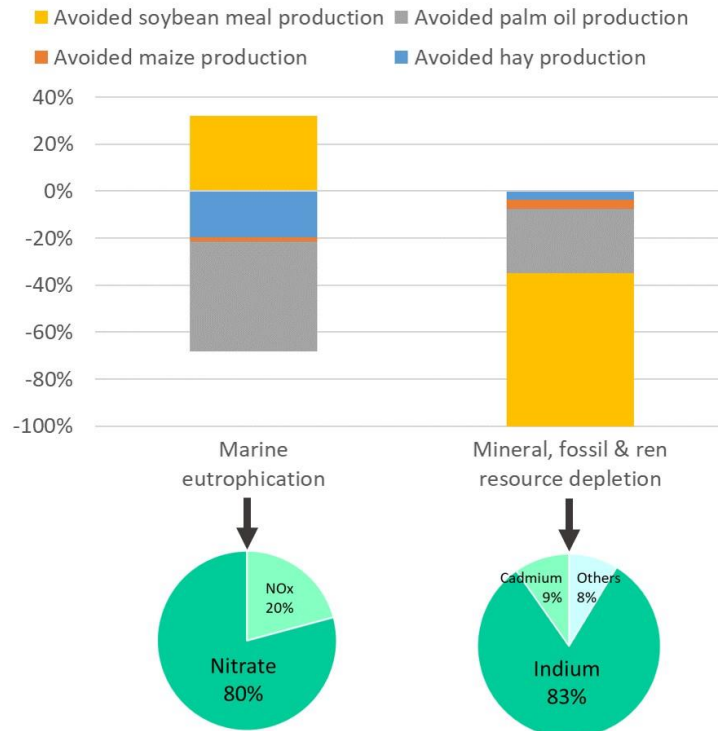

Figure 9. Avoided heat production from natural gas - Individual analysis of the main avoided environmental impact and the substances responsible

Figure 10. Avoided animal feed production - Individual analysis of the main avoided environmental impact and the substances responsible

In general, results show that:

- The *spinning* and *weaving* processes represent between 45% and 95% of the generated environmental impact in all of the categories except for *Mineral, fossil & renewable resources depletion*.

- The *combustion of woody residues* has higher or almost equivalent environmental impact than the benefits generated by the fossil-based heat it avoids (*avoided heat production from natural gas).* This is particularly true for the impact category *Particulate matter.* However, wood-based heat (rather than natural gas heat) contributes to the reduction of *Ozone depletion* and *Climate change,* as well as *Photochemical ozone formation* and *Acidification,* to a lower extent.

- A contribution of the *induced land use change (iLUC)* to the impact category *Climate change* is visible and, to a lower extent, to the impacts *Photochemical ozone formation*, *Acidification* and *Marine eutrophication*.

- The *avoided glass fiber production* (due to the generation of short fibers as a co-product in the *scutching* process) translates into avoiding impacts (i.e. negative values), even if small, in all the environmental categories assessed, except for *Ionizing radiation HH* where a generated (or positive) impact is clearly visible.

- The *avoided animal feed* resulting from the valorization of seeds and flakes (*scutching* process), results in avoided impacts for *Freshwater* and *Marine eutrophication¸* as well as *Acidification* and *Mineral, fossil & renewable resource depletion.* A contribution to a reduction in the impacts *Ionizing radiation* and *Photochemical ozone formation* is also visible, even if lower.

- In the totality of the system, ten substances were identified as the main cause of the generated environmental impacts. These substances (and their cause) being: Carbon dioxide (*iLUC,* Chinese electricity), Halon 1301 (*flax cultivation;* Chinese electricity), Particulate matter <2.5 um (Electricity in China), Radon-222 (Electricity in China), Carbon monoxide (*iLUC*), Nitrogen oxides (*flax cultivation;* Chinese electricity; *iLUC*), Sulphur dioxide (Chinese electricity), Nitrate (*flax cultivation*), Phosphate (*flax cultivation;* Chinese electricity) and Indium depletion (*flax cultivation*).

- Finally, the avoided environmental impacts were mainly due to the avoidance of using or generating the following substances: Halon 1211 & 1301, Indium, Nitrates and Carbon dioxide uptake during flax cultivation (the LCI being cradle-to-gate).

5.2. Sensitivity Analysis (SA)

Figure 11 shows the impacts of an all-French electricity production and use (i.e. no use of the Chinese electricity mix). It highlights that using 100% French electricity rather than a mix of the French and Chinese electricity would be beneficial for every impact category, except for *Ozone depletion* and *Mineral, fossil & renewable resources depletion*.
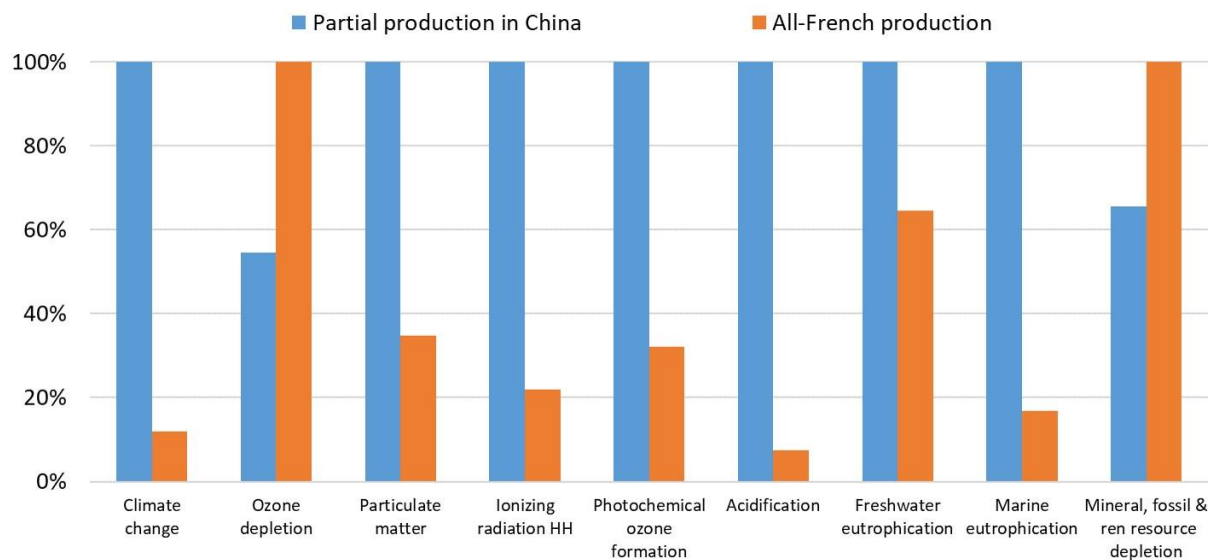

Figure 11. Sensitivity Analysis for production considering different electricity mixes

Nowadays, given its installed capacities and production prices, the production of textile products is most likely to be outsourced to China. However, France counts with the technology to locally produce a flax fiber technical textile. Through Figure 11, it is visible that an all-French supply chain would result in a more performant product, from an environmental point of view.

6. DISCUSSION

Flax cultivation is a process that both generates and avoids environmental impacts (Figure 4). Generated impacts are significant for *Freshwater* and *Marine eutrophication, Ozone depletion* and for *Mineral, fossil & renewable*

resources depletion; mainly due to fertilizers and zinc for soil treatment. For instance, the production of triple superphosphate fertilizer (35%; essentially due to discharges to water compartments) and its application on the field (40%; process detailed in the SI) induces freshwater eutrophication due to leakage of phosphates and phosphorous to water sources. Moreover, the production of the same fertilizer along with zinc used for soil treatment after sowing, causes a depletion of resources as the infrastructure for mines induces an exhaustion of substances such as indium and cadmium. Over 60% of the impact on *Mineral, fossil & renewable resources depletion* is in fact due to flax cultivation, and of this almost 50% is due to triple superphosphate and 35% to zinc.

Results show a high relation between zinc procurement and the depletion of indium, which is the main responsible for the impact on *Mineral, fossil & renewable resources depletion*. This is due to the fact that indium is a by-product of zinc extraction, along with other substances such as cadmium (Classen et al. 2009).

Ozone depletion is caused mainly by Halons and CFCs, these substances are linked to the distribution of fossil-based fuels and the production of plant protection products (bentazone, specifically). Halon gases are used as fire retardant agents in pipelines; the Ecoinvent processes for fossil-based fuels (i.e. diesel and natural gas) consider emissions of halon gases to air to be caused by accidents and values were estimated from corporative environmental reports (Faist Emmenegger et al. 2007).

The NO_x emissions responsible for the *Photochemical ozone formation* and *Acidification* impacts are as well consequences of the use fossil-based energy sources in the production of fertilizers (namely, nitrogen and phosphate fertilizers) and used in agricultural activities (i.e. plowing).

Marine eutrophication is essentially due to the procurement of seeds. The impact originates from the use of nitrogen fertilizers and NO_x emissions issued from the agricultural machines required for their production.

Because this analysis is cradle-to-gate, *flax cultivation* is here shown as a process reducing the *Climate Change* impact. This happens as a result of the CO_2 captured by the plant during its growth; the relevance of this benefit depends upon the time the captured carbon will reside in the technosphere (e.g. as flax-based panels). A short-time period between the sequestration of carbon and its re-emission to the atmosphere at the end-of-life phase of the panel has very little benefit and makes almost no difference in terms of long-term climate change impact (Jorgensen et al., 2015). A lifetime as long as possible as well as end-of-life solutions allowing to recycle (or maintain) the technical textile carbon within the technosphere are thus of tremendous importance to reduce the climate change impact, when the full life cycle will be considered. However, as highlighted in Figure 3, the induced demand for new arable land caused by the additional flax cultivation in France (i.e. *iLUC* process) reduces the global warming benefits from flax cultivation. In this study, the induced land use change represents slightly less than 10% of the impact on *Climate change*; which is coherent with results obtained by different authors where *iLUC* represents 5-20% of the impact (Pehme et al. 2017; EC 2019; though with some outliers at almost 70%). Figure 5 shows that the main cause of the impacts generated by the *induced land use change* are the effects of land expansion. Land expansion itself consists, based on the model used herein, of two processes: land clearing and foregone sequestration. Biomass burning occurring during land clearing produces CO_2, CO and NO_x emissions responsible for over 80% of the *Climate change, Photochemical ozone formation* and *Marine eutrophication*

impacts. For climate change, CO_2 produced during biomass burning (which alone represents over 99% of the impact) is the main contributor to the generated impact. It should be highlighted that previous studies on flax fiber as a bio-based feedstock did not include the effects of land use changes.

Deng and Tian (2015), for example, justified this omission on the premise that *flax cultivation* areas are currently decreasing; a premise that is obviously inconsistent with the starting point of this study, where flax is investigated as a resource to produce a new bio-based material to be introduced in the economy. The vision is thus to produce more of this material, if it is found to be a sustainable alternative to materials based on fossil-carbon. This implicitly suggests an increased demand for it and its source feedstock. In fact, flax represented about 50% of the market share in natural fibers used in the European automotive industry in 2012, and is foreseen to play a dominant role in future composite materials production (Barth and Carus 2015).

The main impact affected by the retting of flax stems was *Climate change*. This was caused by a background process, namely the use of agricultural machinery (i.e. rotary tedder) used for turning the stems over. Specifically, the impact is generated given the use of fossil-based fuels (i.e. diesel) as energy sources by the machinery.

As earlier stated, the *spinning* and *weaving* processes are responsible for more than 60% of the contribution to all impact categories but *Mineral, fossil & renewable resources depletion* (where they represent slightly less than 3% of the impact). Electricity and heat (natural gas used in *spinning*) production and use are responsible for over 85% of the generated impacts by the *spinning* (Figure 6) and *weaving* (Figure 7) processes. These two processes take place in China, where almost 70% of the electricity mix comes from coal burning (hard coal) according to data from the IEA (2016a). Both the burning of coal and the activities related to its procurement have an important contribution to the overall generated impacts from Chinese electricity, in all categories. Impacts are, however, exacerbated by the fact that the Ecoinvent process considers hard coal to be about 75% of China's source of electricity.

Moreover, Dissanayake et al. (2009) also identified *spinning* as a hot spot. These authors pointed out that avoiding that process, if possible, is an opportunity for reducing energy consumption. In fact, on the basis that the *spinning* process might diminish the mechanical properties of fibers, Le Duigou et al. (2011) did not take it into consideration in their LCA. However, their final composite material products consider as reinforcement a flax mat where fibers are randomly dispersed, so there is no need for them to be spun or woven. Bachmann et al. (2018), whom studied the impact of various "novel sustainable panels" for the aviation sector, did consider spinning in their LCI of flax yarn production. Impacts to *Ozone depletion* are a consequence of the procurement (on-shore extraction) of fossil-based energy sources (i.e. natural gas) used during the *spinning* process. This is due to the use of substances such as Halon 1301 and 1211; used as fire suppression agents in oil pipelines (UNEP HTOC 2014). Figure 6 and Figure 7 as well show that impacts from transportation are negligible when compared to those issued from electricity procurement. This means that the degree of the impact of outsourcing production depends more on the way countries produce electricity than the distances between them or the energy source used by the transportation vessels.

Furthermore, the valorization of the co-produced short fibers as a reinforcement component in composite materials results in a diminishment of the production of glass fiber. This, in turn, translates in avoided impacts *Ozone depletion*, *Photochemical ozone formation* and *Mineral, fossil & renewable resources depletion*, predominantly. This is mainly due to the avoided consumption of Halon 1211 and Indium as well as a reduction of NO_x emissions (Figure 8); the impact of Halon 1211 is due to the use of fossil-based energy use in the production of glass fibers as it is used as a fire suppression agent (as previously stated). Moreover, the use of Indium is related to the mining of zinc (as for the *flax cultivation* process), which is used for the coating of steel coils required for the construction of glass fiber factories. NO_x emissions come from electricity production in the Asian markets. The advantages of using natural fibers as reinforcement materials instead of glass fibers have also been proven on various occasions by different authors (Akhshik et al. 2017; Corbiere-Nicollier et al. 2001).

The most visible benefit of *avoiding heat production from natural gas* is the decrease on the use of Halon 1211 and Halon 1303 (Figure 9); which, as previously mentioned, are used in pipelines as fire suppressant agents and contribute to the depletion of the ozone layer. These are directly related to the transportation of natural gas in pipelines.

On the other hand, the *avoided heat production from natural gas* generates impact on *Ionizing radiation*. This is due to the fact that the process used to model the avoided heat production from natural gas (consequential process from Ecoinvent v3.4) considers that producing heat from natural gas through a co-generation plant in Europe reduces the use of current European marginal electricity. By no longer using natural gas, that marginal European electricity is no longer avoided (by the no longer co-generated electricity). Further analysis led to the identification of Radon-22 to be the main cause of the impact. As Radon-22 is a gas resulting from the radioactive decay of Uranium, it leads to the conclusion that no longer producing heat from natural gas increases the use of nuclear power. This was corroborated by an analysis of the Ecoinvent v3.4 process for heat production from natural gas, which considers that electricity produced from co-generation, reduces the use of nuclear power. The same analysis applies for the *avoided glass fiber production* where the generated impact on *Ionizing radiation* is much more visible. In fact, the Ecoinvent process used to model glass fiber production considers an important use of co-generated natural gas heat.

The most visible impact generated by the *woody residues combustion* is the generation of particulate matter, a well-documented issue of biomass combustion (Keller and Burtscher 2017; Nyström et al. 2017; Dasch 2002), which displays a much more complex chemical composition than natural gas.

The major impacts affected by the *avoided animal feed production* are *Marine eutrophication* and *Mineral, fossil & renewable resources depletion* (Figure 10). The impact on the former is essentially explained by the avoidance of nitrate emissions from the *avoided hay* and *palm oil production*. Agricultural activities are linked to the procurement of zinc; it being closely tied to indium mining, leads to the decrease of the *Mineral, fossil & renewable resources depletion* impact. Figure 10 further highlights that the *avoided soybean meal production* increases the *Marine eutrophication* impact. This is explained by the work of Dalgaard et al. (2008) where it is demonstrated that an increase in demand for soybean meal affects the production of palm oil, thus creating

what they refer to as a soybean loop. In other words, the avoidance of soybean meal implies less oil production; palm oil production will thus react to this oil shortage. Therefore, nitrates emitted from the cultivation of palm are the substances responsible for the *Marine eutrophication* caused by the *avoided soybean meal production.* It should also be noted that the avoided soybean meal may have been slightly overestimated. In fact, the substitution considered here was made on the basis of crude protein content. Yet, in terms of protein, it is rather the quality that counts, and more precisely the quantity of essential amino acids.

When comparing scenarios for a production with the *spinning* and *weaving* processes carried out with different electricity mixes, results favored a production with the French electricity mix (Figure 11). This result is coherent with the results obtained by Deng and Tian (2015) when comparing different electricity supply mixes for producing a composite material with flax as reinforcement. Nonetheless, a partial production in China appears more favorable for two impacts, namely for *Ozone* and *Mineral, fossil & renewable resources depletion*. For the former, this is due to an increased use of Halon 1211, as the French electricity induces the use of natural gas as source of energy. Meanwhile, the higher impact on *Mineral, fossil & renewable resources depletion* reflects the higher solar power used in the French electricity mix (making ca. 45% of the mix against <1% in China) and thus resources for photovoltaic panels. A higher impact in *Ionizing radiation* could have been expected for the French electricity mix, given the high percentage of nuclear energy in France (72% of all electricity demand in 2016; IEA 2016). However, this study is consequential and considers the processes that can react as a result of a demand change. Nuclear energy can hardly react to an increased demand for electricity, among others because of the long lag between the decision to establish a new capacity and the moment where the plant is fully operational (Moora and Lahtvee 2009), and because of a legal ceiling on installed nuclear capacity in the specific case of France (EC 2018a). In fact, the low voltage French electricity mix processes used herein (consequential process retrieved from Ecoinvent v3.4) does not include nuclear energy (but rather a high percentage of solar power, as earlier mentioned).

7.   CONCLUSIONS

Through a cradle-to-gate LCA, the environmental performance of a flax-based technical textile was assessed. The presented consequential life cycle inventory aims to (but not limited to) be used by LCA practitioners and interested parties for performing LCA for comparing the environmental impact of products with one of their components being flax fiber. The proposed LCI allows for future assessments to be carried out considering either the whole supply chain of production and transformation of flax or with focus on specific processes, depending on specific system boundaries and the product of interest (i.e. short fibers). Efforts focused on presenting information in a clear and concise fashion for modifications to be easily made, allowing a better representation of a broad spectrum of scenarios as agricultural practices and market trends might evolve.

The herein presented work improved existing LCAs on flax fiber production by the inclusion of the emissions issued from the *retting* process, the valorization of co-products (through system expansion), and the analysis of more impact categories than the regularly addressed in other studies (namely, climate change, ozone layer and

abiotic depletion). Presenting a broader picture of the potential environmental impacts of using flax fiber as a source of materials.

Results show agricultural activities and electricity production (from the *flax cultivation*, *spinning* and *weaving* processes) to be the biggest contributors to the negative environmental performance of a flax technical textile. Very specifically for this case study, the sensibility analysis proved an all-French production to be more efficient from an environmental point of view; however China's installed capacities for fabric production and low manufacturing prices make partial production in China more attractive from a technical and economical perspective. Thus a change in production patterns (change to an all-French production) might not be completely viable. It remains, nonetheless an important factor to take into consideration and further develop as countries' relationship with renewable and fossil energies evolve.

Additionally, the impact generated by land use change from flax culture is diminished (in almost a 25%) by the avoided land use change as a result of the valorization as animal feed of some of the co-products. Consequently, impacts being relatively small compared to those issued from electricity production and use, land use change does not represent a disadvantage for bio-based products.

The larger number of impact categories included/analyzed, contributes to a larger understanding of how co-products might affect the environmental impact of a product. It also makes room for further analysis on different ways in which co-products can be valorized and the options that have a lower environmental impact. With this study, for example, it was made visible that the valorization of shives has a high influence on the formation of particular matter and is, therefore, an important contributor to the overall generated impact. Through this analysis, areas for improvement can be identified concerning not only the main processes but also those related to co-products. In this case, for example, the implementation of better technologies for combustion could be studied in the view of improving the environmental performance.

Moreover, the inclusion of the fate of the co-products by system expansion contributes to a more accurate assessment of the potential environmental impacts. Otherwise, the impact on categories such as *Ozone depletion* and *Marine eutrophication* would have been largely overestimated; while impacts concerning *Particulate matter* and *Ionizing radiation,* underestimated. Given that a consequential approach was taken for this study, decisions aiming to improve the environmental performance of a flax fiber technical textile can be made having a clearer, more close to reality point of view.

Overall, this study shows the relevance of taking into consideration a country's energy mix and the geographical scope of a product's life cycle as it has important impact on its environmental performance. Moreover, when considering the fate of co-products, the valorization they are given plays as well a very important role as they will not forcibly generate a benefit but it was proven that they can contribute to an increase of the impact on different categories. Therefore, correctly defining the former becomes as crucial a factor as having a complete and precise life cycle inventory.

8. ACKNOWLEDGMENTS

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