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Environmental Impact Analysis of Flax Fibre Cultivation for Composite Reinforcement

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ABSTRACT

Searching for environmentally sustainable alternatives for reinforcement of composite materials, flax fibre has one of the most promising potentials due to its desired mechanical properties. The fact that flax is a bio-material, in contrast to conventional synthetic fibres, does not ensure a less environmental impact. One of the major source of environmental impact related to flax fibre as a reinforcement material is the cultivation of flax fibre. In this study the environmental impact of flax fibre cultivation was studied by performing an environmental impact analysis with a life cycle assessment inspired approach. The result showed that the quantification of the environmental impacts varied to a large extent depending on several parameters such as allocation method and whether carbon sequestration was included in the calculations. One striking example is the results for global warming potential, ranging from 10 000 kg CO_2-equivivalents to a negative value per 1 tonne of flax fibre. The study showed the production and use of fertilizers to be the major contribution to the environmental impact by as much as 70-90 %. In order to limit the environmental impact from flax fibre cultivation suggested environmental improvements are to optimise the fertiliser use according to the flax type and soil conditions, improving nitrogen fixation as well as using organic fertilizers.

Keywords: *flax fibre, life cycle assessment, reinforcement, environmental impact assessment*

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1 INTRODUCTION

1.1 BACKGROUND

One purpose of sustainable engineering is to enable resources to provide utilities for future generations as well as our own. Within this concept, choosing materials that both have the desired properties for designing useful products and meet the environmental and sustainability demands (Allenby and Graedel, 2010) is one important part. A good example is plastic materials that have important applications in most parts of our daily life such as food packaging, communication technology, automobiles and medicines (Spierling et al., 2013) thanks to several attractive properties such as light weighted, durable and inexpensive (Hopewell et al., 2009). In 2016 the global and annual plastic production reached 335 million tons which equals about 45 kg per person in the whole world (PlasticsEurope, 2017). The majority of these plastics are based on fossil fuel resources, which makes the contribution to climate change one of the environmental concerns related to current level of plastic usage in society (Spierling et al., 2013). Another issue is the risk of discarded plastics to accumulate and causing harm in natural habitats at the end-of-life stage due to the strong durability of the polymers in the material (Hopewell et al., 2009).

A way towards more sustainable plastic materials is to replace virgin plastic composites with recycled plastic composites that still meets the functional requirements. This has been proven to significantly reduce the environmental impact from fossil fuel use. Another issue of environmental relevance is fibres that are used as reinforcements for both virgin and recycled composites. In cradle-to gate analysis the contribution from fibres to global warming has been identified of different importance depending on if the composite is of virgin or recycled source and as well on the fibre volume level. For recycled composite with high fibre volume the fibres have been found to be the major contributor (90%) of the whole composites impact on global warming (Rajendran et al., 2011). This has created a growing interest of replacing synthetic fibres with natural fibres in order to reduce environmental impact. Natural fibres, or bio fibres also called, are from renewable sources and biodegradable which leads to that they are perceived as more sustainable materials (Bachmann et al., 2017;

Carvalho et al., 2016). Of natural fibres is flax fibre the most used one for polymer reinforcements because of desirable mechanical properties (Bachmann et al, 2017). Earlier research (e.g. Duflou et al., 2014; Deng & Tian, 2015) indicates that flax fibre has potential to be one of the *greener* and more sustainable alternative to synthetic fibres but that further understandings related to environmental impacts and possible improvements of that impact is needed. This study addresses this area looking at the cradle-to-farm gate phase.

1.2 PURPOSE AND OBJECTIVES

The aim of this study is to gain a better understanding of environmental impact, regarding climate change, eutrophication and acidification, of flax fibre cultivation for composite material reinforcement uses.

On the basis of the aim, following research questions are asked:

- To what magnitude contributes flax fibre cultivation to climate change, eutrophication and acidification?
- Which activities of flax fibre cultivation contribute the most to those impacts?

The first question intends to identify and to some extent quantify environmental impacts in a life cycle perspective of existing cradle-to-farm-gate analysis of flax fibre cultivation. The second question aims to identify the main contributing activities of the impacts that have been identified in the answer of the first question, in order to explore possibilities of improvements regarding environmental impact. To answer these questions can help in evaluating flax fibre's potential as a more sustainable reinforcement alternative. This thesis does not intend to entirely cover the possibilities for improving environmental issues related to flax fibre cultivation but to identify and discuss some points for further research.

1.3 SCOPE OF THE STUDY

In this study the cultivation of flax fibre in a cradle to farm-gate perspective will be considered as the scope. Harvest, sometimes combined with rippling, are here counted as farm-gate, see more precise description of flax fibre cultivation in *2.2.2 Crop cultivation.* Due to time limitations, not included in the analysis are fibre processing techniques, manufacturing of flax fibre reinforced composite, use phase and end-of-life stage. Crop production accounts for an important part of environmental impacts from flax fibre, which also justify the choice to look closer on this phase in this study. The environmental impact assessment is limited to the impact categories climate change, acidification and eutrophication. While a European context is the main focus, comparisons with flax fibre cultivation in China are made for some impact categories. Social sustainability issues as well as mechanical properties of the fibre are not included in this thesis. Comparison with other nature fibres or synthetic fibres is not essential within the focus of this thesis since such benchmarking would generally need to include a more complete life-cycle assessment, or at least the full production stage to be relevant. A study of hemp fibre is thus reviewed in relation to the flax fibre studies.

2 FLAX FIBRE AND ENVIRONMENTAL IMPACTS

2.1 FIBRES FOR REINFORCEMENTS OF COMPOSITES

Carbon fibres and glass fibres are synthetic fibres that are used as reinforcement materials in composites. Adverse environmental impacts from production and poor recyclability encourage a search for replacements. Natural fibres such as flax, hemp, jute and ramie give bast fibre and have in recent years increasingly been seen as alternatives to conventional fibre reinforced composites with a potential of being a more sustainable option (Duflou et al., 2014; Duflou et al., 2009). These natural materials have historically been used for other purposes such as textile production (Ljungqvist, 2011). Mechanical performance, like good strength, stiffness, and durability are crucial aspects of fibre materials (Duflou et al., 2014; Yan el al., 2011). One challenge for natural fibres is that they can have a greater variety in quality than synthetic fibres, due to climate and other conditions during cultivation (Charlet et al., 2009). However, according to Yan et al. (2011) flax, hemp and jute have the best potential among bio-fibres for replacing glass fibres, considering mechanical performance, cost and yield.

2.2 FLAX FIBRE CULTIVATION

2.2.1 Flax and its Feedstock Applications

Flax (*Linum usitatissimum)* is grown in cooler regions of the world and can be divided in two types called fibre flax and linseed. Canada is a global leader for linseed production, while Europe (mainly France, Belgium, the Netherlands, Italy and Latvia) and China stands for a great part of the world production of fibre flax (Food and Agriculture Organization of the United Nations, 2009; 2016). A high level of agriculture techniques and good climate gives both good yield and quality from European farms, where the northern France region is known for the best flax fibre quality (Heller et al., 2014). Several varieties of flax fibre have been developed and within the European Union there are currently 184 varieties of flax plants registered, 98 are counted as linseed types and 61 as fibre flax types (EC Common catalogue of varieties of agricultural plant). There are different feedstock applications for the two types of flax. The fibres that are used for textile and different industry purposes such as polymer reinforcements is the main reason of growing fibre flax. The seeds of fibre flax are, however, used for sowing the next crop and some parts are used for oil extraction (Bachmann et al. 2017, Heller et al., 2014). The fibres from fibre flax are both long fibres which are considered as main products and short fibres that are counted as co-products (Rajendran et al., 2011). In the cultivation of the linseed type, the seeds are considered to be the main product (Heller et al., 2014) and they can be used in several ways. Thanks to the high content of omega 3 and dietary fibres, whole flaxseeds are attractive for human nutrition. Cold pressed oil of the seeds does also serve as a food product. Warm pressed oil can be used in painting or for industry uses (Ljungkvist, 2011; Livsmedelsverket, 2018). Lower fibre grades can be used as reinforcements, used in e.g. automotive interior and thermoplastic composites (Food and Agriculture Organization of the United Nations, 2009). The fibres of linseed are not suitable for textile industry since the fibres are consider having lower quality. However, they are still useful in the paper industry and for insulation material (Heller et al., 2014).

In addition to having different feedstock application, fibre flax and linseed also have different sowing technique, harvesting method as well as different weather requirements. More water is needed for cultivation of fibre flax than linseed that can withstand warn weather and drought better (Heller et al., 2014). The two flax types are similar in that they share several challenges such as high fertilizer need and rather week resistance to pesticides (Jankauskienė & Gruzdevienė, 2008). The cultivation of flax fibre is further described in the next section.

2.2.2 Production and Cultivation of Flax Fibre

A typical way of producing flax fibres includes crop cultivation, rippling, retting, scutching and hackling (Rajendran et al., 2011). Ripping is the process of separating the flax seeds from the rest of the plant. Some harvest machines combine the rippling process while harvesting and in other cases the rippling is conducted at a later stage in the production (Le Duigou et al., 2011). Retting of flax is necessary for being able to extract the fibres, it can be both wet or dry retting and also bio-retting. Both the scutching and hacking are fibre processing operations where the fibre gets separated from rest of the stem and turned into finer fibres, both long and short (Rajendran et al., 2011). When flax fibres are produced for textile industry there are further steps that requires high amount of energy, such as bleaching and spinning. Spinning is considered to have a negative effect on the mechanical properties of the fibre for reinforcement purposes and can be skipped (Goutianos et al., 2006).

Looking closer at the crop cultivation, which is the focus of this thesis, the following steps are normally included:

1. Ploughing (Tillage)
2. Drilling (planting) the seed
3. Weed control
4. Plant growth
5. Desiccation
6. Harvest

Before the steps presented above, production of seeds and the breeding processes also takes place. Several methods for ploughing and tillage exists, which are done to prepare the soil. One division can be conventional tillage, conservative tillage and no-till method (Dissanayake et al., 2009; West and Marland, 2001). Biotic stresses, such as weeds, diseases and insects, as well as poor nutrient up-take limits both yield and quality which requires agrochemical inputs for weed control and plant growth (Heller et al., 2014). The method for harvest differ between fibre flax and linseed. Fibre flax is harvested by pulling up the whole plant with flax harvester or a kind of pulling machine while linseed is harvested with a knife mower machine by cutting the straw (Heller et al., 2014). Flax is an annual spring plant and requires ideally a specific order in crop rotation with a general rule of not growing flax on the same field more than once every seven years. The yield of crops grown at the same field has been seen to increase when flax is a part of the crop rotation. (Heller et al., 2014). Irrigation of flax plant is not needed according to Le Duigou et al. (2009) since rainfall meets the water requirements.

2.3 ENVIRONMENTAL IMPACTS

2.3.1 Brief Overview of Environmental Impacts

Earlier studies have shown that flax has a poor developed root system and low nutrient up-take as mentioned above (Heller et al., 2014). Input of fertilizers consist mainly of nitrogen (N), phosphorus (P_2O_3) and potassium (K_2O). Lime is sometimes also applied depending on the pH level of the soil. This, in combination with required weed control and disease management, makes flax one of the most agrochemical intensive bast fibre crops. Energy consumption is one related environmental concern since manufacturing of agrochemicals products is energy-intensive. (Dissanayake el al., 2009). Agricultural machinery also contributes to energy use of flax fibre cultivation (Rajendran et al., 2011). Other environmental impacts related to fertilizer use are eutrophication, acid rain, declines in ecosystem health and release of nitrous oxide, which is a greenhouse gas, to the atmosphere. There are several risks of applying pesticides, causing adverse effects on both surrounding ecosystems and human health, e.g. for bees and other pollinators (Middelton, 2013).

Due to intense use of synthetic fertilizers, Dissanayake et al. (2009) highlights the potential of using organic manure as a solution for environmental improvements. Yan et al. (2014) presents the following suggestions to reduce the environmental impact of flax fibre cultivation: organic fertilizers, biological control of pests, conservation agriculture and changes in agricultural operations e.g. no-till method for ground preparation. Nitrogen fixation, by fast establishment of the next crop, can also reduce the impact on eutrophication (van der Werf & Turunen, 2007).

2.3.2 Life Cycle Assessments of Flax Fibre

In earlier research, a number of LCA studies has been conducted to quantify the environmental impacts of flax fibre. Some studies focuses on flax fibre production while some study LCA of entire composites having flax fibre as reinforcements. A comparative LCA study of flax fibre and glass fibre reinforced composites in a cradle-to-grave perspective was conducted by Duflou et al. (2014). In their study, environmental impacts was compared against both stiffness and strength criteria for equal functional performance. The scope of the LCA study by Duflou et al. (2014) included cradle-to-grave perspective for all impact categories. In contrast, Dissanyake et al. (2009) focused on energy use in flax fibre production for reinforcements of composites, excluding both use phase and end-of-life phase. Other environmental impacts was also excluded in their study. Acquisition of data are made from researchers own studies, compilation of previous studies and data from databases such as Ecoinvent or from SimaPro software (see for example: Dissanyake et al., (2009); Rajendran et al., 2011; Duflou et al., 2014).

Another set of aspects of LCA studies is system expansion, level of details and allocation, which are necessary to differentiate the input and output data between the main and the co-products (Baumann & Tillman, 2012). Some studies exclude co-products in the calculations while for instance Le Duigou et al. (2011) argue for including the added value of co-products in an environmental evaluation of flax fibres. They refer to a European directive on how to distinguish co-products from waste products (European Union, 2008). One method of allocation that is used by van der Werf and Turunen (2007) and Rajendran et al. (2011) is economic allocation, where impacts are allocated in proportion of the economic value of the different products. Other methods are allocation by weight or mass (Baumann & Tillman, 2012). A problem with economic allocation is price variations for natural fibres, which can differ at every harvest due to demand (Le Duigou et al., 2011; van der Werf and Turunen, 2007), and this is the reason why Le Duigou et al (2011) instead chose an allocation by weight. On the other hand, van der Werf and Turunen (2007) chose the economic allocation method and argue that this is better than allocation based on physical relationship since both short and long fibres only stand for a small part of the stem mass. In Deng et al. (2016) their sensitivity analysis indicates that mass allocation gives lower environmental impact values than economic allocation.

2.3.3 Comparison with Glass and Hemp Fibres

Flax fibre reinforced composites has been compared to glass fibre reinforced ones in a life-cycle perspective by e.g. Deng and Tian (2015). Their study showed that environmental impacts was lower mainly in the use phase of changing to flax fibre as reinforcement material. The impact reduction in use phase and end of life stage of using flax fibre was, however, exceeded by higher impact from the production stage.

This was true in the case of using a fibre mix of 70 % Chinese flax fibre and 30 % French flax fibre. A scenario of only French fibre was also studied and in this case an environmental impact reduction could be seen in most of the impact categories. Le Duigou et al. (2011) presented lower environmental impact in all studied impact categories (abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, photochemical oxidation, land use, terrestrial ecotoxicity) except eutrophication and land use for flax fibre production compared to glass fibre production. Other studies have however showed higher total energy use for flax fibre production compared to glass fibre (Dissanayke et al., 2009). Results from comparison of flax and hemp fibre production vary among different studies. A study by Yan et al. (2013) concluded that flax has higher energy and pesticide use but less impact for global warming, acidification and eutrophication. In a study by van der Werf and Turunen (2007), flax fibre production had similar overall impact compared to hemp fibre production, but slightly lower eutrophication. These differences in results between different studies will be further discussed in result and discussion part of this study. Yan et al. (2013) as well as van der Werf and Turunen (2007) agrees on that water use is lower for flax than hemp fibre cultivation.

3 METHOD

3.1 METHODOLOGY APPROACH

In order to answer the research question, a review of existing LCA studies and data of flax fibre cultivation will be conducted, which means that secondary data will be used for accounting of environmental loads. In all found studies, the environmental impact of flax fibre is analysed using life cycle assessment (LCA) methodology. LCA aims to quantify resource use and environmental impact over the whole life cycle (Baumann & Tillman, 2012). The general steps of the framework are goal and scope definition, inventory analysis, life cycle impact assessment and interpretation and presentation of results. This study is not to be seen as an LCA. However, part of the LCA framework serves as a guide for how to conduct this review study of environmental impacts of flax fibre cultivation. The choice of method is partly based on a review made by Weiss et al. (2012) of environmental impacts of bio-based materials. In their study they review existing LCA studies and follows LCA methodology as applied in most of their reviewed articles. The studies and data to be reviewed in this study are all based on LCA methodology. The LCA approach is further suitable in this study since it provides a structural way of understanding and analysing environmental impacts at a holistic as well as detailed perspective. Several parts of the LCA methodology is relevant for collecting and treating the data as well as analysing and interpreting the results. How the LCA methodology is to be used in this study will be described below.

3.2 GOAL, SCOPE AND INVENTORY ANALYSIS

3.2.1 Goal and Scope

The aim of this study is stated in section *1.2*. Looking at the ISO standard 14041, cited in Bauman and Tillman (2012) it defines that the goal of the study "shall unambiguously state the intended application, the reason for carrying out the study and the intended audience". To clarify the goal as well as the scope helps to determine what to include and which methods to use. It also indicates what level of data that is required. In this study, where the aim is to gain a better understanding of the environmental impacts of flax fibre cultivation, it is acceptable to use less detailed data (Bauman & Tillman, 2012). The scope, cradle to farm gate as described in *1.3 Scope of the study* implies that it can be necessary to recalculate the collected data during inventory analysis to fit the scope. Functional unit of this study is determined to be 1 tonne of flax fibre. It was chosen in combination with the scope of the study on the basis of being suitable for the aim and to facilitating comparison of different studies.

3.2.2 Inventory Analysis

The description of the cultivation steps presented in *2.2.2 Production and Cultivation of flax fibre* functioned as a guide for acquisition of data as well as recalculations of data to be accordant to scope and aim. Considerations of data acquisition are based on life cycle inventory analysis (LCI) as presented in Bauman and Tillman (2012). The following requirements was set up when collecting the articles:

- Data for flax fibre (not natural or bio fibres merged together)
- Consider the production or cultivation phase
- Sufficient information for necessary recalculations
- Provide data needed for impact categories of this study, see next section
- Example of used search words: *flax fibre LCA, flax fibre cultivation, flax fiber cultivation, flax environmental impacts*

Findings of the data acquisition in this study showed that most of the existing studies referred back to a relative small amount of articles and data. The methodology choices in the remaining studies varies to a rather large extent, which will be presented in section *4 Result*. In addition to data from literature, a data search is conducted in SimaPro software. During this study, no data for fibre flax was found but data for linseed existed that was useful for calculation of eutrophication. Even though several of the agriculture operations differ among these two types of flax, the inputs in form of fertilizers seemed fairly comparable and was therefore used within this study. Emission data from Agri-footprint 2.0 database per hectare on a typical farm in Belgium is used since this data can be consider geographical similar to the other references for Eutrophication, see Table 2 in the result section. Furthermore, this database also provided sufficient information. In order to recalculate energy use (GJ) into emissions in CO_2-equivalents, the energy mix of China and France (International Energy Agency, 2015) were used since these are the two major flax fibre producers in combination with information on greenhouse gas emissions from different energy generation technologies. Data from 50th percentile was chosen (Moomaw et al., 2011). It should be noted that this gives generic results. Different varieties within the flax plant and possibly different requirements has not been consider in this study,due to lacking information.

3.3 ENVIRONMENTAL IMPACT ASSESSMENT AND INTERPRETATION

The identification and classification of impact categories for this study has been made according to CML's guide (Guinée et al, 2002). When deciding impact categories, the following points are to be considered: completeness, practical issues, independence (avoiding double accounting), possibility to integrate in LCA calculations (existing characterization methods), environmental relevance and scientifically validity of available characterisation method (Bauman & Tillman, 2012). Based on this criteria, the following impact categories been chosen:

- Climate change – GWP (kg CO_2-eq),
- Acidification (kg SO_2-eq),
- Eutrophication (kg PO^{3-}_4-eq).

Emissions, flows and other environmental loads that has been excluded are the following:

- Ecotoxicity (freshwater, marine, terrestrial). Human toxicity.
- Resource use; Abiotic and biotic.
- Land use (occupancy and transformation).
- Stratospheric ozone depletion (CFC, halons).
- Photochemical ozone (photo-oxidant) formation.
- Ionising radiation, noise, odour, waste heat.

In addition to the points mention above, the choice of impact categories has also considered which impact categories that are relevant for agricultural crops (van der Werf and Turunen, 2007). Ecotoxity and land use are example of two impact categories that are relevant in flax cultivation but are excluded due to time constrains as well as complicated, uncertainty or no consensus of characterisation methods (Baumann & Tillman, 2012). Some of the used literature in this study provided data in impact categories that simply needed to be recalculated according to the aim and scope as described above. Other data required characterisation, which means a sorting of parameters into the different impact categories, where one parameter can be relevant for several categories. The characterisation method for global warming, eutrophication and acidification are considered well-developed and acceptable, while other methods, e.g. land use and toxic substances are more uncertain. Within this study, emission data from Agri-footprint 2.0 database is retrieved and the eutrophication potential was calculated in $PO^{3-}{}_4$-equivivalents according to CLM's guide (Guinée, 2002; Baumann & Tillman, 2012). Allocation is conducted by weight as given in Le Duigou (2011). This choice is based on practical reasons since the data of weight allocation is assumed to be more correspondent than economic allocation between the two flax types. For the climate change category, data on energy use from Dissanayake et al. (2009) is calculated into global warming potential for a 100 year time horizon as advised in Guinée (2002). These calculations are based on the energy mix and GHG emissions from electricity generation technologies as mentioned in the inventory analysis. A reference result for hemp fibre is as well recalculated to fit the functional unit and scope of this study and presented among the results.

Another part of LCA methodology that to some extent is used in this study is dominance analysis which aims to provide understanding of which part of the life cycle that gives the greatest (most dominant) environmental impact. It can be either in more general categories such as production, use and waste management or more detailed as to look at each activity in a certain stage of the life cycle (Baumann & Tillman, 2012). This study searched for existing information on emissions and impacts related to a certain activity assigned to the cultivation phase.

4 RESULTS

4.1 QUANTIFICATION OF ENVIRONMENTAL ASPECTS OF FLAX FIBRE CULTIVATION

4.1.1 Environmental Impacts

Table 1 shows the chosen environmental impact categories of this study for the cultivation of one tonne of flax fibres, presenting data derived from for different references. These result show a large variety due to what has been accounted for in the studies and how the calculations have been conducted.

Table 1 Environmental impacts of climate change, acidification and eutrophication for the cultivation of 1 tonne flax fibre, based on the references given in the table.

References	Climate Change (kg CO_2-eq)	Acidification (kg SO_2-eq)	Eutrophication (kg PO^{3-}_4-eq)
Dissanayake et al. (2009)*	316 (a) / 10833,1 (b)	-	-
van der Werf and Turunen (2007)	2000	8	21
Le Duigou et al. (2011)	-1,4*	1,75	1,37
Agri-footprint 2.0	-	-	59,3

(a) Energy production mix France (b) Energy production mix China

*Values including fibre processing operations and photosynthesis

Differences that have been identified to influence the result are choice of allocation method, treatment of carbon sequestration in calculations, yield and some more parameters that are presented in Table 2. Le Duigou et al., (2011) uses weight allocation and assigns 15 % of the environmental impacts to their main product and presents that an economic allocation instead would have implied an allocation of 81 %. The differences in Table 2 are further discussed in the text below.

Table 2 Presentation of identified differences of parameters that can affect the result of environmental impact in the reviewed literature and data.

	Dissanayake et al. (2009)	**van der Werf and Turunen (2007)**	**Le Duigou et al. (2011)**	**Agri-footprint 2.0***
Geographical area cultivation	Not specified (review)	France, Belgium and the Netherlands	France (Normandie)	Belgium
Energy mix	France and China*	European UCPTE	France	
Co-products	Excluded	Included	Included	Included
Allocation	-	Economic	By weight	By weight
Production fertilizers and pesticides	Included	Included	Included	
Carbon sequestration (photosynthesis)	Excluded (not mentioned)	Excluded (not mentioned)	Included	
Production seeds	Excluded	Excluded	Excluded	
Infrastructure, buildings	Excluded	Excluded	Excluded	

*Only information of interest for eutrophication is presented for Agri-footprint 2.0

4.1.2 Climate Change

The results within the impact category of climate change shows a spread of values for global warming potential from -1.4 to 10 833 kg CO_2-eq (Fig 1 and Table 1). One difference in the achieved results derives from the fact that Le Duigou et al (2011) consider the carbon dioxide sequestration by photosynthesis while the two other references for the climate change category do not. The choice of allocation method is also different between van der Werf and Turunen (2007) compared to Le Duigou et al. (2011).

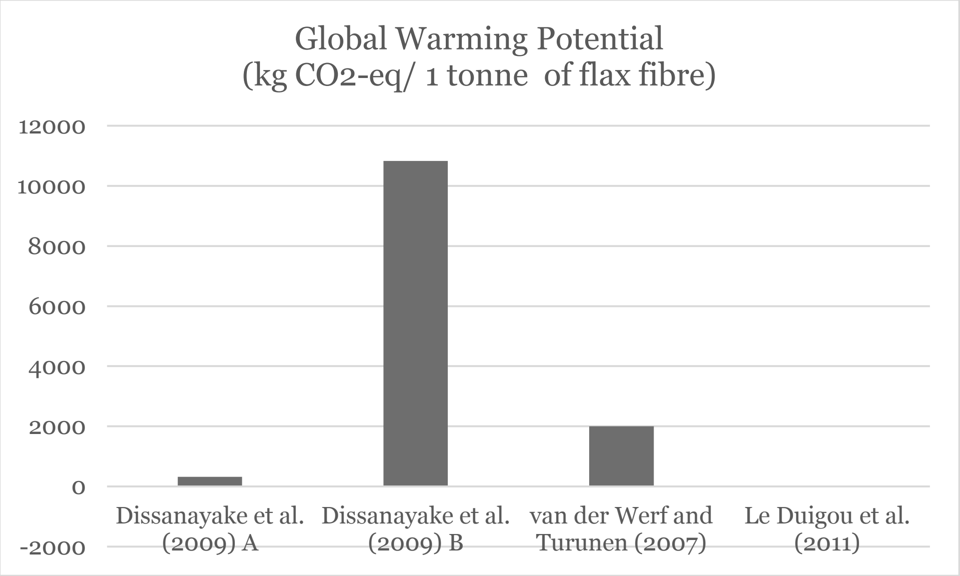

Fig 1 Global warming potential expressed as CO_2-equivivalents per 1 tonne of flax fibre from the three different references.

Yet another difference is the energy mix used in the calculations. Energy use for cultivation of one tonne of flax fibre with warm-retting is 49.29 GJ according to Dissanayake et al. (2009). The method of retting is relevant due to the fact that bio-retting demand for other agricultural operations. None of the other studies uses bio-retting. Calculations of energy use, converted from GJ into kWh, to CO_2-equivivalents are presented in Table 3 below. For further information on data and sources see *3.2.2 Inventory analysis.*

Table 3 Calculations of energy use into CO_2-equivivalents based on energy mix data and greenhouse gas emissions from different energy generation technologies.

Energy Use and Climate Change							
		France			China		
Energy product	kg CO2-eq/kWh	(%)	kWh	Kg CO2-eq	(%)	kWh	Kg CO2-eq
Nuclear	0,016	82,75	11330,6	181,3	1,78	244,4	3,9
Fossil energy (coal and oil)	0,9205	0,71	97,2	89,5	83,46	11427,8	10519,3
Natural gas	0,469	0,01	1,4	0,7	4,37	597,2	280,1
Renewables (solar, hydro, wind)	0,021	16,52	2125	44,6	10,37	1419,4	29,8
Total				**316,0**			**10833,1**

Dissanayake et al. (2009); International Energy Agency (2015); Moomaw et al. (2011).

The energy mix "France" is mainly based on nuclear energy (83%) while in the energy mix for China fossil energy dominates (83%), as presented in Table 3. This implies a difference of about 10 500 kg CO_2-equivivalents only in the cultivation phase per tonne flax fibre, based on energy use data in Dissanayake et al. (2009). Both in Le Duigou et al. (2011) and in van der Werf and Turunen (2007), only the resulting climate change impact in CO_2-equivivalents are presented and their calculations are based on French energy supply mix from the Eco-Invent database and European UCPTE energy mix from BUWAL database (Table 2) respectively.

There are as well similarities among the reviewed studies, in particular which activities and steps in the cultivation of flax fibres that contributes the most to climate change. In Dissanayake et al (2009) fertilizers and pesticides contribute 84 % (49 % of entire production phase) to climate change impact from the cultivation of flax fibre. Slightly lower contribution is presented in Le Duigou et al. (2011) where 73 % of climate change contribution is assigned to fertilizers and pesticides (50 % entire production). Tillage is another activity within the agricultural operations that has been identified in Le Duigou et al (2011), contributing 18% to the climate change impact and different methods of tillage/ploughing are recognized by Dissanayake et al (2009) to give some variations in amount of energy use. In van der Werf and Turunen (2007), the climate change contribution for separate activities within flax fibre cultivation is not available.

4.1.3 Acidification

Two results are achieved within this study for acidification (Fig 2, and Table 1), 1.75 kg SO_2-eq (Le Duigou et al., 2011) and 8 kg SO_2-eq (van der Werf and Turunen, 2007). The method for allocation, as presented in table 2, differs between the two references. Le Duigou et al. (2011) which is based on Labouze et al., (2007) consider a higher yield of green stems (7500 kg/ha) as well as higher proportion of long fibre per flax stem (15 %) compared to 6000 kg/ha of green stems and 5 % in van der Werf and Turunen (2007).

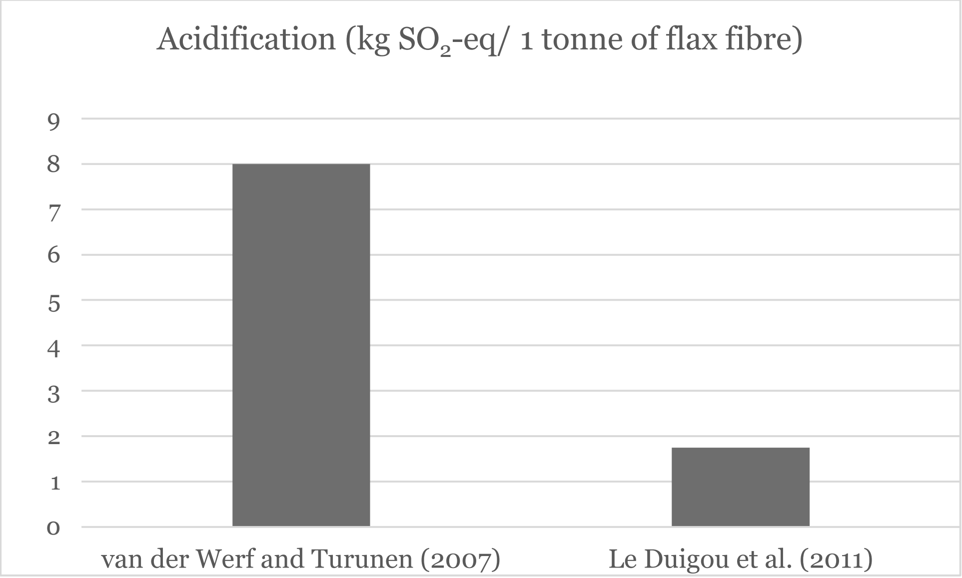

Fig 2 Acidification expressed as SO_2-equivivalents per 1 tonne of flax fibre from the three different references.

According to Le Duigou et al., (2011), the cultivation of flax fibre stands for 79.4 % of the acidification impact of the entire production of flax fibre. Within the cultivation, fertilizers production and use contribute 68 % while tillage processes contribute 18.5

%. Regional and local differences that affects the severity of the effect on the ecosystems from acidification is not accounted for in the reviewed studies. In van der Werf and Turunen (2007) there is no attribution of the acidification to different activities within flax fibre cultivation.

4.1.4 Eutrophication

This review gave two literature results for eutrophication, 1.37 kg PO^{3-}_4-eq (Le Duigou et al., 2011 and 21 kg PO^{3-}_4-eq (van der Werf and Turunen, 2007) (Fig 3 and Table 1). A difference that has been noticed within this study is that different methods of allocation are used. Economic allocation is used in van der Werf and Turunen (2007) and allocation by weight is used in Le Duigou et al. (2011). Furthermore, there is the difference in yield described in section *4.1.3 Acidification.* In addition, a third value is presented from calculations based on data from Agri-footrint 2.0 databased available in the SimaPro software. Yield is assumed to be 1000 kg long fibre per hectare as in Le Duigou et al. (2011).

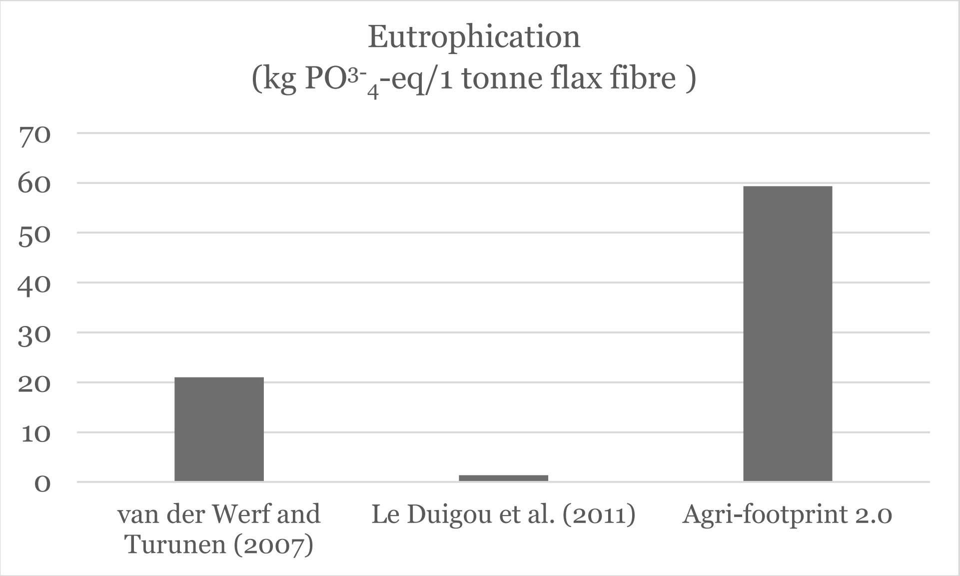

Fig 3 Eutrophication expressed in PO^{3-}_4-equivivalents per 1 tonne of flax fibre from the three different references.

The emission data per hectare (Table 4) consist of 28 kg ammonia (NH3), 186 kg nitrate (N) and 100 kg phosphorus (P). Information is also given for emission source and activity.

Table 4 Emission data eutrophication

Emissions to air	**Comment**	**kg / ha**
Ammonia (NH3)	Due to use of manure	25,73
Ammonia (NH3)	Due to use of fertilizers	2,43
Total NH3		**28,16**
Emissions to water		
Nitrate (N)	Due to use of manure	140,76
Nitrate (N)	From crop residues	18,45
Nitrate (N)	Due to use of fertilizers	26,57
Total N		**185,78**
Emissions to soil		
Phosphorus (P)	Due to use of manure	65,53
Phosphorus (P)	Due to use of fertilizers	35
Total P		**100,53**

Sourced from Agri-footprint 2.0 database

The result for the eutrophication category without allocation is presented in Table 5, based on the emission data in Table 4. The presented result (Fig 3 and Table 1) using allocation by weight is 59.3 kg $PO^{3-}{}_4$-eq is higher than what the others presented. The used allocation method by weight implies that hacked flax fibres stand for 15 %. Without allocation the result is even more significant, see Table 5 and if economic allocation would have been used based on data for fibre flax in Le Duigou et al. (2011) would 81 % of the environmental impact had been allocated to the fibres. Emissions of phosphorus is the largest contributor of eutrophication according to this results. The significant differences of values are to be further treated in the discussion section, what can be seen in Table 4 is that emission from the category *Due to use of manure* represent a large amount.

Table 5 The contribution to eutrophication for different substances (without allocation).

Substance	kg	Eutrophication potential (kg PO3-4-eq/kg)	Eutrophication (kg PO3-4-eq)
Ammonia (NH3)	28,16	0,35	9,9
Nitrate(N)	185,78	0,42	78,0
Phosphorus (P)	100,53	3,06	307,6
Total			**395,5**

Based on data from Agri-footprint 2.0, Guniée et al (2002)

Le Duigou et al. (2011) presents that 97.9 % of the eutrophication impact stem from the cultivation phase of total production of flax fibre. In van der Werf and Turunen (2007), emissions from soil, mainly N and P, contributes about 90 % to the eutrophication impact from flax fibre production. Other agriculture operations, not more specified, are mentioned to cause the remaining 10 %.

4.2 COMPARISON WITH HEMP FIBRE

From van der Werf and Turunen (2007) one result for hemp fibre could be retrieved. Their study included three hemp fibre scenarios and one scenario for flax fibre. The presented scenario uses warm water retting and are according to van der Werf and Turunen (2007) the hemp fibre scenario most suited for comparing with the flax fibre scenario. The other hemp scenarios implied in general higher environmental impact. As presented in Table 6 environmental impact of hemp fibre are slightly higher for hemp fibre compared to flax fibre for all three studied impact categories.

Table 6 Comparison of environmental impacts for 1 tonne of hemp fibre and 1 tonne of flax fibre.

Fibre type	Climate Change (kg CO_2-eq)	Acidification (kg SO_2-eq)	Eutrophication (kg PO^{3-}_4-eq)
Hemp fibre	2600	10	22
Flax fibre	2000	8	21

Based on data from van der Werf and Turunen (2007)

5 DISCUSSION

The aim of this study is to gain a better understanding of the environmental impact of flax fibre cultivation for composite material reinforcement usage. A quantification of the impacts categories: climate change, eutrophication and acidification, by reviewing existing LCA studies is presented. If excluding the result from Le Duigou et al. (2011) that included carbon sequestration and if only using the results based on French or European energy mix, the aggregated result is 1 158 kg CO_2-equivivalents for 1 tonne of flax fibre. For acidification, the result is 4.9 kg SO_2-equivivalents and for eutrophication, if excluding the result on linseed, 11.2 kg $PO^{3-}{}_4$-eq. The higher value on linseed might be explained by different requirements of the two types of flax or different considerations during the calculation of the emission data into $PO^{3-}{}_4$-equivivalents. Another possibility is that Le Duigou et al. (2011) as well as van der Werf and Turunen (2007) included only the added synthetic fertilizers and not emissions from the manure. This has not been possible to verify since emission data used of Le Duigou et al. (2011) and van der Werf and Turunen (2007) is not available.

Even though the same functional unit and the same scope has been adopted the result from different references varies to a great extent. Variations of results for climate change are found mainly due to three reasons: choice of allocation method, whether carbon sequestration is accounted for and which energy mix that has been used. As for climate change, the results for acidification and eutrophication was found to vary and a possible reason for that is differences in allocation method. Using an economic allocation tends to give higher results for environmental impact than allocation by mass or weight, which is also indicated by the result of this study to be true as well for allocation by weight. The energy mix used in calculations can make a difference in environmental impact of flax fibre cultivation. If the flax fibre is cultivated in a country with a less greenhouse gas intense energy mix, the environmental impact can be considerably lower. In general this differences needs to be carefully considered when evaluating the environmental impact of flax fibre cultivation and particularly in comparison between different fibres.

Production and use of fertilizers is an activity of flax fibre cultivation that is a major contributor (about 70-90 %) of the impacts climate change, acidification and eutrophication. Some agriculture operations like tillage are as well identified in the reviewed literature to contribute significantly. Based on this result can solutions to achieve improved environmental performance be organic fertilizer, conservational agriculture and using catch crop for fixation of nitrogen. Further evaluation of these solutions´ environmental impact combined with impact on quality and mechanical performance of the fibres would be desirable. There are other environmental impacts excluded in this study, e.g. ecotoxicity and land use, that also would need to be evaluated.

As discussed in theory does flax fibre seem to be a more sustainable alternative if comparing with the most sustainable way of producing flax fibre regarding for example energy source in production of fertilizers and pesticides. Further study would however be required in order to justify that. Comparison with hemp fibre showed within this study that production of flax fibre has slightly lower environmental impact. This kind of comparison is thus to be treated carefully due to large variations of the quantification of environmental impact as discussed above. Looking at flax fibre as a reinforcement of composite material and its potential of being a more sustainable alternative, there are several aspects during the rest of production phase, use phase and end of life phase that matters. Mechanical performance and durability are some aspect that are related to cultivation which also affect how sustainable flax fibre is as an alternative. Harvest method and soil quality, as previously mentioned, are examples of conditions that have implications for the quality and properties of flax fibres. Since different composite materials require different quality levels and properties, it can also be of interest to optimize the combination of type and quality of flax fibre to use for the intended composite material.

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