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LIFE CYCLE ASSESSMENT OF FLAX FIBRES FOR THE REINFORCEMENT OF POLYMER MATRIX COMPOSITES

by

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Life Cycle Assessment of Flax Fibres for the Reinforcement in Polymer Matrix Composites

Abstract

This thesis aims to investigate the sustainability of bast fibres specifically flax fibres as the reinforcement for polymer matrix composites (referenced to glass fibres) by undertaking a quantitative Life Cycle Assessment using the eight environmental impact classification factors of global warming, acidification, eutrophication, human toxicity, aquatic toxicity, ozone depletion, photochemical oxidants creation and non-renewable/abiotic resource depletion.

A data set was compiled from numerous literature sources to complete the Life Cycle Inventory for the production of flax fibres. Three scenarios were studied for the production of either flax sliver (pre-spun fibre) or yarn (post-spun fibre): low (no-till combined with warm water retting), average (conservation tillage with stand/dew retting) and high (conventional tillage with bio-retting) energy routes considering different agricultural and fibre preparation (retting) methods. The best agricultural practice for the flax fibre production is identified from this study as the no-till method combined with warm water retting. The environmental credentials for flax fibre can be further improved by using organic fertilisers and biological control of pests. Spinning is the most energy intensive fibre processing operation hence by eliminating this operation energy use and the associated environmental impacts could be reduced. Based on the energy analysis continuous glass fibre reinforcement appears to be superior to spun flax yarn but glass fibre mat and flax sliver are equivalent and embody similar quantities of energy per tonne. The environmental benefit arising from substitution of glass fibres by natural fibre is dependent on the chosen reinforcement format. The key consideration is to use sliver (pre-spun fibres) as reinforcement in polymer matrix composites instead of yarn.

Table of Contents

List of Tables

List of Figures

Abbreviations and Glossary

AP	Acidification Potential
ATP	Aquatic Toxicity Potential
ATP/ADP	Adenosine triphosphate/Adenosine diphosphate
CE	Carbon Equivalent
CFC	Chlorofluorocarbons
CMC	Ceramic Composite Matrix
CML	Centre for Environmental Studies at Leiden
CST	Critical Surface Time
DEFRA	Department for food and rural affairs
EICF	Environmental Impact Classification Factor
EP	Eutrophication Potential
FCC	Flax Council of Canada
FMP	Fused Magnesium Phosphate
GWP	Global Warming Potential
HDPE	High-density polyethylene
HTP	Human Toxicity Potential
IPCC	The Intergovernmental Panel on Climate Change
ISO	International Organization for Standardisation
ISO/TR	International Organization for Standardisation / Technical Report
MMC	Metal Matrix Composite
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis (as defined in ISO 14040)
LCIA	Life Cycle Impact Assessment (as defined in ISO 14040)
LCM	Liquid Composite Moulding
LDPE	Low-density polyethylene
LPG	Liquefied petroleum gas
LMT	Liquid Moulding Technologies
NFRP	Natural Fibre Reinforced Plastics/Polymers
NMVOC	Non-Methane Volatile Organic Compounds
NRADP	Non Renewable/Abiotic Resource Depletion Potential
ODP	Ozone Depletion Potential
PMC	Polymer Matrix Composites
POCP	Photochemical Oxidants Creation Potential
POEA	Poly Oxy Ethylene Amine
PSD	The Pesticides Safety Directorate
PST	Ploughless Soil Tillage
QLCA	Quantitative Life Cycle Assessment
RIFT	Resin Infusion under Flexible Tooling
RTM	Resin Transfer Moulding
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SSPP	Selected Stormwater Priority Pollutants
TSP	Triple Super Phosphate
UV	Ultra Violet
VOC	Volatile Organic Compounds

A glossary of fibre/textile terms complied by John Summerscales can be found in:
http://www.tech.plym.ac.uk/sme/MATS324/MATS324A9%20FibreGlossary.htm

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Author's Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

This study was undertaken with personal funding and received limited financial assistance from the School of Engineering and Faculty of Technology of University of Plymouth.

Relevant scientific seminars and conferences were regularly attended and papers were often presented. Some of these papers were subsequently published in refereed journals. The details are on the following pages.

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University of Warwick, 12-13 September 2007

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SAMPE Europe Student Conference
Paris, 29-30 March 2008

SAMPE Europe International Conference & Forum
JEC Composites Show
Paris, 31 March – 2 April 2008

BIOCOMP Seminar – Bio-composites
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Graduate Teaching Associates Course, 30 July-03 August 2007
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Planning a career in research, 19 November 2008
Introduction to R, 26 November 2008
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Essential tools for viva, 17 February 2009
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The journal papers and conference papers published during and since the research programme are given in Appendix A (CD-ROM).

Chapter 1. Introduction

Natural fibres were used in resin matrix composites in the early years of the composites industry including flax and hemp fibres for the bodywork of a Henry Ford car in 1941 [1], but then fell from favour due to continuous glass fibres becoming commercially available. Environmental concerns have resulted in renewed interest in sustainable composites focusing on bio-based fibres and resins. After decades of high-tech developments of artificial fibres like glass, carbon and aramid it is remarkable that there is renewed interest in natural fibres as potential reinforcements for composites instead of man-made fibres. The UK government publication “Securing the Future: Delivering UK Sustainable Development Strategy” emphasised sustainability in both industry and in agriculture with a revival of interest in materials from sustainable sources [2].

The natural fibres are categorised into three groups: vegetable (cellulose), animal hair (protein) and mineral. Bast (stem) fibres from plants such as flax, hemp, kenaf, jute, and ramie are more likely to be adopted as reinforcement in composites. These bast fibres are advantageous over the other cellulose based fibres (seed fibre, leaf fibre or fruit fibre) due to high modulus, tensile strength and low specific gravity i.e. stiffness and strength to weight ratios [3]. **Flax is chosen as the candidate fibre for this study as it is one of the most agro-chemical intensive plants among the other bast fibres.**

Fibres like flax/linseed and hemp are currently grown commercially in UK/Europe and used in natural fibre composites for a wide range of automotive applications such as the interior panels of passenger cars and truck cabins, door panels and cabin linings as substitutes for glass fibre composites [4].

However, it is timely to consider whether the claimed environmental benefits of the materials can be justified**.** Life Cycle Assessment (LCA) is an environmental assessment method which, according to the international standard Environmental Management – Life Cycle Assessment – principles and frameworks, ISO 14040:2006(E), “considers the entire life cycle of a product from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal” [5].

A LCA study has four phases:

- The **goal and scope definition** – aims and objectives of the study
- **Life Cycle Inventory analysis (LCI)** – compilation and quantification of inputs and outputs for a product through its life cycle.
- **Life Cycle Impact Assessment (LCIA) -** understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product, and
- **Life Cycle Interpretation** – the findings of the LCI or LCIA or both are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

Jonathon Porritt in Capitalism As If The World Matters (2005) [6] has said

"One of the most popular tools used by companies to achieve these efficiency gains is life-cycle analysis, assessing the impact of a product from manufacture through to final disposal, reuse or recycling. It sounds simple; but I suspect few people understand the complexity of the kind of analysis that has to be done to work out how best to make those gains".

Although the concept of the LCA is simple, the analysis is quite complex in reality, primarily due to the difficulty in establishing the correct system boundaries, obtaining accurate data and interpreting the results correctly [7].

A study was carried out by Joshi et al [8] to determine the most environmentally friendly reinforcement for composites between natural fibres and glass fibres. This was assessed through a comparative LCA technique for a glass fibre reinforced composite component and natural fibre reinforced composite component. It was suggested that the non-renewable energy required to produce a flax fibre mat is 9.55GJ/tonne and china reed fibre mat is 3.64GJ/tonne considering the seed production, fertiliser, transport, cultivation, fibre extraction and mat production. The energy used to produce a glass fibre mat is 54.7GJ/tonne accounting for raw materials, mixture, transport, melting, spinning and mat production. The latter figure echoes that in a German study in 1999 by Diener et al [9]. The scope of each of above assessments is limited by ignoring the use of agriculture machinery, agro-chemicals and stages of fibre processing.

A comparative study by van Dam [10] on environmental implications of manufacture of polypropylene (PP), high density polyethylene (HDPE) and polyurethane (PU) fibres relative to natural fibre based products concluded that jute fibre production requires less than 10% of the energy used for PP fibres (energy requirement is around 90GJ/tonne). When the use of fertiliser was included in the calculations, the energy requirement for fibre production increased to about 15% of that for PP fibres. However the data are for jute fibres produced without powered mechanical assistance and environmental impacts other than energy use were not considered in the above study.

In an environmental comparison of China Reed fibre (which are obtained by grinding and sieving of the stem) as a substitute for glass fibre in plastic transport pallets, Corbière-Nicollier et al [11] found that cultivation of the reed had a dominant role in the factors for terrestrial ecotoxicity, human toxicity (when crop rotation has China Reed followed by edible food) and eutrophication due to (a) heavy metal emissions to soil from diesel usage and (b) phosphate emissions (from manure and fertiliser) to water.

The cited literature on LCA studies rarely considers the full eight environmental impact classification factors (EICF) as outlined in ISO/TR 14047/2003 [12] (listed below) and are mainly referenced to a specific end product. Therefore a comparative quantitative LCA considering the eight environmental impact factors for flax fibre would help to identify whether the substitution of glass fibres with natural fibres is truly environmentally beneficial. In particular, while governments and the media are currently preoccupied with global warming/climate change, there is increasing concern expressed by pressure groups in respect of the availability of potable water, the use of land for industrial products (fibre, feedstock and fuel) rather than for food and loss of biodiversity arising from acidification, eutrophication and toxicity.

The scope of this LCA is cradle-to-gate (from seed to composites factory gate) and the functional unit of the analysis is regarded as one tonne of fibre ready for reinforcement in polymer matrix composites. Three stages of natural fibre production considered in this study are:

i. agricultural operations (ploughing, sowing, applying fertiliser/pesticides and harvesting)
ii. fibre extraction (retting and decortication) and
iii. fibre preparation/processing (hackling, scutching, and spinning).

In the context of LCI, inputs (such as energy and water) and outputs (such as emissions and waste) are quantified at each production stage of flax fibre. The environmental issues analysed in LCIA are:

i. Acidification Potential (AP)
ii. Aquatic Toxicity Potential (ATP)
iii. Human Toxicity Potential (HTP)
iv. Eutrophication Potential (EP)
v. Global Warming Potential (GWP)
vi. Non-Renewable/Abiotic Resource Depletion Potential (NRADP)
vii. Ozone Depletion Potential (ODP), and
viii. Photochemical Oxidants Creation Potential (POCP)

as outlined in ISO/TR14047:2003 [12] and also closely echoed by Azapagic [13, 14]. These eight EICFs are discussed in detail in Chapter 2 – Literature Survey.

For flax cultivation, use of inorganic fertilisers (N, P, K) may result in nitrogen run off causing environmental impacts such as acidification, aquatic toxicity, human toxicity and eutrophication. Primary sources of green house gases which contribute to global warming and hence arguably to climate change are from energy used to power agricultural equipment and to produce and apply fertilisers and pesticides in flax fibre production, and in textile processes.

Glass fibre production would result in global warming due to the energy use in the production and the associated emissions (volatile organic compounds, CO, NO_x, SO_x etc) would result in ozone depletion, photo chemical oxidants creation and human toxicity.

The objective of this research study is to carry out a quantitative and comprehensive Life Cycle Assessment (LCA) for flax fibres as the reinforcement of polymer matrix composites. This study seeks to evaluate eight environmental impact classification factors for flax fibre production and glass fibre production in order to determine the most sustainable production method and/or best practice.

Chapter 2. Literature Survey

This chapter contains a review of the literature on flax fibre production, glass fibre production, life cycle assessment and the eight environmental impact classification factors.

2.1 Introduction

Concern for the environment is not a new phenomenon. In the fifth century BC, Plato wrote about the effects of unsustainable practice regarding forests, referring to the deforestation of the hills around Athens as a result of logging for shipbuilding and to clear agricultural land [15]. In 1543, Henry VIII passed laws to prevent shipbuilders from felling too many trees and hence protect the forests when he realised that creating his naval fleet could compromise future supplies of wood, particularly oak [16]. In 1713, von Carlowitz [17] explained that if forest resources were not used with caution (i.e. planned on a sustainable basis to achieve continuity between increment and felling), then humanity would plunge into poverty and destitution. In 1798, Malthus [18] presented his *Essay on the Principles of Population* in which he proposed that population tends to increase faster than the means of subsistence, and its growth could only be checked by moral restraint or disease and war. In 1962, Carson [19] published *Silent Spring* which warned against profligate use of synthetic chemical pesticides, challenged the agricultural practices of the time and suggested that there were methods of pest control which were less damaging to the natural world. Her work is often suggested as the primer for the rise of the environmental movement in the 1960s. In 1987, the World Commission on Environment and Development suggested that Sustainable Development should be defined as "Meeting the needs of the present without compromising the ability of future generations to meet their own needs" [20]. There is a far more extensive literature on concern for the environment but that topic is beyond the scope of this research. This thesis aims to undertake a comprehensive study of one small specific topic and compare the environmental burdens arising from natural (flax) fibres relative to the burdens from synthetic glass fibres.

2.2 Introduction to composites

Composites are materials which are made from two or more distinct materials that when combined are better (stronger, tougher and or more durable) than each would be separately. Although composites are a high technology development, there are composites in living organisms such as the microstructure of wood and bio ceramics like mollusc shells.

Composites consist of reinforcing fibres or particles impregnated by a matrix material which acts to transfer loads to the fibres and also to protect fibres from abrasion and environmental attack. It may also include coating to improve bonding and load transfer at the fibre-matrix interface and fillers which are added to polymers to reduce cost and improve dimensional stability. Fibres occupy the most volume in a high performance composite and carry most of the applied load. Fibre type, quantity and orientation have a major influence on the composite properties such as specific gravity, tensile strength and modulus, compressive strength and modulus, fatigue strength, electrical and thermal conductivity and cost [21].

Composites can be broadly categorised into groups depending on the nature of the matrix as polymer matrix composites, metal matrix composites, ceramic matrix composites and carbon matrix composites [22].

Metal matrix composites (MMCs): These composites contain a metal matrix such as aluminium, magnesium and titanium and reinforcement fibres such as carbon and silicon carbide. The elastic stiffness and strength of the metals are increased and the thermal and electrical conductivities are reduced by adding the fibres such as silicon carbide [22].

Ceramic matrix composites (CMCs): They contain a ceramic matrix such as alumina, calcium, aluminium silicates and reinforcement fibres of silicon carbide. The advantages of CMCs include high strength, hardness, high service temperature limits for ceramics, chemical inertness and low density. These composites offer the same high temperature tolerance of super alloys without such a high density. The brittleness of the ceramics makes the fabrication complicated and usually the ceramic material is used in powder form during production. There are four classes of ceramic matrices: glass (easy to fabricate due to low softening temperatures, include borosilicate and aluminium silicates), conventional ceramics (silicon carbide, silicon nitride, aluminium oxide and zirconium oxide are fully crystalline), cement and concrete and carbon compounds [22, 23].

Carbon matrix composites: These composites contain a carbon matrix and carbon fibres. They are used in very high temperature environments up to 3500 ^{0}C [22].

2.2.1 Polymer Matrix Composites (PMCs)

The most common advanced composites are polymer matrix composites. PMCs consist of a polymer (resin) matrix combined with a fibrous reinforcing dispersed phase. They provide high strength, stiffness, toughness along with good resistance to corrosion, abrasion and puncture. Their popularity arises from their ability to be easily formed into complex shapes with simple fabrication methods and low cost. The main disadvantages of PMCs are low thermal resistance and high coefficient of thermal expansion [22].

The two types of material systems used for fabrication of polymer matrix composites are thermosets (polyesters, epoxies, phenolics) and thermoplastics (polypropylene, nylon, and PEEK). Reinforcing fibres used includes glass, carbon and aramid (Kevlar, Twaron). These reinforcing fibres are arranged in different forms such as unidirectional, roving, veil mat (thin plies of randomly orientated and looped continuous fibres), chopped strands (thin layer of randomly orientated and looped short fibres) and woven fabric [23].

The techniques for the manufacture of fibre-reinforced polymer matrix composites have been reviewed by Åström, Gutowski , Davé and Loos and Campbell [24-27], albeit that their emphasis is very much on synthetic fibres and thermosetting resins. Thermoset processes have been considered in greater detail:

- vacuum bagging, including autoclave cure [28-30]
- Compression moulding [no key text]
- Liquid Moulding Technologies (LMT) or Liquid Composite Moulding (LCM), including Resin Transfer Moulding (RTM) [31-35].
- Resin Infusion under Flexible Tooling (RIFT) [36-39].
- Filament winding [40].
- Pultrusion [41, 42].

The latter two processes will require that the natural fibres be spun to form a continuous yarn. For thermoplastic matrix short fibre composites, there are additional processes including extrusion (for constant cross section) and injection moulding. LMT and RIFT are possible only with a few thermoplastic systems supplied as low viscosity monomers and these are normally polymerised in-process. Vacuum bagging, filament winding and pultrusion are also possible.

The overall properties of PMCs are determined by properties of the fibre and resin, the ratio to fibre to resin in the composite (Fibre Volume Fraction) and the geometry/orientation of the fibres in the composite. PMCs are widely used for manufacturing load bearing aerospace structures, boat hulls and superstructure, canoes, kayaks, automotive parts, sport goods (golf clubs, skis, tennis racquets, fishing rods), bullet proof vests and other armour parts etc.

2.2.2 Measurements of mechanical properties of composites

The elastic modulus of a composite material can normally be predicted using the standard rule of mixtures (Equation 1) [43]:

$$E_c = \eta_l \eta_o V_f E_f + V_m E_m$$ **Equation 1**

where η_l is the fibre length distribution factor, η_o is the fibre orientation distribution factor, E_f is the elastic modulus of the fibre (Vincent [44] has estimated a modulus of up to 140 GPa for cellulose fibres), E_m is the elastic modulus of the matrix, V_f is the fibre volume fraction and V_m is the matrix volume fraction (assuming $V_f + V_m = 1$, i.e. no voids or other inclusions).

Fibre length distribution factor, η_l, can be calculated using the Cox equation (Equation 2) [45]:

$$\eta_{1=1-} \frac{tanh\,(\beta L/2)}{(\beta L/2)}$$ **Equation 2**

where:

$$\beta = \frac{2\pi G_m}{E_f A_f \, ln(R/R_f)}$$ **Equation 3**

and,

$$V_f = \frac{2\pi r^2}{\sqrt{3}R^2}$$

Equation 4

and where G_m is the shear modulus of the matrix, L is the fibre length, A_f is the cross sectional area of the fibre, R_f is the radius of the fibre and R is the mean separation of the fibres. If the fibre is shorter than the critical length (l_c) – see below, it will never carry a load high enough to cause fibre fracture. The composite will instead fail in shear, either at the fibre/matrix interface or in the matrix itself.

The **critical length** (when there is no debonding) is given by the expression

$$l_c = \frac{R_f \sigma_{11}}{\sigma'_{12}}$$

Equation 5

where R is the fibre radius, σ_{11} is the tensile stress in the fibre and σ'_{12} is the shear strength (of the interface or of the matrix as appropriate).

The Krenchel [46] equation (Equation 6) permits calculation of the effectiveness of a mis-aligned fibre reinforcement, as a fibre orientation distribution factor, η_o, using the proportions of fibre at each angle and the fourth power of the cosine of the angle between the fibre and the reference direction.

$$\eta_o = \sum_{i=0^\circ}^{180^\circ} V_{fi} \cos^4 \theta_i$$

Equation 6

2.3 Synthetic Fibres

Synthetic (man-made) fibres are widely used as reinforcement for composites include glass, carbon and aramid (Kevlar/Twaron).

Glass Fibres: There are four major types used in composites; E-glass (good strength and electrical resistivity), S-glass (40% high strength and better performance at high temperatures), C-glass (corrosion resistant) and quartz (low dielectric properties). Glass fibres are used in different forms such as rovings (used directly for processes such as pultrusion and winding), fabrics (made by weaving continuous rovings) and mats (chopped strand, continuous strand or surface veil) for reinforcement [23].

Carbon Fibres: They were first developed in 1960s and have high strength and high modulus. Typical diameters of carbon fibres are in the range between 5 and 10 μm. Continuous carbon fibres are grouped together in bundles called "tows". There are between 400-320,000 filaments per tow and these tows can be directly processed in to composites or woven into fabrics [23].

Kevlar: The fibres were first introduced commercially in 1971 and used in commercial applications such as tires, industrial belts, bullet proof vests, high strength cloths and composite structures. Kevlar fibres have high tensile strength and good damage tolerance, but they have poor performance in compressive strength. There are several types of Kevlar such as Kevlar 29 (high toughness), Kevlar 49 (high modulus) and Kevlar 149 (ultra high modulus) [23].

2.4 Natural Fibres

The composites industry has grown rapidly over the past seventy years since the introduction of commercial continuous fibre reinforcements (glass in 1937, carbon in the 1960s and aramids in 1971). Natural fibres were used in resin matrix composites in the early years of the industry including flax and hemp fibres for the bodywork of a Henry Ford car in 1941 [1], but due to economic limitations at that time the vehicle was not mass produced. The company claimed that the composite could withstand 10 times more shock than steel.

There are a number of reasons for the increased emphasis on natural fibres such as recent concerns over dwindling petroleum supplies and the “end of oil” in the distant future, increased government legislation on landfill taxes and increased pressure for sustainability and biodegradability. The bio-based fibres and resins are perceived to be “sustainable” and “greener”. The types of natural fibres currently been investigated for use in plastics includes flax, hemp, jute, wood, rice husk, wheat, barley, oats, rye, cane (sugar and bamboo), grass, reeds, kenaf, ramie, oil palm empty fruit bunch, sisal, coir, water, hyacinth, pennywort, kapok, mulberry, raphia, banana fibre, pineapple leaf fibre and papyrus [4].

The fibres most likely to be adopted as reinforcements are bast (stem) cellulose fibres from plants including flax and hemp (in temperate zones) or jute and kenaf (in tropical zones). Two comprehensive reviews of bast fibres as the reinforcement for composites by the author of this thesis and colleagues are published [47, 48] and are included in Appendix A1 and A2. The first part of the review considers the growth, harvesting and fibre separation techniques suitable to yield fibre of appropriate quality and the characterisation of fibres. The second part considers the prediction of the properties of natural fibre reinforced composites (NFRP), manufacturing techniques and composite materials characterisation.

2.4.1 Advantages of natural fibres

Natural fibres have recently attracted the attention of industry and academia as a good reinforcement due to their advantages over established materials. They are perceived to be environmentally friendly, fully biodegradable, renewable, widely available and cheap and have low density. They are also light in weight compared to synthetic fibres such as glass, carbon and aramid fibres. Natural fibres are less abrasive than synthetic fibres adding an advantage in processing and recycling of the composite material in general. Natural fibre reinforced plastics with biodegradable polymer matrices are seem to be the most environmental friendly materials as far as the end of life treatments are concerned. The biodegradability contributes towards a healthy ecosystem and low cost and the performance of the fibres satisfy the economic interest of industry.

Natural fibres have weaknesses in areas such as moisture absorption which limits its ability to be used in different environments and incompatibility with some polymeric matrices. Mechanical properties of natural fibres are much lower than glass fibres, but their specific properties especially stiffness are highly comparable.

Whether the use of natural fibres as reinforcement is truly beneficial to the environment is discussed in detail in this thesis (in terms of energy use and emissions).

2.4.2 Flax

Flax [1, 49-52] (grown for fibre) and linseed (grown for seed oil) are cultivars: varieties of the same plant species *Linum usitatissimum* bred with an emphasis on the required product. In the UK the flax plant is normally sown in March-May and may grow to one-metre high dependent on the variety (there are 180 species [1]). Generally flax is cultivated where daily temperature remains below 30^{o}C [53]. The Flax Crop Production page of the Flax Council of Canada (FCC) website [51] is an especially useful resource giving comprehensive details of the husbandry of this plant. The life cycle of the plant consists of a 45 to 60 day vegetative period, a 15 to 25 day flowering period and a maturation period of 30 to 40 days with 12 distinct growth stages in the flax plant [50]. Flax is amongst the natural fibres now finding use in thermoplastic matrix composite panels for internal structures in the car industry (including car door panels, car roof and boot linings, and parcel shelves) [4, 54].

The diameter of the stem at the base varies between 1 and 2 mm, and the height is about 80 cm (Figure 2.1 – Stem). The bark (the outer layer of the stem) protects the material from external attacks, confers the rigidity of the stem, and also allows the water and other nutrients to penetrate to the centre of the stem. Both the bark and the xylem (the woody body/shive) are eliminated during the flax processing stages of retting and scutching. These processes are described in the next section.

The fibre bundles are made of several elementary fibres glued together by pectin cement (Figure 2.1 – Bundle). Initially, the technical fibres are extracted by partial separation of these fibre bundles (for example during hackling). The fibres can be as the same length as the flax stem.

Elementary fibres have two types of cell walls; the outer primary and the inner secondary cell walls (Figure 2.1 – Elementary fibre). These cell walls can be divided into three sections in terms of thickness and structure. The fibre also has a hollow space (lumen) which is filled by cytoplasm during cell life and disappears when the plant dies (i.e. during retting).

Each cell wall consists of concentric lamella in which the cellulose fibrils are embedded in an amorphous matrix composed of pectin and hemicelluloses (Figure 2.1 – Lamella) [55].

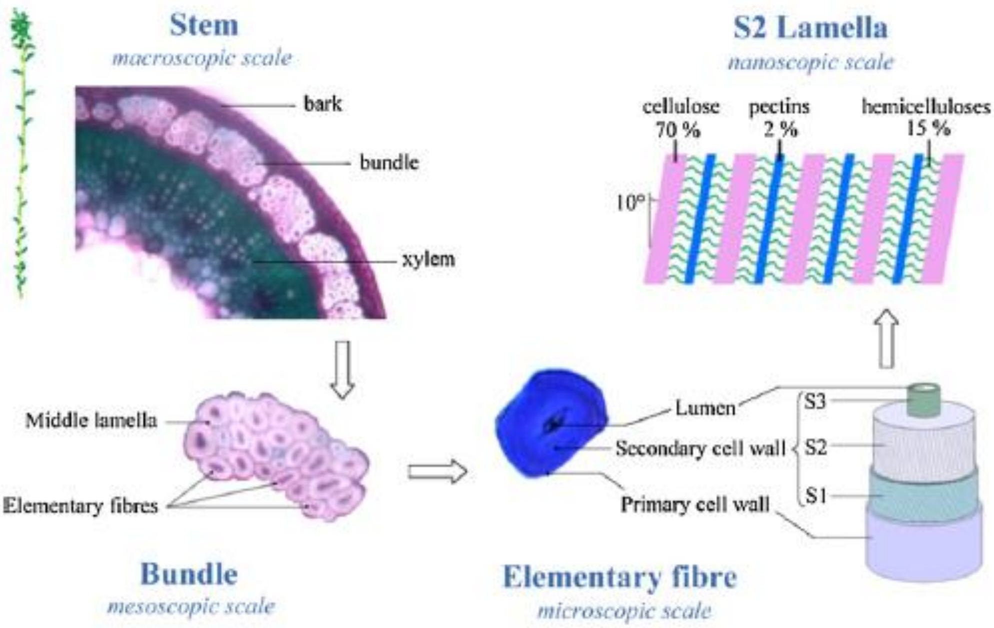

Figure 2.1 Cross-sections and schematic representations of flax stem showing the cellulose fibrils at different scales [55].

2.5 Production of Flax Fibres

The typical production cycle for flax fibres [56], which are probably the most labour and agro-chemical intensive of the natural fibres, is:

Tillage: the preparation of land for cropping by ploughing, harrowing or similar operations. Conventional tillage (Figure 2.2) is preferred in flax cultivation which is primary tillage followed by early spring tillage and planting. No-till methods (Figure 2.3) have been trialled by some growers with no significant change in flax yield [57]. Three tillage systems considered in this LCA study include conservation tillage (mouldboard ploughing), conventional tillage (chisel ploughing) and no-till.

Figure 2.2 Conventional tillage systems which leave a minimum of 30% crop residue on the soil surface [58]

Figure 2.3 No-till systems with minimum soil disturbance and crop residue [59]

West and Marland [60] give the following definitions:

- conventional tillage (CT): practices that leave <15% residue cover after planting This usually involves mould-board ploughing and includes a sequence of soil tillage, such as ploughing and harrowing, to produce a fine seedbed. The method removes most of the plant residue from the previous crop as shown in Figure 2.2.

- reduced tillage (RT): practices that leave 15-30% residue cover This usually involves discs or chisels without intensive ploughing. Reduced tillage is a practice of minimising soil disturbance and allowing crop residue or stubble to remain on the ground instead of being thrown away or incorporated into the soil. The method involves reduced the number of tillage passes and reduced ploughing depth.

Figure 2.4 Reduced tillage involving chisel ploughing [58]

- conservation tillage: any practice that leaves >30% residue cover after planting The method includes no-till (NT) practices which leave the soil relatively undisturbed. The crops are simply planted on previous year's crop residue.

Herbicides are typically used for weed control in no-till systems. No-till methods offer excellent soil erosion control and soil quality improvements as earthworms and other soil organisms increase in number as shown in Figure 2.3.

Fertilisers: The Henfaes Research Centre suggests that for flax grown in UK, the levels of fertiliser are 40 kg/ha of nitrogen (N), 50 kg/ha of phosphorus (P) as P_2O_3 and 50 kg/ha of potassium (K) as K_2O – [61]. For flax in Northern Ireland (NI), the suggested levels of fertiliser are 20 kg/ha N, 20 kg/ha P_2O_5 and 80 kg/ha K_2O. Agricultural lime ($CaCO_3$) may be applied to maintain soil pH. Fertiliser levels included in the study are according to the UK standard and lime application is also considered.

Drilling (planting) the seed usually occurs between the end of February and early April in Belgium, France and the Netherlands or in early April in Northern Ireland. Flax is planted in narrow rows (150-200 mm apart) using similar equipment to that used for cereals (Figure 2.5). The homogeneity of the fibres depends on the seed distribution. Optimum seed depth is 25-40 mm and optimum seeding rates are 35-50 kg/ha [57].

Figure 2.5 Flax planted in narrow rows [61]

Weed control: Flax is a poor competitor with weeds which can contaminate the scutched (i.e. decorticated - see below) flax fibres. Herbicides are applied to control weeds. Pesticides (herbicides, insecticides and fungicides) use is included in the study.

Plant growth for flax consists of a 45 to 60 day vegetative period, a 15 to 25 day flowering period and a maturation period of 30 to 40 days and is well illustrated in Linseed Law [50].

Dessication: Chemical desiccation or drying of the crop (Figure 2.6) has numerous advantages over field retting including earlier harvesting, elimination of the need for swathing, reduction in combining time and less wear and tear on machinery. Glyphosate is typically applied 10-14 days after full flower at about mid-July in Northern Ireland.

Glyphosate is only used where stand retting (see below) is adopted followed by direct combine harvesting of the crop.

Figure 2.6 Dessicated flax field [61]

Harvest: by either combine harvester or pulling, in August/September.

Rippling: the removal of flax seed capsules by drawing pulled stems through a coarse steel comb (Figure 2.7).

Figure 2.7 Rippling of flax [62]

Retting is defined for flax as the "subjection of crop or deseeded straw to chemical or biological treatment to make the fibre bundles more easily separable from the woody part of the stem. Flax is described as water-retted, dew-retted or chemically–retted, etc., according to the process employed" [56].

Water Retting: This method was widely used in Europe several decades ago and it is the preferred method of retting as it yields superior quality fibre. However it has gradually disappeared due to being too labour intensive, costly and shortage of water resources.

In this retting process, the stalks of the flax plants are immersed in cold or warm water. The duration for the stalks to remain submerged in water is between 4 days to several weeks. During this time the stalks should be closely monitored as the under retting makes the separation process very difficult and it also affects the fibre yield. Over retting will affect the fibre quality and extracted fibres will be weak.

In natural water retting, stagnant or slow moving water sources such as ponds or bogs are used in which the bundles of stalks are dropped in to the water and weighted down with stones or logs. The retting time is decided depending on the temperature and the mineral content of the water.

Figure 2.8 Water retting of flax at Cloney Farm, Knocknacarry around 1914 [63]

(This picture was taken from the famous Welsh Collection at Ulster Museum)

Flax plant stalks are also retted using purpose built tanks and there is control over water quality and condition hence the fibres obtained are of good quality and consistent. The water used in tanks is heated for warm water retting process, which is considered in this LCA study. Generally water is changed after the initial eight hours of submerging to aid the retting process by removing waste and toxins. The waste water can be treated and used as liquid fertiliser as it is rich in chemicals.

There is a trial and error method known as double retting, in which the stalks are retted in water for shorter time period than optimum, removed, dried for a long time and then allowed to be retted again. It was found that fibres extracted from this method are generally of very good quality.

Stand/dew Retting: In stand retting method, the crop is left for standing after the dessication. Pre-harvest retting of flax, when glyphosate is applied at the mid-point of flowering, depends on uniform desiccation of the entire stem and is difficult to achieve during a dry season [64]. This method has the potential of producing a large quantity of high quality fibre as the straw loss is low. This method also reduces the soil contamination and works well when there is high rainfall, but the stand retting process takes longer than other retting methods [61].

In dew retting the crop is swathed following dessication and left on the field to rett. The crops need to be turned at least once to allow even retting. All swathers (and rakes) must be set at correct level and should avoid raking stones into the fibre crop. Normally, dew retting takes about 10-20 days [61]. As in dew-retting, stand-retting of the desiccated flax in the field relies on microorganisms and is dependent on the vagaries of the weather.

Figure 2.9 Field of dew retted flax [61]

Bio-retting: In bio-retting, enzymes (*e.g.* pectinase to digest pectin binder [65]) are used to assist the retting process, but termination of the retting process may be a problem and failure to achieve this can result in reduced fibre properties.

The bio-retting considered in this study is similar to warm water retting except that instead of relying on natural bacteria, an inoculum of selected pectinolytic bacteria is added to water to improve retting.

Decortication [66, 67] is the mechanical removal of non-fibrous material from retted stalks or from ribbons or strips of stem to extract the bast fibres. For flax, the process is usually referred to as “scutching”. This is usually achieved by a manual operation, hammer mill, inclined plane/fluted rollers or willower.

Figure 2.10 Decortication/Scutching [68]

Hackling is the combing of long (line) flax fibres in order to remove short fibres, to parallelise the remaining fibres and also to remove any extraneous matter (shive).

Figure 2.11 Hackling using a metal comb [68]

Carding is defined as "the disentanglement of fibres by working them between two closely spaced, relatively moving surfaces clothed with pointed wire, pins, spikes or saw teeth" [56]. The product is known as **sliver**.

Spinning is "the drafting [decreasing the mass per unit length] and twisting of natural (or man-made) fibres". The product is known as **yarn** or filaments. In the bast-fibre industry, the terms 'wet spinning' and 'dry spinning' refer to the spinning of fibres in the wet state or in the dry state respectively.

For thousands of years, the simple spinning wheel was used to turn the fibres into thread or yarn (Figure 2.12). The modern spinning machines are now used to spin fibres to cope with mass production as it is much faster than hand spinning.

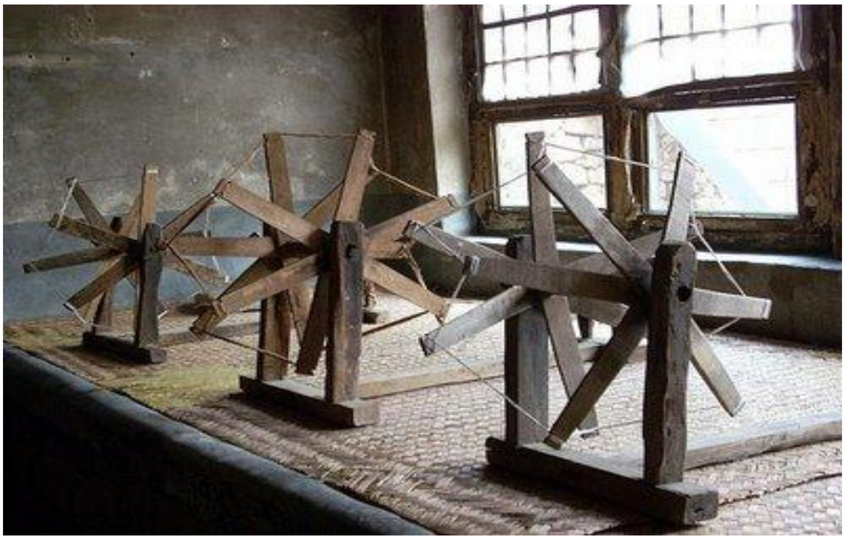

Figure 2.12 The old spinning wheel used to twist fibres together to form yarn [69]

Figure 2.13 Modern spinning machines powered by electricity [69]

2.6. Production of Glass Fibres

Glass fibre manufacturing is the high-temperature conversion of various raw materials into a homogeneous melt, followed by the conversion of this melt into glass fibres [70]. Glass fibres come in a variety of forms although >95% of all reinforcements are E-glass. The formulation of these fibres includes several minerals, notably [71]:

- sand – particles of minerals including quartz (silica: SiO_2), mica (complex silicates usually with K, Na, Li, H and Mg) and feldspar (aluminium silicates with varying amounts of K, Na, Ca and Ba). "Pure sand is white in colour and consists of silica" [72]
- kaolin – hydrated aluminium silicate ($Al_2O_3.2SiO_2.2H_2O$) also known as china clay [72]
- limestone – mostly calcium carbonate ($CaCO_3$) with other oxides (Si, Al, Fe), carbonates (Fe, Mg) and calcium phosphate [72], and
- colemanite – hydrated calcium borate ($2CaO.3B_2O_3.5H_2O$) [72].

Glass fibre production can be segmented into three phases:

i. raw material extraction,

ii. glass melting and refining and

iii. fibre forming and finishing [70].

2.6.1. Raw material extraction

The primary component of glass fibre is sand and there are two principal methods for obtaining sand: quarrying or sand mining and dredging from coastal waters [73]. When extraction is in the form of open pit excavation, equipment like power shovels, draglines, front-end loaders and bucket wheel excavators are used. Dredging is excavation carried out under water and it is used to extract settled sands in coastal waters or other water bodies. After extraction the sand often undergoes considerable processing such as crushing, screening to remove coarse and very fine fractions, physical and chemical processes to remove iron, chromium, other deleterious materials followed by washing and drying using rotary or fluidized bed dryers [73]. Generally silica sand from hard rock areas (e.g. granite or basalt) will require a large amount of processing.

Glass fibre manufacturing plants usually are located within the proximity of reliable economical supplies of raw materials other than boric acid which is always imported to the plant. The extraction and processing of kaolin in south-west England involves the production of very large quantities of mineral waste. The main excavation techniques include: blasting with explosives and using breaker hammers, which results in noise production and ground vibrations in surrounding environment. It was found that although the use of explosives is not popular due to security reasons, it allows faster excavations, is safer for the surrounding structures and has less environmental impact than the breaker hammers [74]. The glass fibre production may also result in resource depletion by using up the natural materials such as sand, kaolin, limestone and colemanite at large scale over a long period of time.

2.6.2. Glass melting and refining

The raw materials are melted at ~1600ºC with controlled cooling to around 200^{o}C and are transformed through a sequence of chemical reactions to molten glass [70]. A typical glass fibre furnace consists of three sections: melting, refining and cooling. In operation raw materials are introduced continuously on top of a bed of molten glass, where they slowly mix and dissolve. Mixing is effected by natural convection, gases rising from chemical reactions and in some operations by air injection into bottom of the bed. As a part of the process molten glass passes from the furnace to the refining unit, where bubbles and particles are removed by settling and the melt is slowly allowed to cool to the viscosity required for the fibre forming.

Common heating methods used in glass melting furnaces are combustion-heating (oxy-fuel, air-fuel burners) and direct electrical heating ("Joule heating"), as well as combinations of both ("electric boosting"). Due to the high temperatures in the tank, glass melting is a large source of nitrogen oxides (NO_x) emissions. Modern glass furnace technology aims to increase the use of oxygen as a way to increase fuel efficiency and reduce emissions of nitrogen oxides. The main environmental impacts from this process include global warming resulting from energy use and nitrogen oxides emissions [75].

2.6.3. Fibre forming and finishing

At the forming stages the molten glass is spun through heated micro-fine bushings to produce filaments of 5-24 μm in diameter. The continuous fibres emerging as cooled filaments are drawn together into a strand (closely associated) or roving (loosely associated), and coated with a water-soluble sizing and/or coupling agent [71]. Surface treatments on fibres exist for a variety of reasons: filament cohesion, antistatic agents, lubricants for textile processes and coupling agents to promote good adhesion between the fibres and the resin. The most common coupling agents are organofunctional silanes. The coated fibres are gathered and wound onto a spindle. The spindles of glass fibres are next conveyed to a drying oven where moisture is removed from sizing and coupling agents and are then sent to an oven to cure the coatings. The final fabrication includes twisting, chopping, weaving and packaging the fibre [70]. Manufacture of glass fibres may involve significant transport distances both from the raw materials source to the industrial-scale fibre factory and from the factory to the textile plant and finally to the customer.

The main forms of energy used in forming are electricity and natural gas. Most of the electricity is used to drive forming machines, fans, blowers, compressors, and conveyors. The proper working temperatures need to be maintained, fuels (e.g. natural gas) and electricity are used to control the process heat in forming. The energy used in forming is highly product dependent and the energy use in forming varies from 12% (for flat glass) to 34% (for fiber forming) of the total primary energy consumed in glass production. The environmental impact in glass fibre forming and finishing is global warming which mainly results from the high energy use [75].

2.7 Life Cycle Assessment

The new focus on planning for a sustainable world has revived interest in natural materials. However, it is timely to consider whether the claimed benefits of these materials can be justified quantitatively. Life Cycle Assessment (LCA) is an environmental assessment method which, according to ISO 14040:2006(E), "considers the entire life cycle of a product from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal" [5]. A LCA study has four phases as shown in Figure 2.14.

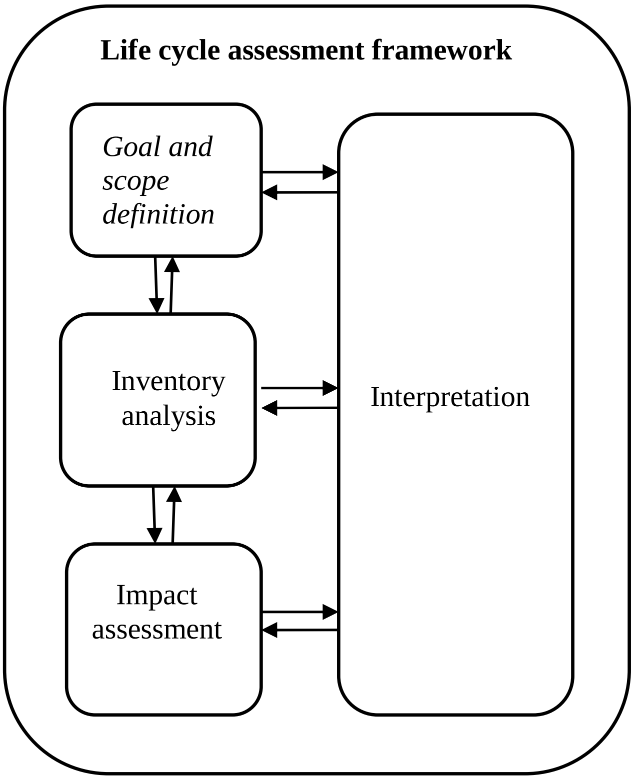

Figure 2.14 Phases of an LCA study [76]

The outline methodology is defined by the international standards for Environmental Management Systems [5, 12, 76-78]. The LCA is carried out to assess the environmental impacts arising from the flax fibre production and is referenced to glass fibre production.

There are a variety of assessment methods which can be applied to the LCA problem, including CML92 [79], Critical Surface-Time (CST95) [80], Ecopoints [81] Eco-indicator 95 [82], SimaPro [83] and EcoInvent [84]. Descriptions of some of the LCA methodology are given in Table 2.1.

Table 2.1 Descriptions of LCA methodology

Method	Description	Origin
CML92	This is one of the first LCA methods available which includes characterisation and normalisation. This is claimed to include the most important multi-score valuation methods in LCA.	Centre for Environmental Studies (CML), University of Leiden in 1992
Critical Surface Time (CST95)	This method provides characterisation of toxicity, together with a clear separation of scientific and societal weighting in the valuation step. The impact categories considered are human toxicity, terrestrial ecotoxicity, aquatic ecotoxicity, global warming, photochemical oxidation, acidification, eutrophication and energy consumption.	Olivier Jolliet & Pierre Crettaz, EPFL Lausanne in 1997
Ecopoints	Environmental impacts are evaluated directly and there is no classification step. The Eco-Points methods have been accepted as a useful instrument, but the lack of a classification step is also regarded as a disadvantage - only a very limited number of impacts can be evaluated. Eco-points Method was/is widely used in Switzerland and Germany. It is also used in UK, Norway and Netherlands.	Developed in Switzerland
Eco-indicator 95	The evaluation method for calculating the Eco-Indicator 95 strongly focuses on the effects of emissions on the ecosystem. The targets values are related to three types of environmental damage: • deterioration of ecosystems • deterioration of human health • damage to mineral and fossil resources.	Developed in a joint project carried out by companies, research institutes and the Dutch government.
EcoInvent	Contains up-to-date Life Cycle Inventory (LCI) data with more than 4'000 LCI datasets in the areas of agriculture, energy supply, transport, biofuels and biomaterials, bulk and speciality chemicals, construction materials, packaging materials, basic and precious metals, metals processing, ICT and electronics as well as waste treatment.	Developed by Swiss Centre for Life Cycle Inventories.
SimaPro	The LCA software allows to model products and systems using systematic features such as parameters, Monte Carlo analysis, and integrated ecoinvent database. It also has applications such as: • Carbon footprint calculation • Product design and eco design • Environmental Product Declarations (EPD) • Environmental impact of products • Environmental reporting (GRI) • Determining of key performance indicators	Developed and supplied by PRé Consultants in Netherlands.

ISO/TR 14047:2003 [12] identifies eight environmental impacts which closely mirror the environmental impact classification factors (EICF) used by Azapagic [13, 14] (Table 2.2). These are discussed in detail in following sections 2.8-2.15 and Chapter 6.

Table 2.2: Environmental Impact classification factors

ISO/TR 14047:2003(E) [12]	Azapagic et al [13, 14]
Acidification	Acidification Potential (AP)
Ecotoxicity	Aquatic Toxicity Potential (ATP)
Human toxicity	Human Toxicity Potential (HTP)
Eutrophication/Nitrification	Eutrophication Potential (EP)
Climate change	Global Warming Potential (GWP)
Depletion of abiotic/biotic resources	Non-Renewable/Abiotic Resource Depletion Potential (NRADP)
Stratospheric ozone depletion	Ozone Depletion Potential (ODP)
Photo-oxidant formation	Photochemical Oxidants Creation Potential (POCP)

Additional factors might be considered including land use (where industrial materials from non-food crops displace food plants or where waste materials are dumped into landfill sites), loss of biodiversity (if not adequately reflected by ecotoxicity), and/or noise, vibration and odour.

ISO 14040:2006(E) [5] suggests that the **goal of an LCA** should state:

- The intended application
- The reasons for carrying out the study
- The intended audience
- Whether the results are intended to be disclosed to the public

The scope should be sufficiently well defined that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal. LCA is an iterative technique, and as data and information are collected, various aspects of the scope may require modification in order to meet the original goal of the study. The **scope of an LCA** should include the following items:

- The product system to be studied - determining the framework for the LCA to be carried out
- The functions of the product system (or systems for comparative studies) – behaviour and the process of the production system
- The functional unit – the key element of LCA which has to be clearly defined. The functional unit is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related. This enables comparison of two essential different systems.
- The system boundary – determines which unit processes are included/not included in the LCA. Defining system boundaries is partly based on a subjective choice, made during the scope phase when the boundaries are initially set.
- Allocation procedures – which attribute shares of the total environmental impact to the different products of a system.
- Impact categories selected and methodology of impact assessment, and subsequent interpretation to be used
- Initial data/data requirements - Reliability of the results of LCA study depends on the extent to which data quality requirements are met which includes precision, completeness, representativeness, consistency and reproducibility.
- Assumptions – which include engineering estimates or decisions based on values and are clearly and comprehensively explained in conclusions drawn from the data.
- Limitations – which are incompleteness due to cut offs and lack of process specificity

- Type of critical review, if any – which can be a simple peer review of the final report, or integrated quality assurance involving typically three review steps (after the scope definition, after the data collection, and after the conclusion)
- Type and format of report required for the study – in which the the results, data, methods, assumptions and limitations are clearly, fairly, and accurately reported in sufficient detail to allow the intended audience to comprehend the complexities and trade-offs inherent in the study.

Before setting the goal and scope, it is necessary to review the key factors which may be appropriate in the context of this study.

2.8 Acidification

Acidification is a consequence of acids (and other compounds which can be transformed into acids) being emitted to the atmosphere and subsequently deposited in surface soils and water. Increased acidity of these environments can result in negative consequences for coniferous trees (forest dieback) and the death of fish in addition to increased corrosion of manmade structures (buildings, vehicles etc.).

Acidification considerably reduces the fertility of the soil, mainly by affecting its biology, by breaking up organic matter, and causing loss of plant nutrients [85]. Growing plants remove alkalinity from the soil and the soil acidification increases when the harvested products are removed. Soil acidification is closely linked to water acidification, which can affect aquatic life, groundwater and the related drinking water supply. Turunen and van der Werf [86, 87] found that acidification was largely (62-79%) due to the yarn production stage in the life cycle assessment carried out for hemp yarn production. They also suggested that the three impacts, energy use, climate change and acidification are strongly interrelated, as energy demand is largely met by fossil fuels, the combustion of which results in the emissions of CO_2 and SO_x.

Acidification Potential (AP) [13, 14] is based primarily on the contributions of five chemicals, SO_2, NO_x, HCl, NH_3 and HF to the potential acid deposition in the form of H^+ (protons) and thus needs to be considered in the context of nitrogen fertilisers as run-off to water. The AP classification factors are expressed relative to the SO_2.

2.9 Aquatic Toxicity/ Ecotoxicity

Eco- Toxicity results from persistent chemicals reaching undesirable concentrations in each of the three elements of the environment (air, soil and water) leading to damage to animals, eco-systems and aquatic systems. The modelling of toxicity in LCA is complicated by the complex chemicals involved and their potential interactions. The assessment of potential toxic effects from pesticides in the aquatic environment on non-target organisms such as aquatic biota and soil micro-organisms, is becoming increasingly important [88]. Herbicides constitute >50% of pesticide production in Denmark, France and the UK [89].

Glyphosate, *N*-(phosphonomethyl) glycine [H_2O_3P-CH_2-NH-CH_2-COOH], is a systemic, broad-spectrum, non-selective herbicide used to kill broad-leaved grasses and sedge species. It is one of the most used xenobiotics in modern agriculture [90] and is used as a dessicant for flax. Petit et al [89] state that it is completely degraded by micro-organisms in soil, with a half-life of 60 days, primarily to non-toxic aminomethylphosphoric acid (AMPA [H_2O_3P-CH_2-NH_2]) which is further degraded in soil. Glyphosate decomposition occurs under both aerobic and anaerobic conditions. It is also inactivated by adsorption to clay in benthic or suspended sediment.

Eriksson et al [91] proposed a scientifically justifiable list of "selected stormwater priority pollutants (SSPP)" to be used, for example, in evaluating the chemical risks posed by different water handling strategies. Glyphosate was included with the selected herbicides as it is extensively used in urban areas and along motorways in the UK, France, Denmark and Sweden. They considered 15 routes for the removal of glyphosate from stormwater and predicted that infiltration basins were best management practice, followed by sub-surface flow constricted wetlands and porous pavements. Glyphosate is most readily removed by adsorption and microbial degradation. Settlement tanks were judged to be the least efficient technique for the removal of glyphosate.

The commercial herbicide Roundup® is a formulation of 36% glyphosate (normally considered the active ingredient) as the isopropylamine (IPA) salt with a surfactant, polyoxyethyleneamine (POEA) [88]. Martinez and Brown [92] found that just 1/3rd of the amount of Roundup® relative to glyphosate alone was required to kill rats suggesting that ingredients labelled as "inert" should be considered otherwise. Peixoto [90] clearly demonstrated the ability of Roundup® to impair mitochondrial bioenergetic reactions, especially at higher concentrations, while glyphosate alone did not affect mitochondrial respiration and membrane energisation. They attribute the effect to non-specific membrane permeabilisation probably as a result of other ingredients (suspecting the POEA surfactant) or a synergy between components of the formulation.

Sandermann [93] reported that a 1997 review [94] listed 183 herbicide resistant biotypes in 42 countries, including the first observation of glyphosate resistance (plants which survive and set seed). By 2004, eleven weed biotypes had been recorded as glyphosate-resistant. The risk assessment for herbicide-resistant transgenic plants, notably Roundup-Ready® crops (e.g. alfalfa, canola, cotton, maize and soybean), may well underestimate the long-term effects of dependence on glyphosate as a herbicide.

Petit et al [89] also considered Diquat [Dipyrido (1,2-a:2',1-c) pyrazinediium-6,7-dihyro- dibromomonohydrate] and Paraquat [4,4'-bipyridium-1,1'-dimethyldichloride]. Both of these herbicides undergo photodegradation with half lives of 2-11 and 1.5 days respectively. These herbicides also undergo biodegradation (Diquat half-life = 15-32 days; Paraquat not given) and adsorption to clay.

Using diesel in transportation and running machinery for both natural fibre and glass fibre production has potential contaminants of concern including carbon monoxide (CO), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2). The direct impacts of these gases and pollutants include global warming, acidification and ozone layer depletion. In an environmental comparison of China Reed fibre as a substitute for glass fibre in plastic transport pallets, Corbière-Nicollier et al [95] found that cultivation of the reed had a dominant role in the factors for terrestrial ecotoxicity, human toxicity (when crop rotation has edible foods following the China Reed) and eutrophication due to (a) heavy metal emissions to soil and (b) phosphate emissions (from manure and fertiliser) to water.

Aquatic Toxicity Potential (ATP) [13, 14] is calculated based on the maximum tolerable concentrations of different toxic substances in water by aquatic organisms. Azapagic [96] has recently stated that "Toxicity estimations in LCA are notoriously unreliable and difficult".

2.10. Human Toxicity

Human and eco-toxicity results from the persistent chemicals reaching undesirable concentrations in each of the three segments of the environment - air, soil and water leading to damage in humans, animals and eco systems. The modelling of toxicity in LCA is complicated by the complex chemicals involved and their potential interactions.

Abrahams [97] reviewed the effect of soils on the health of humans and concluded that contaminants are a known global problem which needs further research in respect of their behaviour and the pathways to humans.

The toxicological factors are calculated using scientific estimates for the acceptable daily intake or tolerable daily intake of the toxic substances. The human toxicological factors are still at an early stage of development so that HTP can only be taken as an indication and not as an absolute measure of the toxicity potential. Carbon monoxide has a human toxicology classification factor of 0.012. For agricultural chemicals, the human toxicology classification factors are for ammonia (from fertiliser) 0.0017-0.020, arsenic as solid (herbicide) 1.4, nitrates (fertiliser) 0.00078, phosphates (fertiliser) 0.00004 and pesticides 0.14 [13, 14].

Human Toxicity Potential (HTP) [13, 14], calculated in kg, takes account of releases of materials toxic to humans in three distinct media - air (A), water (W) and soil (S) based on the human toxicological factors.

2.11. Eutrophication/Nitrification

Eutrophication is defined as the potential for nutrients to cause over-fertilisation of water and soil which in turn can result in increased growth of biomass.

Nitrogen (constituent of amino acids, nucleotides, and chlorophyll), carbon (major cellular constituent), and phosphate (constituent of ATP, ADP, and phospholipids) are essential nutrients for algal growth [98].

Algae refer to a diverse group of eucaryotic (containing a nucleus enclosed within a well-defined nuclear membrane) microorganisms that share similar characteristics. They are unicellular to multi-cellular plants that occur in freshwater, marine water, and damp environments and range in size from minute phytoplankton to giant marine kelp. Algae possess chlorophyll, the green pigment essential for photosynthesis, and often contain additional pigments that mask the green color (e.g., fucoxanthin (brown) and phycoerythin (red)) [99] [100].

Typically, algae are autotrophic (derive cell carbon from inorganic carbon dioxide), photosynthetic (derive energy for cell synthesis from light), and contain chlorophyll. They are also chemotrophic in terms of night time respiration, e.g., metabolism of molecular oxygen (O_2). Algae utilize photosynthesis (solar energy) to convert simple inorganic nutrients into more complex organic molecules. Photosynthetic processes result in surplus oxygen and non-equilibrium conditions by producing reduced forms of organic matter, i.e., biomass containing high-energy bonds made with hydrogen and carbon, nitrogen, sulfur, and phosphorus compounds.

The organic matter produced serves as an energy source for non-photosynthetic or heterotrophic organisms (animals, including most bacteria, which subsist on organic matter). Heterotrophic organisms tend to restore equilibrium by catalytically decomposing these unstable organic products of photosynthesis, thereby obtaining a source of energy for their metabolic needs. The organisms use this energy both to synthesize new cells and to maintain old cells already formed [101].

From the point of overall reactions, these heterotrophic organisms only act as reduction-oxidation catalysts - they only mediate the reaction (or more specifically the electron transfer). Oxidation may produce several intermediate reduction-oxidation states prior to reaching a fully oxidized state (e.g., inorganic state) [101].

Phosphorus is an essential element in biological systems as it is a constituent of nucleic acid in phospholipids of cell membranes and ATP and ADP which are involved in energy exchange in biological systems. ATP, adenosine triphosphate (one adenosine attached to three phosphate groups), is the energy carrier in all cells. The energy produced by respiration is kept in these molecules and is stored as phosphate bonds [102].

Orthophosphate is the only form of P, (PO_4^{3-}) that autotrophs, can assimilate. The results are excessive production of autotrophs, especially algae and cyanobacteria. This high productivity leads to high bacterial populations and high respiration rates, leading to hypoxia or anoxia in poorly mixed bottom waters and at night in surface waters during calm, warm conditions. Low dissolved oxygen levels causes the loss of aquatic animals and release of many materials normally bound to bottom sediments including various forms of P. This release of P reinforces the eutrophication [103].

Reddy et al [104] and Stoate [105] report that phosphorus is the nutrient which limits plant growth in most fresh (river/pond/lake) waters. Nitrogen contamination of fresh water does not necessarily result in a significant eutrophication hazard [106] although it may be the limiting nutrient in coastal waters [104, 105]. Van Dolah [107] stated that increasing industrial and agricultural activities result in enhanced discharges of nitrate and phosphate in coastal waters, which have been correlated with strong algal growth. Phosphorus binds tightly to soil particles and hence is a particular problem when sediment enters watercourses as it leads to excessive algal growth. In turn, the algal blooms reduce light penetration into the water and hence inhibit the growth of macrophytes and their invertebrate predators. Further, as the excessive plant biomass decomposes it consumes dissolved oxygen in the water initially affecting top predators and hence disrupting the ecosystem.

According to the life cycle assessment carried out by Turunen and van der Werf [86, 87], the emissions from the soil (N and P) contributed about 90% of the eutrophication and the remaining 10% results from diesel combustion in field operations. The use of fertilisers in agriculture is perceived as a major cause of eutrophication. However, Stoate [105] has suggested that phosphorus and other nutrients from village sewage works and from septic tanks at isolated dwellings also contribute to depletion of downstream invertebrate communities. He reports that the Game Conservancy Trust Allerton project revealed that phosphorus concentrations from septic tanks were more than ten times those from arable field drains.

The nitrate anion, NO_3^-, has high solubility in water and is not significantly adsorbed onto most soils [97]. When both soil nitrate levels and water movement are high, leaching and run-off may be significant contributors to the nitrogen load in watercourses. Whilst fertilisers are a source of nitrates, Abrahams [97] suggests that in the climatic conditions of NW Europe mineralisation of soil organic matter and crop/animal residues is a more significant source of leached nitrates because mineralisation is not well synchronised with nitrogen uptake of the crop.

Crews and Peoples [108] reviewed the use of legume-derived nitrogen against synthetic fertiliser-derived nitrogen and concluded “that the ecological integrity of legume-based agroecosystems is [only] marginally greater than that of fertiliser-based systems”. That advantage could be eroded where best management practices are considered. However, nitrogen biologically fixed by legumes is derived from solar energy, whereas synthetic fertiliser is a heavy user of (fossil fuel) commercial energy and hence is likely to become less attractive in the future (especially in the context of Global Warming Potential). Leguminous cover-crops allowed to grow throughout the fallow season can substantially reduce nitrogen leaching as they scavenge nitrogen available in the soil. Further, nitrogen synchrony (availability during crop nitrogen uptake) can be increased by planting cover-crops in the off-season and ploughing-in crops in spring rather than autumn.

Bradshaw et al [109] reported that a major eutrophication of Dallund Sø (a lake in Denmark) occurred as a result of the changing agricultural system and of the retting of flax and hemp during the Mediæval period (AD 1050-1536). Turunen and van der Werf [86, 87] found that the water retting process of hemp has contributed 13% of the total eutrophication which is higher than other retting processes such as bio-retting and stand/dew retting. Fibre processing operations also contributed to eutrophication through the emissions of electricity generation.

In an environmental comparison of China Reed fibre as a substitute for glass fibre in plastic transport pallets, Corbière-Nicollier et al [95] found that China Reed fibre was the better option for all factors except eutrophication. The CML and Eco-indicator measures confirm the CST95 results (China Reed is considered better on all factors relative to glass fibre) except for eutrophication. The China Reed has a better score from the former two methods as they consider NO_x emissions to contribute to eutrophication whereas CST95 considers that only phosphates contribute to eutrophication in Europe where lakes are normally phosphorus limited.

Cuttle et al [110] have reviewed the methods available for the control of diffuse water pollution from agriculture. At the retting stage, eutrophication can be significantly reduced by stand/dew retting rather than immersion/water retting.

Eutrophication Potential (EP) [13, 14] value is calculated in kg based on a weighted sum of the emission of species such as N, NO_x , NH_4^+ (ammonia), PO_4^{3-} (phosphates), P and chemical oxygen demand (COD) measured relative to PO_4^{3-}. The classification factors for EP are expressed relative to phosphates.

2.12. Global Warming Potential/Climate Change

Global Warming is caused by the ability of the Earth's atmosphere to reflect some of the heat radiated from the earth's surface back to the ground. This reflected radiation is increased by greenhouse gases (GHG) in the atmosphere. Increased emission of GHGs (CO_2, N_2O, CH_4 and volatile organic compounds (VOCs)) will change the heat balance of the earth and result in future climate change.

An increase of weather extremes has been a fundamental prediction of climate science for decades. Basic physics suggests that as the earth warms, precipitation extremes will become more intense, winter and summer, simply because warmer air can carry more water vapour. Weather statistics confirm that this has begun to happen [111].

The worldwide climate change signs include [112]:

- The rising average temperature on earth, which has climbed up by 0.8^0C since 1880 with much of this is in recent decades. The Figure 2.15 illustrates the global warming predictions for year 2070-2100 vs. 1960-1990 averages.
- The increased rate of warming - The 20th century's last two decades were the hottest in 400 years and possibly the warmest for several millennia, according to a number of climate studies. The United Nations' Intergovernmental Panel on Climate Change (IPCC) reports that 11 of the past 12 years are among the dozen warmest since 1850 [113].
- The temperatures in Arctic - Average temperatures in Alaska, western Canada, and eastern Russia have risen at twice the global average, according to the multinational Arctic Climate Impact Assessment report compiled between 2000 and 2004 [114].

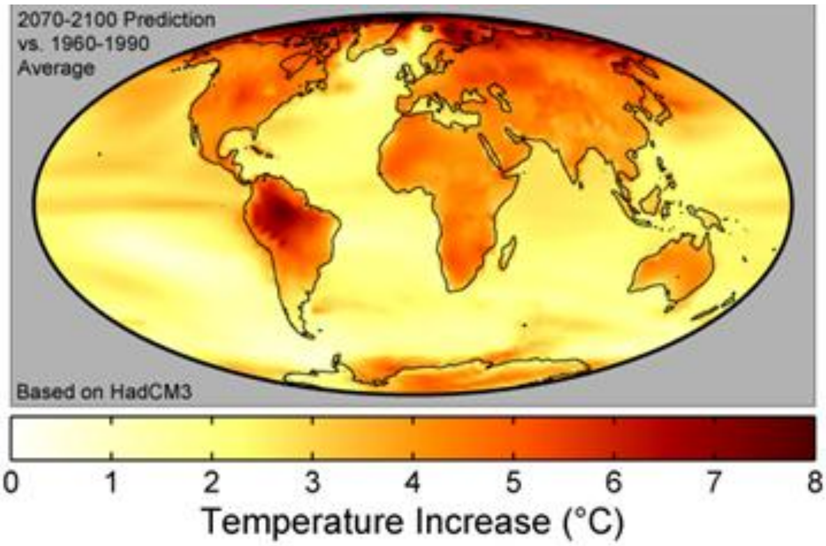

Figure 2.15 Global Warming Predictions for 2070-2100 vs 1960-1990 averages [115]

- Rapid disappearance of the Arctic ice - the region may have its first completely ice-free summer by 2040 or earlier. Polar bears and indigenous cultures are already suffering from the sea-ice loss.
- Rapidly melting Glaciers and mountain snows—for example, Montana's Glacier National Park now has only 27 glaciers, versus 150 in 1910. In the Northern Hemisphere, thaws also come a week earlier in spring and freezes begin a week later. Sea levels are also expected to increase by 90 - 880 mm. in the next century, mainly from melting glaciers and expanding seawater. Warmer ocean water may result in more intense and frequent tropical storms and hurricanes.
- Coral reefs, which are highly sensitive to small changes in water temperature, suffered the worst bleaching or die-off in response to stress, ever recorded in 1998, with some areas seeing bleach rates of 70 percent. Experts expect these sorts of events to increase in frequency and intensity in the next 50 years as sea temperatures rise.
- Effects on biodiversity - the wildlife and species that cannot survive in warmer environments may become extinct. Human health is also at risk, as global Climate Change may result in the spreading of certain diseases such as malaria, the flooding of major cities, a greater risk of heat stroke for individuals, and poor air quality.

Industrialisation, deforestation, and pollution have greatly increased atmospheric concentrations of water vapour, carbon dioxide, methane, and nitrous oxide, all greenhouse gases that cause global warming/climate change. It was also reported that, global warming could lead to large-scale food and water shortages and have catastrophic effects on wildlife [116].

The most recent report, issued by IPCC in 2007, concludes that *"The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land-use change, while those of methane and nitrous oxide are primarily due to agriculture."* The report goes on to note that these findings come with a *"very high confidence rate* [words emphasized in italics in the report summary] *that the globally averaged net effect of human activities since 1750 has been one of warming"* [116].

Primary sources of GHG in the context of this study include:

(a) for glass fibres,

  i. production energy used in glass melting and spinning
  ii. production energy used in fibre forming and curing
  iii. emissions from glass melting, volatile organic compounds, raw material particles and small amounts of CO, NO_x, SO_x and flourides

(b) for natural fibres,

  i. production energy used to power agricultural equipment,
  ii. production energy used to produce and apply fertilisers and pesticides,
  iii. releases of CO_2 from decomposition and oxidation of soil organic carbon (SOC) following soil disturbance, and CO_2 and CH_4 (methane) from retting, and
  iv. production energy used in fibre processing

in addition to emissions resulting from transport for both types of fibre.

The Stern Review [117] lists fertiliser manufacture as the fourth most energy intensive industry with energy consuming 13.31% of total costs (after electricity production and distribution: 26.70%, gas distribution: 42.90% and refined petroleum: 72.83%). The 123

UK production sectors were also ranked in terms of carbon intensity by detailed case study considering direct and indirect carbon costs applied to various fossil fuel inputs (oil, gas and coal) and traced through production process to final goods prices by using an illustrative carbon price of £70 per tonne of Carbon. The manufacture of fertiliser is ranked as the fifth in 123 UK production sectors at 4.61% immediately behind cement, lime (also used in agriculture) and plaster at 9% and its use produces both methane and nitrous oxide emissions.

Smil [118] suggests that while there have been significant reductions in the energy required for industrial fixation of ammonia, the energy costs remain very high (27GJ/t NH_3 in the most efficient plants operating in the late 1990s *vs* >80 GJ/t NH_3 before 1955). Globally around 1.3% of all energy produced is used for fertilisers. Da Silva and Kulay [119] performed an environmental comparison between two phosphate fertilisers, FMP (fused magnesium phosphate) and TSP (triple superphosphate) used in Brazil with six of the ISO/TR 14047:2003 [12] environmental impact classification factors (i.e. excluding NRADP and POCP). In both cases, energy was the main negative environmental impact arising from the extensive electricity dependence for FMP and from transport distances for the TSP. Eutrophication was also an issue due to phosphate losses during the manufacture of FMP or to leaching of the phosphogypsum by-product in the case of TSP.

Abrahams [97] states that there "is an appreciable flux of CO_2 from the oxidation of soil organic matter, whilst soils are also important sources of the greenhouse gases CH_4 and N_2O". The management of the land and any future climatic warming may increase these emissions.

Lal [120] reviewed the available information on energy use in farm operations and converted the data into kilograms of carbon equivalent (kg CE) shown in Table 2.3. The kg CE value is directly related to the rate of enrichment of atmospheric CO_2.

The energy use in irrigation is the highest among the farm operations. Lift heights obviously depend on the water depth and the energy differs with the pumping pressures and. The values quoted on the table are for water from deep wells used for surface irrigation which includes the energy in terms of electricity, diesel, gasoline, natural gas, LPG and installation costs.

Table 2.3: Energy use in various farm operations [120] – data from abstract.

Operation	kg CE/ha	Notes
Tillage	2-20	Not included in totals below
Conventional till	35.3	Included in highest total below
Chisel till	7.9	Not included in totals below
No-till seed bed preparation	5.8	Included in lowest total below
Spraying chemicals	1.0-1.4	
Drilling or seeding	2-4	
Combine harvesting	6-12	
Fertiliser (N)	0.9-1.8	
Fertiliser (P_2O_5)	0.1-0.3	
Fertiliser (K_2O)	0.1-0.2	
Fertiliser (lime)	0.03-0.23	
Herbicides (active ingredients)	6.3	
Insecticides (active ingredients)	5.1	
Fungicides (active ingredients)	3.9	
Irrigation (apply 25 cm water)	31-227	From deep wells and/or sprinklers
Irrigation (apply 50 cm water)	66-453	From deep wells and/or sprinklers
Lowest possible total	**62.23**	**Each appropriate item …**
Highest possible total	**513.73**	**… included only once**

West and Marland [60] report that average data for the USA suggests that conversion from Conventional Tillage to No Till will result in sequestration of 337±108 kg C $ha^{-1}y^{-1}$ in agricultural soils to a depth of 300 mm. Further following such a change, the total change in flux of CO_2 to the atmosphere on non-irrigated crops is expected to be about 368 kg C $ha^{-1}y^{-1}$.

Global Warming Potential (GWP) [13, 14] is calculated for each of the different green house gases and expressed relative to the CO_2 which is therefore defined as unity.

2.13. Depletion of Resources

ISO/TR14047:2003(E) [12] includes both abiotic (non-biological) and biotic resources within this category. Van Oers et al [121] consider abiotic resources to include both non-renewable and renewable resources and define an abiotic depletion potential (depletion of availability) for non-renewable resources as "not replenished or broken down by geologic forces within a period of 500 years". They divide abiotic resources into three categories:

1. Deposits (resources that are not regenerated within human lifetimes, e.g. minerals, sediments, clays and fossil fuels).
2. Funds (resources that can be regenerated within human lifetimes, e.g. groundwater and some soils),
3. Flows (resources that are constantly regenerated, e.g. solar energy, wind and river water)

and suggest that it "is debateable whether all three types of abiotic resource can or should be aggregated into one measure for abiotic depletion".

They further divide deposits into Groups:

I. Primary materials for industrial processing, including both (a) the atomic elements, and (b) compounds (called "configurations" in their paper, which has specific physical-chemical composition e.g. silicon oxide, feldspar and gypsum)

II. Primary materials for building applications (e.g. stone and construction sand),

III. Energy carriers (e.g. oil and natural gas).

Group I materials may have many heterogeneous functions (e.g. transparency or electrical conductivity), including some not anticipated by the current generation that may arise from future technological developments. Groups II and III can be regarded as “substitutes”: if one form is scarce, then another material can be used (e.g. brick as a replacement for stone or alloys used as structural materials can be replaced by composite materials containing polymer and resins).

Van Oers et al [121] suggest that reserves may be found in nature, in the economy (e.g. within consumer goods) and in landfills. Materials in the economy (e.g. copper in electrical wires) can be an appropriate source of materials, minimising the depletion of primary stocks, subject to economic conditions. They redefine abiotic resource depletion as “the decrease of availability of *functions* of resources, both in the environment *and the economy*”. Materials in landfill may be a richer source of particular elements than those in nature but may be less accessible as a resource due to technological and economic conditions or to the potential for greater environmental impacts than when extracting the elements directly from primary resources. Loss in quality of materials should be considered as a loss of function.

Sand used in glass fibre production is naturally occurring and although abundant it is a non-renewable resource which should be conserved by reduced use [73]. Both quartz and feldspar are used in the manufacture of glass, and feldspar is used in the manufacture of fertilisers. The ultimate reserves of these minerals within the top 1 km of the earth's crust are 5×10^{20} and 1×10^{20} kg respectively [121]. The relative contribution (based on the normalisation data for the global extraction of elements and compounds) to the depletion of abiotic resources is effectively zero.

Depletion of biotic resources is a complex issue closely related to Ecotoxicity. At its most dramatic, this issue manifests itself as loss of biodiversity and in the limit as the extinction of plant and animal species. However, as with abiotic resources, loss in quality of life forms should be considered as one part of the depletion of the total resource; reduced fertility of a species may ultimately lead to extinction when other external factors combine to exert undue pressure. The direct loss of habitat is associated with some dredging operations in sand extraction in production of glass fibre. Dredging activities are known to affect the reproductive success of some species such as herring, that are known to spawn on gravel sediments in a very few, highly specific locations [73]. They are thus vulnerable to the impacts of aggregate extraction. Clearing of extraction areas and also the operations as a whole for the on-land processes, significantly reduce habitats and bio-diversity for the duration of the operations.

Soil consists of a mixture of small particles of various minerals together with organic materials and micro-organisms. Soil also contains water and air in variable amounts. The proportions of each component vary with geographical location and over time. The fertility of the soil can also be influenced by the presence of larger animals (from earthworms to burrowing mammals). Soil depletion hence crosses the boundary between abiotic and biotic resources. Intensive farming using inorganic fertilisers (mainly of nitrogen, phosphorus and potassium, often referred to as NPK) with some lime (Ca) and iron (Fe) may not replace key trace elements in the soil. Herbicides and insecticides may inadvertently affect beneficial organisms (e.g. plants with nitrogen-fixing nodules on the roots or microorganisms).

Zwerman and de Haan [122] reviewed the significance of the soil in environmental quality improvement outlining the plant and animal ecology and the impact of agriculture and industry upon them. They discussed remedial measures necessary to maintain and/or improve this environment. They state that data exist to show that overfertilisation actually decreases crop yield under a wide range of conditions.

O'Sullivan and Simota [123] have reviewed the problems of combining soil compaction models with crop production and environmental impact models. Håkansson and Lipiec [124] have reviewed the use of relative bulk density values in the study of soil structure and compaction. The "degree of compactness" was found to be more useful than either bulk density or porosity parameters when studying biological effects of soil compaction. This parameter facilitates modelling of soil and crop responses to machinery traffic.

Reeves [125] has reviewed the lessons learnt from long-term continuous cropping systems and found that maintenance and improvement of soil quality was critical in the context of sustaining agricultural productivity and environmental quality for future generations. Even with crop rotation and manure additions, continuous cropping results in a decline in soil organic carbon (SOC) – a key soil quality indicator. Loveland and Webb [126] undertook a review of the critical level of soil organic matter (SOM, with an equivalence of 2% SOC ≈ 3.4% SOM) in agricultural soils in temperate regions but their analysis proved inconclusive.

Reeves [125] suggests that long-term conservation tillage (practices which reduce losses of soil and water when compared to conventional unridged or clean tillage) can sustain or actually increase SOC in intensive cropping systems within climatic limits. Agronomic productivity and economic sustainability have a more critical requirement for sound rotation practices in conservation tillage systems relative to conventional tillage systems. Sturz et al [127] observe that conservation tillage tends to concentrate plant debris and consequently microbial biomass in the top 50-150 mm of soil and could promote the survival of pathogens in humid climates. They reviewed plant diseases, pathogen interactions and microbial antagonisms in these circumstances and found that while conventional wisdom still favours the expectation of increased plant disease development, the literature is contradictory in respect of promotion or suppression of the problem. Rasmussen [128] reviewed the impact of ploughless soil tillage on yield [wheat, rape and potatoes] and soil quality in the four Scandinavian countries. Ploughless soil tillage (PST) resulted in a decrease in the volume of macropores (drainable pores) and an increase in the volume of medium (waterholding) pores with no significant effect on small (non-available water) pores. PST resulted in reduced infiltration of air and water, more plant residues on or near the soil surface (hence higher water content in the upper soil layer, lower evapotranspiration, lower soil temperature and more stable soil aggregates), increased activity and biomass of some earthworms and reduced erosion. There was also a long-term reduction in soil pH.

Karlen et al [129] have defined a framework for soil quality which requires identification of critical soil functions, selection of meaningful indicators for those functions, development of appropriate scoring functions to interpret the indicators for various soil resources, and combination of that information into values that can be tracked over time to determine if the soil resources are being sustained, degraded or aggraded. Their review provides background for land managers, resource conservationists, ecologists, soil scientists and others seeking tools to help ensure that land-use decisions and practices are sustainable.

Non-renewable/Abiotic Resource Depletion Potential (NRADP) [13, 14] is calculated for fossil fuels, metals and minerals by dividing the quantity of resource used by the estimated total world reserves of that resource.

2.14. Ozone Depletion

Ozone is formed and depleted naturally in the earth's stratosphere (between 15-40 km above the earth's surface). As the ozone in the stratosphere is reduced more of the ultraviolet rays in sunlight can reach the earth's surface affecting health of humans, animals and plants [130]. Large ozone depletions in the stratospheric zone was first reported by the Farman et al in 1985 [131]. The depletion of the global ozone layer has emerged as one of the major global scientific and environmental issues of the twentieth century.

Halocarbon compounds are persistent synthetic halogen containing organic molecules that can reach the stratosphere leading to more rapid depletion of the ozone. Chlorfluorocarbons are a family of non-reactive, nonflammable gases and volatile liquids, which were widely used in refrigerators, air-conditioners and spray cans. The Montreal Protocol banning CFCs was signed by leading industrial nations in 1987, based on negotiations started between European-Scandinavian countries and the US over CFC's in aerosol sprays in 1983. The protocol has gone through a series of revisions (each one named after the city where the revision committee met) as new information from science and industry has become available. Scientists believe, the dramatic reduction in the production of chlorofluorocarbons (CFCs) will eventually reduce the ozone hole and a complete recovery is possible with time [132, 133].

Ravinshankara et al [134] reported that anthropogenic N_2O is now the single most important ozone-depleting emission and is expected to remain the largest throughout the 21st century. N_2O is unregulated by the Montreal Protocol. Limiting future N_2O emissions would enhance the recovery of the ozone layer from its depleted state and would also reduce the anthropogenic forcing of the climate system.

The new report published by the United Nations Environment Programme following the Scientific Assessment of Ozone Depletion 2010 [135], highlights the effects of climate change on the ozone layer, as well as the impact of ozone changes on the Earth's climate. It also claims that the Montreal Protocol is a success and it has protected the stratospheric ozone layer from much higher levels of depletion by phasing out production and consumption of ozone depleting substances. Changes in climate are expected to have an increasing influence on stratospheric ozone in the coming decades, and these changes derive principally from the emissions of long-lived greenhouse gases, mainly carbon dioxide, associated with human activities.

The key findings on the ozone layer from the scientific assessment were:

1. Over the past decade, global, Arctic and Antarctic ozone is no longer decreasing but is not yet increasing.
2. As a result of the phase-out of ozone depleting substances under the Montreal Protocol, the ozone layer outside the Polar Regions is projected to recover to its pre-1980 levels some time before the middle of this century.

3. In contrast, the springtime ozone hole over the Antarctic is expected to recover much later.
4. The impact of the Antarctic ozone hole on surface climate is becoming evident, leading to important changes in surface temperature and wind patterns.
5. It is reaffirmed that at mid-latitudes, surface UV radiation has been about constant over the last decade.
6. In Antarctica, large UV levels continue to be seen when the springtime ozone hole is large.

Ozone Depletion Potential (ODP) [13, 14] indicates the potential for emissions of chlorofluorocarbon (CFC) compounds and other halogenated hydrocarbons to deplete the ozone layer.

2.15. Photo-Chemical Oxidants

Photochemical Ozone Formation results from the degradation of volatile organic compounds (VOCs) in the presence of sun light and the oxides of nitrogen (NO_x). Excess ozone can lead to damaged plant leaf surfaces, discolouration, reduced photosynthetic function and ultimately death of the leaf and finally the whole plant. In animals, it can lead to severe respiratory problems and eye irritation.

Photochemical Oxidants Creation Potential (POCP) [13, 14] is related to the potential for VOCs and oxides of nitrogen to generate photochemical or summer smog. It is usually expressed relative to the POCP classification factor for ethylene. Methane, which is a significant proportion of the gas produced by decomposing organic materials, has a classification factor for photochemical oxidation of 0.007 relative to ethylene [13, 14].

2.16. Other Factors

In natural fibre production, there are number of other factors to be considered such as land occupation, water usage, noise and vibration, odour and loss of biodiversity. According to Dornburg et al [136], in the analysis and system extension of life cycle assessment studies, few studies took into account the land demand in their assessment of environmental impacts. Furthermore the studies suggested that to address the land use, the area of medium quality agricultural land occupied for biomass production should be used as a functional unit.

Irrigation of flax is regarded as complementary but secondary in cultivation. On well structured, moisture retentive soils, flax is regarded as low priority for irrigation [57]. Water is used in retting and results in odour due to methane production in the retting process. Noise and vibration result from agricultural equipment and fibre processing machinery. Loss of biodiversity closely echoes eco-toxicity and this is mainly due to the fertiliser and pesticides (insecticides, herbicides and fungicides) used in the crop production.

Best environmental practice: Stoate [105] has reported that the direction of cultivation appears to be the overriding influence on how much run-off, soil and phosphorus leaves the field: cultivating across slopes (rather than up and down) and adopting a minimum-tillage system could help to improve water quality, albeit that there are issues in implementing this practice with current agricultural machinery. Further, rough grass buffer strips between arable land and streams can prevent run-off from fields, especially where small pools catch the sediment before it enters the watercourse. The legally permissible buffer zones are defined in for example DEFRA/PSD documents [137].

In glass fibre production, factors such as air quality, noise, loss of biodiversity and water quality should be also considered. The transportation stages provide the main negative impacts on air quality with possible impacts also arising from any particulates generated during the processing stages e.g. crushing and screening stages. Other handling stages in the crushed form may also pose an impact. Associated noises derive largely from transport activities, sand excavation and machinery used in production. Noise levels greater than 70dB during the day or 45dB at night are considered to be annoying to people [73]. Sand dredging is also implicated in loss of biodiversity. Significant reductions in biodiversity during the operations were noticed [73] and carefully planned restoration may actually increase biodiversity. Surface water hydrology is affected in many ways and in various stages of operations. The on-site structures, either during extraction or during processing, often result in soil compaction resulting in increased surface runoffs [73]. In some areas this can result in an increased flood risk. Washing and dewatering of the extracted sand may also present a potential problem especially when sand is from saline environments.

Most of these factors are discussed in detail in Chapter 8.

2.17. Summary

The environmental burdens arising from the production cycle of flax fibres from growth to the fibre extraction and glass fibres from raw material extraction to fibre formation has been reviewed. Life Cycle Assessment according to the ISO 14040 series of standards has been identified as the best method to assess the environmental impacts of the production processes. Eight environmental classification factors are selected to measure the potential environmental burdens in the Life Cycle Impact Assessment. The literature on potential impacts within the eight categories and other factors are thoroughly studied and presented in this chapter. The studies carried out on Life Cycle Assessments by various researchers are also reviewed and some of the identified results are presented.

The next chapter discusses the approach of Life Cycle Assessment study in the production of reinforcement fibres.

Chapter 3. Research Methodology

This chapter discusses the methodology used in the crop growth and fibre processing phases of the production of flax fibres and the glass fibre manufacturing processes to evaluate the environmental impacts.

This research aims to quantify the environmental impacts associated with natural fibre production as many believe that using products based on biological resources (cellulose) are much more sustainable than products based on natural mineral resources such as glass fibres [138-148]. For a proper judgement, it is necessary to study the production processes of both natural fibre and glass fibre with their respective environmental impacts over the full life cycle.

3.1 Life Cycle Assessment

Quantitative Life Cycle Assessment (QLCA) is identified as the best route to establish the sustainability of natural fibres for the reinforcement of polymer matrix composites. The four stages of LCA and the methodology are as discussed in Section 2.7.

Flax is chosen as the candidate fibre in this study because it is a temperate zone plant and one of the most agro-chemical intensive among the bast fibres. Therefore the other bast fibres should be "greener" provided the yield/hectare and mechanical performance are satisfactory. Initially the generic method of flax fibre production was studied and flow charts were created to analyse both inputs and outputs at each stage of the production.

The Qualitative Life Cycle Assessment was then carried out step by step and environmental impact classification factors were weighted using a colour coded matrix for the production of flax fibre and glass fibre using a thorough literature survey (without assigning quantitative values) as shown in Tables 3.1 and 3.2 using the key at Table 3.3.

Table 3.1 Environmental impact classification factors for flax fibre production.

Environmental Impact Classification Factor	Tillage	Sowing	Herbicides	Insecticides	Fertiliser	Dessication	Harvest	Retting	Scutching	Hackling	Spinning
Acidification Potential (AP)	Yellow	Yellow	Yellow	Yellow	Red	Red	Yellow	Yellow	Green	Green	Green
Aquatic Toxicity Potential (ATP)	Green	Green	Red	Red	Red	Red	Green	Yellow	Green	Green	Green
Eutrophication Potential (EP)	Yellow	Yellow	Red	Red	Red	Red	Green	Red	Green	Green	Green
Global Warming Potential (GWP)	Red	Red	Red	Red	Red	Red	Red	Green	Yellow	Yellow	Yellow
Human Toxicity Potential (HTP)	Green	Green	Red	Red	Red	Red	Green	Green	Green	Yellow	Yellow
Non-Renewable/Abiotic Resource Depletion (NRADP)	Red	Red	Red	Red	Red	Red	Red	Green	Yellow	Yellow	Yellow
Ozone Depletion Potential (ODP)	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Photochemical Oxidants Creation Potential (POCP)	Green	Green	Yellow	Yellow	Yellow	Yellow	Green	Green	Green	Green	Green
Noise and Vibration	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Green	Yellow	Yellow	Yellow
Odour	Green	Green	Green	Green	Yellow	Green	Green	Red	Green	Green	Green
Loss of biodiversity	Yellow	Green	Red	Red	Yellow	Yellow	Green	Red	Green	Green	Green

Table 3.2. Environmental impact classification factors for glass fibre production.

Environmental Impact Classification Factor	Raw material handling	Crushing	Weighing	Mixing	Melting	Refining	Forming	Sizing	Binding	Spinning	Oven Drying	Oven Curing
Acidification Potential (AP)	Green	Green	Green	Green	Yellow	Green	Green	Green	Green	Green	Green	Green
Aquatic Toxicity Potential (ATP)	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Eutrophication Potential (EP)	Green	Green	Green	Green	Yellow	Green	Green	Green	Green	Green	Green	Green
Global Warming Potential (GWP)	Red	Red	Green	Red	Red	Red	Red	Yellow	Yellow	Yellow	Red	Red
Human Toxicity Potential (HTP)	Red	Red	Red	Red	Green	Red	Red	Red	Green	Yellow	Green	Green
Non-Renewable/Abiotic Resource Depletion (NRADP)	Red	Red	Yellow	Yellow	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Red	Red
Ozone Depletion Potential (ODP)	Green	Green	Green	Green	Green	Green	Green	Yellow	Green	Green	Green	Green
Photochemical Oxidants Creation Potential (POCP)	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green
Noise and Vibration	Yellow	Yellow	Green	Yellow	Green	Green	Yellow	Green	Green	Yellow	Green	Green
Odour	Green	Green	Green	Green	Yellow	Green	Green	Green	Green	Green	Green	Green
Loss of biodiversity	Green	Green	Green	Green	Yellow	Green	Green	Green	Green	Green	Green	Green
Fugitive Dust	Red	Red	Red	Red	Green	Red	Red	Red	Green	Red	Green	Green

Table 3.3 Key for above tables

KEY	
Very High Effect	Red
Low Effect	Yellow
No Effect	Green

The first step in LCA was to define the goal and scope of the study to be carried out. This includes intended application, reasons for carrying out the study, the intended audience and whether the results of the study are intended to be communicated [76]. In defining the scope of the study, the items considered and clearly described are the production system to be studied, the functions of the product system, the functional unit, the system boundary, allocation procedures, LCIA methodology and types of impact, interpretation to be used, data requirements, assumptions, limitations, elements of data requirement, value choices and optional elements, data quality requirements, type of critical review and type and format of the report required. For this study these items are discussed in Chapter 4.

3.2 Data Accumulation – Agricultural Phase

The data were collected from numerous literature sources [86, 87, 149-156] to complete the Life Cycle Inventory for the flax fibre production. These data sources include peer reviewed journal articles, reports, conference proceedings, websites and various other sources. Data for the energy use was collected in two phases (crop production and fibre processing) and recorded in a database using MS Excel. The operations considered in crop production are ploughing, harrowing, cultivating, fertiliser and pesticides application, harvesting using mower, swather and baler as shown in Figure 3.1.

The problem in obtaining data from the literature is the variable quality, arising from old data and geographically differing agricultural practices. Data from some literature sources are more than 10 years old, for example references [149, 151]. Therefore, it was assumed that agricultural practices have not changed significantly in the last decade and they do not differ geographically. Further, the location dependent agricultural practices may cause inaccurate estimations of fertiliser and pesticides levels use. This is a major difficulty in obtaining a generic dataset. Some of the values recorded are not specific for growing flax, but when checked against a study specifically for flax the values are very similar. Five or more data points were obtained for each specific operation from the literature and where there was no or minimal consistency the numbers were checked with original references to identify the reason for the differences (Appendix B).

There is more than one method used in practice to carry out each of these agricultural operations as shown in Figure 3.1.

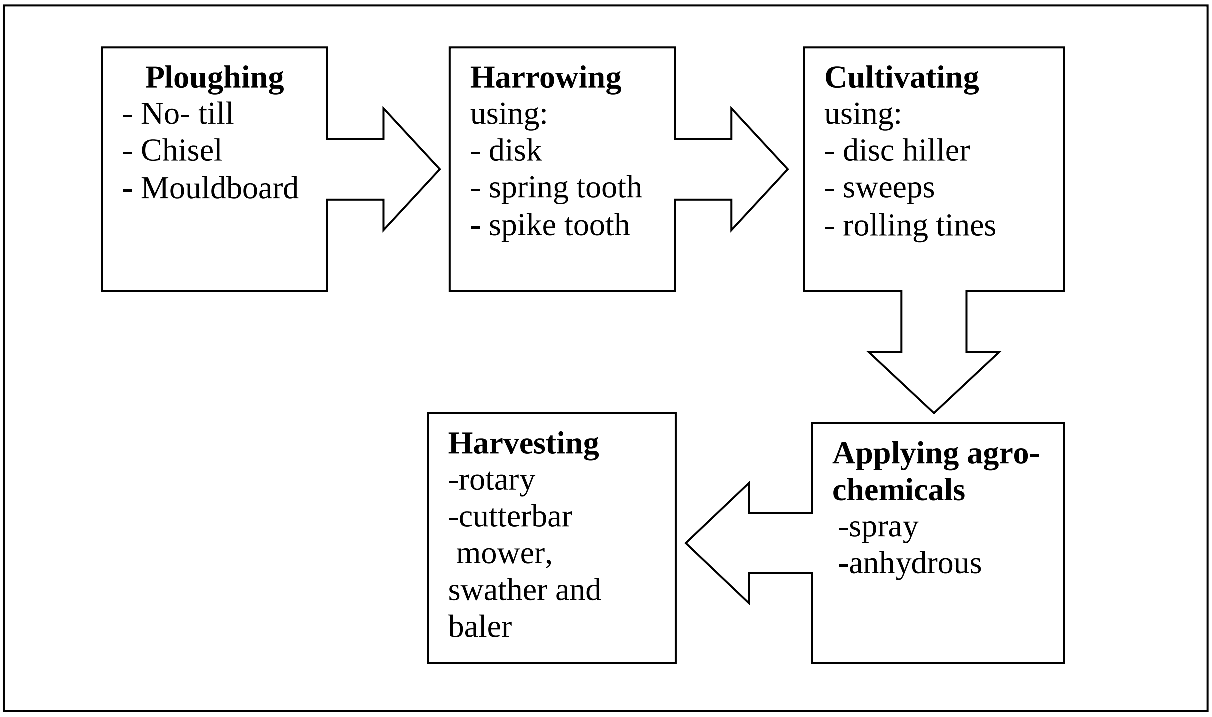

Figure 3.1 Options considered in crop production phase (Growth phase is omitted from the figure)

Significant differences in the values of energy consumption were noticed between three methods of ploughing, no-till, conservation (chisel ploughing) and conventional (mouldboard ploughing). Therefore, three final data sets for crop production were created using the low, medium and high energy demands from each of the stages illustrated in Figure 3.1.

The production of agro-chemicals such as lime, N (Nitrogen), P (Phosphorus) and K (Potassium) fertilisers and pesticides used in flax production is included within the system boundary. A similar approach was used to collect the data for embodied energy values for fertiliser and pesticides. About seven data points are used to calculate an arithmetic mean and this value was used in this study. The average embodied energy of insecticides, fungicides and herbicides was used as the embodied energy for pesticides (Appendix C). Flax is regarded as a plant which does not need irrigating [50] in UK therefore such water use is not included in the crop production phase of this study.

3.3 Data Accumulation – Fibre Processing

Fibre extraction operations of retting and decortication/scutching and fibre preparation/processing operations such as hackling and spinning are considered in this section as given in Figure 3.2. Collecting data for fibre processing from real life sources and literature was extremely difficult. The data for fibre processing techniques used specifically for flax are not readily available. Initially, the researcher attempted to collect some real life data for flax production and processing by a questionnaire, but flax growers and fibre processing plants could not be identified within UK. At the start of the project there was an expectation that there would be collaboration with the Fibre Developments Limited in Launceston (a fibre processing plant in Cornwall), but that operation ceased when the owner died intestate.

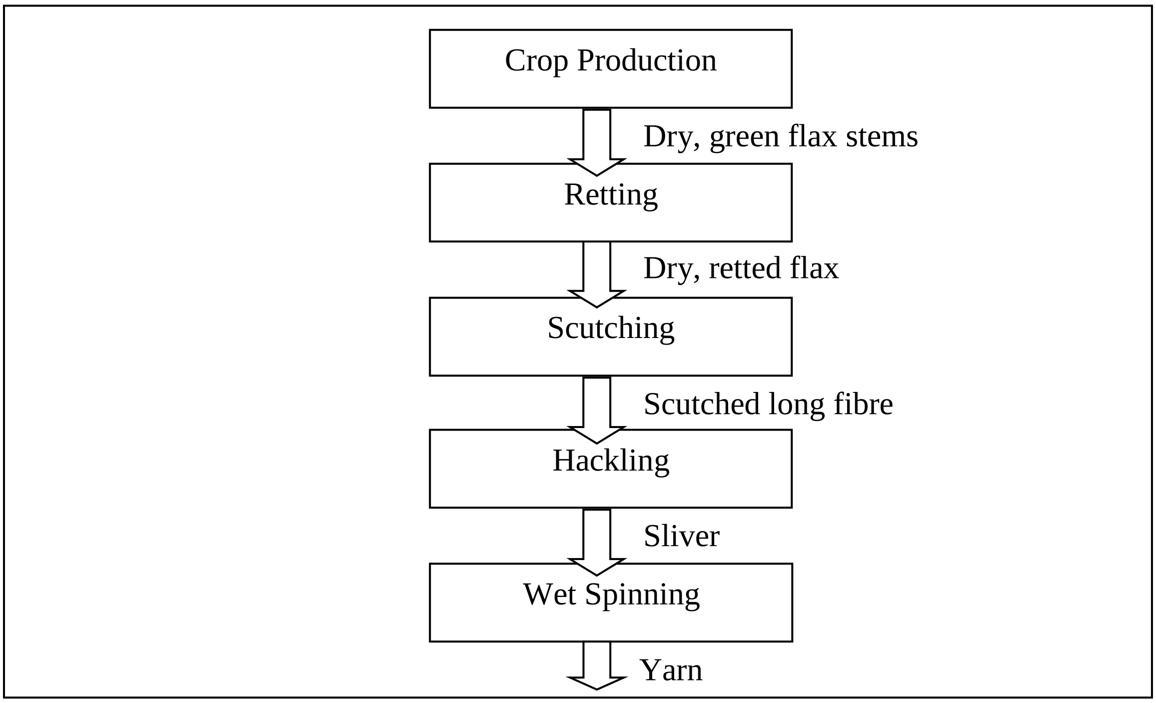

Figure 3.2 Flax fibre production phases

The values for energy consumption at each of these stages are obtained from a single study of flax fibre yarn production by Turunen and van der Werf [86, 87]. Their study aimed to quantify major impacts associated with the production of hemp, flax and baby hemp yarn using LCA methodology. For hemp crop production, a generic Central European scenario was sketched based on the crop production practices in Hungary and France. The traditional warm water retting method for hemp fibre was treated as the reference based on the current practices in Hungary. The flax crop scenario was based on the production practices in France, Belgium and the Netherlands which are at the leading edge of European flax production. They compared three scenarios with the reference (warm water retting of hemp):

i. Bio-retting of hemp
ii. Stand/dew retting of baby hemp (pre mature hemp)
iii. Stand/dew retting of flax

Bio-retting involves post harvest field operations, green scutching and hackling. Stand/dew retting involves dessication, post harvest field operations and hackling. The hackling process differs with the type of fibre. Wet ring spinning technology (commonly used in the production of fine bast fibre yarns) was considered and the process was identical for all scenarios. The other processing stages considered in yarn production were preparation and bleaching. The appropriate data for the study was sourced from project partners, producers and experts. This was complemented by the literature sources [85, 86] and the impact assessment was carried out with the aid of computer software SimaPro 5.1 (developed by Pre Consultants, The Netherlands).

A bottom up approach was used to calculate the energy consumption for the production of flax fibre from the study carried out by Turunen and van der Werf [86, 87]. The final product was taken as one tonne of flax sliver/yarn (the functional unit) to calculate the energy production in spinning, hackling, scutching and retting respectively, considering the mass loss from each operation. The process of preparation (converting sliver to rove) and bleaching stages were not included in this analysis. After back-calculation to determine the amount of green flax stems required to produce the final product, the energy required in crop production (agricultural operations, fertilisers, pesticides etc) was proportioned accordingly from the data extracted from literature.

In the absence of data specific to flax fibre, warm water retting and bio-retting of hemp are considered to have similar energy requirements per tonne of flax fibre. Three methods of retting considered in this study are warm water retting, stand/dew retting and bio-retting. The post-retting processing method changes with the respective retting method used. The amount of diesel, electricity or natural gas consumption at each stage is used for energy calculations. These values are proportioned according to the input at each processing operation. The electricity consumption is assumed to be supplied from a balance of generation facilities reflecting the proportions in the UK national supply.

Where a fibre producer can clearly demonstrate a higher proportion of energy taken from renewable resources, then the global warming potential (GWP) will be reduced along with other burdens associated with the generation route.

A further limitation in this study is that the energy used by textile processing equipment varies considerably with the nature of the fibre processed [157]. This LCA study is incomplete in this respect and will need further improvement with regard to the clarity of the data used in the analysis, location of the crop production and climate. The initial desire was to compare the flax fibre with glass fibre production by two quantitative LCAs. It was not possible to identify the data sources for the reference glass fibre production LCA. Therefore, the comparison with glass fibre is based on values from published sources and the EcoInvent LCA database (the software is described in Table 2.1, Page 32) [84, 158].

3.4 Calculation of Environmental Impact Potentials

The emissions associated with each input (diesel, electricity, fertiliser and pesticides) were identified and obtained from various literature sources as given in Appendix E. These values were recorded on an MS Excel spread sheet and LCI was completed according to the functional unit of one tonne of flax fibre which can be used for reinforcement in polymer matrix composites.

The method identified to calculate the eight environmental impact potentials used the equations defined by Adiza Azapagic [13, 14]. No commercial computer software was available for the calculations beyond MS Excel. Azapagic [13, 14] has defined classification factors for the environmental potentials that are expressed relative to respective benchmark substances which are then defined as unity as given in Table 3.4.

Table 3.4 Bench mark for the classification factors for environmental potentials

Environmental Potential	Benchmark for the classification factors
Acidification Potential (AP)	SO_2
Eutrophication Potential (EP)	Phosphates (PO_4^{3-})
Global Warming Potential (GWP)	CO_2
Ozone Depletion Potential (ODP)	Trichlorofluoromethane (CFC-11)
Photochemical Oxidants Creations Potential (POCP)	Ethylene

Classification factors for Human Toxicity Potential (HTP) and Aquatic Toxicity Potential (ATP) are not defined using a bench mark and they can only be taken as an indication (not as an absolute measure) of the toxicity potential.

In the impact assessment interpretation of the LCI data, the inventory data are multiplied by the appropriate characterisation factor to calculate the environmental impact potential, E_x , for each factor, x [13, 14] with summation is carried out for each emission or resource consumption j,

$$E_x = \sum_{j=1}^{n} (C_x B_x)_j$$

Eq. (1)

where B_x = burden (release of emission or consumption of resource per functional unit for factor x), and C_x = characterisation factor.

The characterisation factors represent the potential of a single emission or resource consumption to contribute to the respective impact category as given in Appendix G [78]. Seven EICF; acidification, eutrophication, global warming, aquatic and human toxicity, ozone depletion, photochemical oxidants creation potentials, are calculated using Eq. (1).

Non-renewable/abiotic resource depletion potential is calculated using Eq. (2) as an indication against the world reserves of coal, oil and gas.

$$NRADP = \sum_{j=1}^{n} \frac{B_j}{R_j}$$

Eq. (2)

B_j = burden (consumption of resource j per functional unit), and R_j = estimated total world reserves of resource j.

Non-Renewable/Abiotic Resource Depletion Potential (NRADP) was calculated for diesel and electricity usage at each stage of production of flax fibres.

3.5 Selection of scenarios

This section pre-empts the analysis undertaken, but is included here in the interest of clarity in the ensuing text.

Three crop production options (no-till, conservation and conventional) and three available retting options (warm water retting, stand/dew retting and bio-retting) were combined to create three distinct scenarios with their respective minimum, average and maximum energy requirement:

Scenario 1: (minimum energy): No-till and warm water retting

Scenario 2: (average energy): Conservation tillage (chisel ploughing) and stand/dew retting

Scenario 3: (maximum energy): Conventional tillage (mouldboard ploughing) and bio-retting

The complete Life Cycle Inventory Analyses for the above three scenarios are given in Appendices D1, D2 and D3 respectively for the production of flax fibre. Life Cycle Impact Assessments are given in Appendices F1, F2 and F3 respectively for flax fibre. Two products were considered: sliver (compared with glass mat) and yarn (compared with glass roving). Note that the scenarios are selected on the basis of energy use and the ranking of the other EICF may differ.

3.6 Summary

The chapter has discussed the methodology used in carrying out the LCA study and the difficulties in data acquisition. Three crop production methods are considered (according to the ploughing method) and combined with three available retting methods to produce three scenarios for the study (minimum, average and maximum energy requirement in the production) of flax fibres.

The next chapter focuses on the initial step of the LCA study, goal and scope definition.

Chapter 4. Definition of Goal and Scope

The Life Cycle Assessment (LCA) has been carried out according to the ISO14040:2006 [76]. The framework outlines four stages in the LCA as shown in figure 2.14 (Chapter 2). The current chapter focuses on the definition of goal and scope in this LCA study.

4.1 Goal of the study

The goal of the study is Life Cycle Assessment to evaluate the environmental impacts associated with natural fibre when used as reinforcement in polymer matrix composites. The analysis may subsequently be used to establish best practice. This study also aims to determine whether the substitution of glass fibres with natural fibres is truly environmentally beneficial. Flax is chosen as the candidate fibre in this study because it is a temperate zone plant and one of the most agro-chemical intensive among the bast fibres. Therefore the other bast fibres should be "greener" provided the yield per hectare and mechanical performance are comparable to flax.

This study considers the flax fibre production including the agricultural operations and fibre processing operations and compares the flax fibre sliver (product for mat reinforcement) and yarn (product for aligned reinforcement) as the final product in three scenarios.

4.2 Scope of the study

4.2.1 The product system

The product system under investigation includes agricultural operations from preparing the ground through to harvest, fibre extraction (retting and decortication), fibre preparation (hackling and carding) and yarn processing (spinning or finishing) operations for flax fibres.

4.2.2 The functional unit

The functional unit has to be a clearly defined measure of performance which the system delivers [76]. For this study, the functional unit is defined as “one tonne of fibres ready for reinforcement in a polymer matrix composite”. The design of commercial composites is normally stiffness-limited therefore the specific tensile modulus is the chosen parameter. Flax fibre (E = 42GPa, ρ = 1500kgm^{-3}) and glass fibre (E = 70GPa, ρ = 2500kgm^{-3}) have the same numerical value for E/ρ.

4.2.3 System Boundary

The scope of this study is limited to cradle-to-gate and the agricultural boundary ideally starts from the farm gate and stops at the composite factory gate, following the principles of ISO14040 series of international standards for LCA. The production of agricultural products such as fertiliser (N, P and K) and pesticides is included within the system boundary. The use phase and disposal and sequestration of CO_2 by plant growth are outside the system boundary.

4.2.4 Allocation Procedures

Allocation is the partitioning of input or output flows of a unit process to the product system under study, as stated in ISO14040. Allocation within this study was conducted on a mass allocation basis as recommended in ISO 14041.

The flax long fibre remains as the high value product through the analysis and co-products such as short fibre, shive, dust and coarse plant residues are assumed to have economical value which simply covers their processing costs after separation from the reinforcement fibres. In consequence, co-products, disposal costs and environmental effects for these elements are not included.

Agricultural land occupation, human labour and transport were excluded from the study.

4.2.5 Data requirements & data quality requirements

The inventory step combines data on the flows of energy and material entering the system and corresponding energy and materials being emitted into the environment both inside and outside the system. For this study, the input and output data were quantified or derived using one or more values from the literature. Inputs considered within the production system include seeds, fertiliser, pesticides, water, diesel and electricity. Co-products, waste, emissions into water and air are considered as outputs (Figure 4.1). The emissions are mainly from diesel combustion, electricity generation, chemical fertiliser and pesticides production and application.

4.2.6 Impact assessment categories and methodology

The emissions are used in Life Cycle Impact Assessment (LCIA) to calculate the eight environmental impact classification factors (EICF) as listed in ISO/TR 14047:2003 [159]. The EICFs are more coherently defined by Azapagic [13, 14] using different terminology and with equations to inform an analytical method.

The eight environmental impact classification factors are given in Page 5, Chapter 1.

An indication of the impact potentials was calculated by multiplying the aggregated resource used/emissions (from the LCI) with a classification factor which is substance specific. The classification factors used in this study for each impact category are as defined by Azapagic [13, 14] and given in Appendix G.

4.2.7 Assumptions and Limitations

There were some limitations in carrying out this study based on the available literature sources and some of those limitations have resulted in assumptions. Sometimes these assumptions were made to avoid confusion or to reduce complications of the data sets.

As the LCA study was carried out using the literature sources, it was impossible to define a specific geographical location or the quality and the quantity of the land used. The three scenarios studied are generic UK/European situations and do not represent any single geographical location. The data used in the scenarios are mainly from UK and European sources. During the data collection, it was evident, that agricultural and fibre extraction/preparation processes differ considerably within the same country or continent. The amount of fertiliser and pesticide used is calculated according to the recommendations of the Henfaes Institute, (Bangor, UK) [61]. Therefore, the situation may differ according to the location, climate or the quality and the quantity of the land.

There was no record of the soil quality before planting and after the growth of flax, therefore it was assumed that there is no difference in soil quality and quantity arising from the agricultural stages of flax acquisition. The soil pH value at the beginning of the planting was not known: the lime application is included in all three scenarios in equal amounts. Generally, the application of lime and other nutrients depends on the quality of the soil, which are mainly N, P, K and lime. It was impossible to judge the quantity of weeds and other predation which may affect the flax growth. Therefore, the amounts of herbicides, insecticides and fungicides applied to the field are taken from the study by Turunen and van der Werf [86, 87]. The same level of pesticides (includes herbicides, insecticides and fungicides) were applied in all three scenarios.

The crop rotation and ploughing affects the levels of fertiliser required and could not be included in the analysis due to the absence of a reliable dataset. It was very difficult to identify the previous crop in the field or the depth used in different ploughing methods. The possible environmental impacts relating to the ploughing depth was not included (eg. N leaching).

The ploughing depth in all different methods, individual machine or equipment performance was ignored from the analysis. The energy used in agricultural machinery/equipment construction, production of seed, transportation, storage and man power is not included within the chosen system boundary. The system boundary was selected focusing more on fibre production cycle and the environmental burdens, therefore other sources (energy used in diesel production, electricity generation) were avoided except the fertiliser and pesticides production. The embodied energy and emissions of diesel, electricity, fertiliser and pesticides were included within the system boundary of this study.

Irrigation is not included in the study as it was assumed that the flax plants are grown in normal range/condition where irrigation is not required. Linseed Law does state that irrigation is not required for flax [50]. Effects of extensive irrigation is discussed in Chapter 8 but not included in the analysis.

The long fibres are regarded as the sole high value product through the analysis and the only flax product used as reinforcement in polymer matrix composites. The co-products such as short fibre, shives, dust and coarse plant residues have an economical value which simply covers their processing costs after separation from the reinforcement fibres. These elements (post-separation) can be sold into specific sectors, so wastage (pre-separation) disposal costs or environmental burdens are allocated to the co-product. All other burdens are included in the analysis for flax fibres as reinforcement.

The outputs from this analysis assign all environmental burdens to the flax reinforcement fibre. The data is thus available to others who may wish to apportion burdens on the basis on economic value or of mass, but following this route they should add any burdens arising from post-processing of co-products before reassigning the respective impacts.

A key consideration is that the two fibres compared are (a) flax – very much a material in development for structural engineering applications, produced in batch quantities where the process could be subject to significant improvement and (b) glass – an established material produced from very large continuous processing plants that have been optimised by over half a century of development.

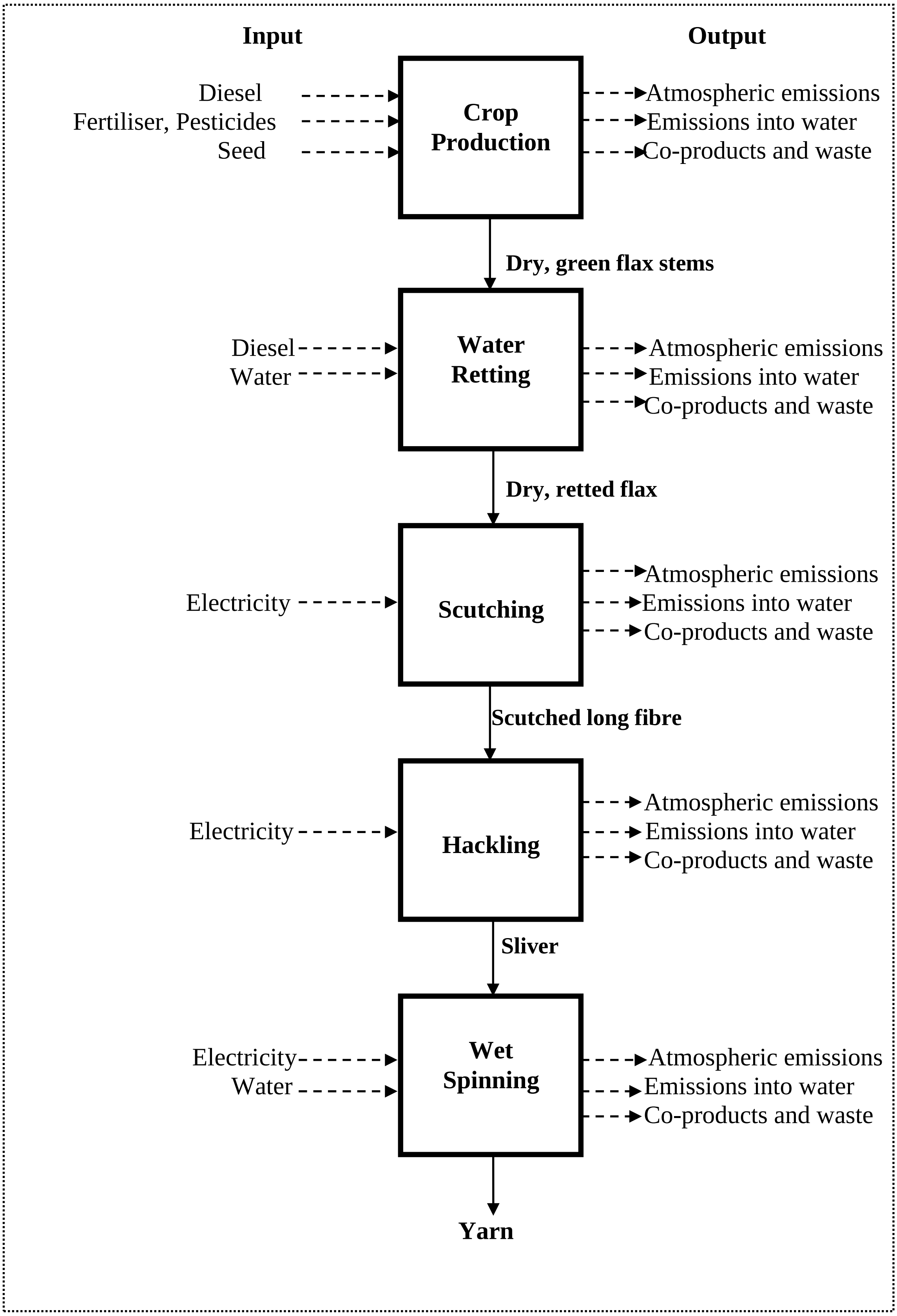

Figure 4.1 Scope and system boundaries for flax fibre production with inputs and outputs

4.3 Summary

The aims and objectives of the study were defined in this chapter according to the LCA frame work. The scope of the study is cradle-to-gate and limitations/assumptions made within the study are clearly stated in this chapter.

The next chapter focuses on the second stage of LCA, Life Cycle Inventory Analysis (LCI).

Chapter 5. Life Cycle Inventory Analysis

This chapter focuses on the life cycle inventory analysis, which is a process of quantifying energy and raw material requirements, atmospheric emissions, emissions into air, co-products, waste and other releases for the entire life cycle of the product.

5.1 Crop Production

To analyse the agricultural operation in the crop production phase of flax, data were obtained from various sources including peer reviewed journals, reports and websites. It has not been possible to identify flax growers in UK, therefore the represented data could not be regarded as regional or national, and the presented analysis is generic to Northern Europe.

Tillage is used to prepare the seedbed and to control weeds. There are different methods of ploughing (tillage) methods in practice:

1) No-till: leaves the soil relatively undisturbed.
2) Conservation tillage: reduced number of passes over the field for land preparation with increased surface residues to protect soil and reduce water loss. This includes single disking, chiselling and sub soiling.
3) Conventional tillage: a full tillage programme combining primary and secondary tillage operations performed in preparing a seedbed [160]. This leaves <15% residue cover after planting and usually involves mouldboard ploughing [60].

Traditional or conventional tillage methods of mouldboard ploughing drastically affect the soil structure, breaking up its natural aggregates and burying the residues of the previous crop. Therefore the bare soil becomes unprotected and exposed to the action of wind and rain [150]. No-till has a minimal disturbance for the soil and the minimal or shallower ploughing requires considerably lower energy. This reduces the soil erosion or run off of soil sediments especially on a sloping field [150]. It was also found that, the reduction in ploughing depth reduces the wheel slip and the fuel consumption [161].

Table 5.1 shows the average energy required (as diesel to operate agricultural tractors etc using values from Appendix A) to plough one hectare of land in 3 different tillage methods of no-till, chisel plough and mouldboard plough. The energy density of diesel is taken as 34.92MJ/l [162]

Table 5.1 Diesel and energy consumption in different tillage methods

	Diesel consumption (l/ha)*	Energy consumption (diesel) MJ/ha
Mouldboard Plough	15.1	527±77
Chisel Plough	8.8	307±87
Pass with no soil tillage	0.94	33±0

*Values are the averages from Appendix B [149-154]

Figure 5.1 shows the average energy consumption (diesel) in 3 different tillage methods.

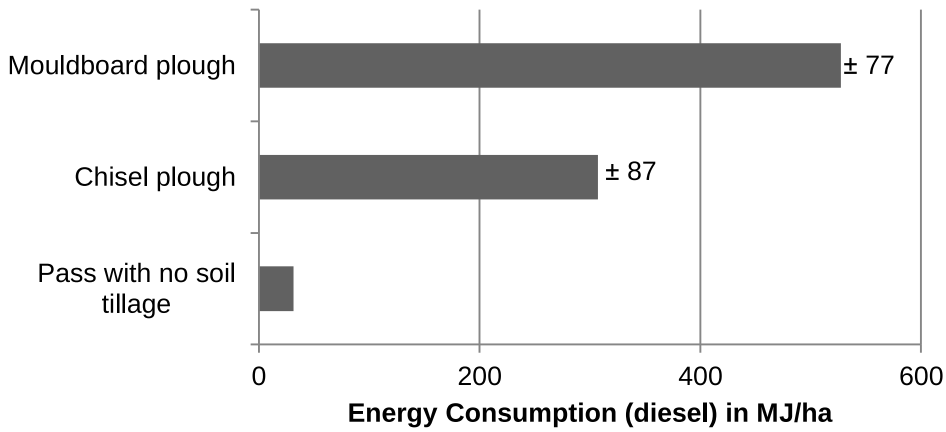

Figure 5.1. Energy consumption in different ploughing methods in MJ/ha

Mouldboard ploughing uses 42% more energy than chisel ploughing and 94% more than the no-till method. Ploughing is normally followed by harrowing (secondary tillage operation) to pulverise the clods of earth and level the soil. Disc harrowing, harrowing, spring tooth and spike tooth are widely used in agriculture and they differ in terms of energy use for the operation. The final stage of the crop production is harvesting, just before the flowering of flax ends using either rotary or cutterbar mower and swather and baler. The data obtained for agricultural operations are recorded and an arithmetic mean value is determined to use in the LCI. (Appendix – B)

The fertiliser levels of N, P, K included in this study are according to the recommendations of Henfaes Institute, Bangor, UK and taken as 40kg/ha of N and 50kg/ha each of $P_2\,O_5$ and K_2O [61]. If the soil pH is below 6, lime is applied before cultivation [61] and application of lime is considered in this study as 666 kg/ha [87], although the specific value of soil pH at the beginning of the cultivation is not known. The level of fertiliser or lime to be applied on a field could not be generalised as this mainly depends on the soil nutrient status. Flax is prone to lodging and it is recommended to provide the crop with no more than the required quantity of nitrogen to avoid this. The control of nitrogen level is very important, as excess nitrogen not only increases the risk of lodging, but also decreases the yield of fibres [53]. Nitrogen fertilisers have the highest embodied energy relative to P and K. Setting the correct level of nitrogen for the crop is important for the reduction of the potential environmental impacts. Sultana stated that K fertiliser is a requirement during flowering and 20% of K was removed from soil [53]. The P is less important even if 50% mineral is removed from the soil [53]. Lime has the risk of damaging growing flax so it is recommended to apply the fertilisers just before sowing. Flax does not remove large quantities of major nutrients from the soil apart from consuming the organic matter from the soil by mineralization of nitrogen. Repeated cultivation will reduce the soil fertility. Sultana stated that it is advisable not to grow flax in the same field at intervals less than 6 to 7 years and considered it as a good crop in the beginning of rotation [53].

Insecticides, herbicides and fungicides are used for flax at a total level of 2.5 kg of pesticides for one hectare. The sprayer was assumed to be used three times to apply each pesticide seperately. The embodied energy of agro-chemicals is given in Appendix C. It was assumed that 115 kg/ha of flax seed was sown and a yield of 6000 kg of dry, green flax stems was achieved from one hectare based on the study by Turunen and van der Werf [86, 87].

5.2 Fibre Processing

Stages of fibre processing differ according to the chosen retting process. There are three methods of retting discussed in this study: warm-water retting, stand/dew retting and bio-retting. An overview of fibre processing after each retting process is shown in Figure 5.2.

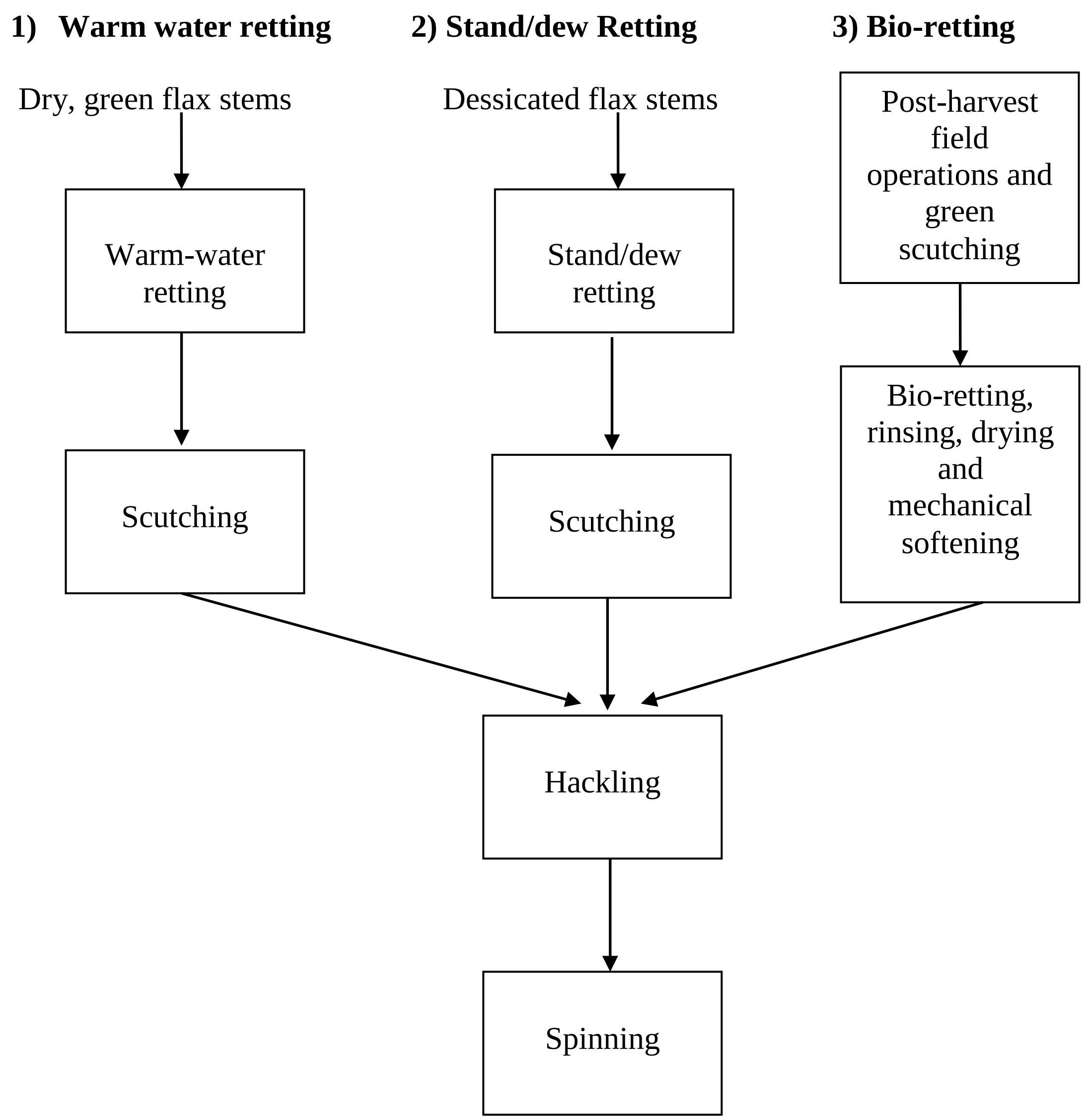

Figure 5.2 Fibre processing stages for different retting methods

Warm water retting is a traditional retting method which relies on natural micro-organisms to function. In warm water retting, natural micro-organisms are provided with good growth conditions (temperature) to grow rapidly [87]. Open concrete retting pools which are filled with water at about 28^{o}C (mixture of heated water about 47^{o}C and ordinary water) and loose bales of flax and then left to ret for 5 days. Mass was lost at retting process and during storage due to spoiling. The retted stems were dried using heat to prevent spoilage and to prepare for scutching as outlined in the study carried out by Turunen and van der Werf [87].

In stand/dew retting, standing crops are dessicated (termination of growth) using glyphosate based herbicides. The application of herbicides should be no later than the mid point flowering stage to achieve both an uniform level of ret on matured fibres and an economical yield [163]. The harvested flax stems are left in the field exposed to rain for several weeks. This process is extremely weather dependent and during that time stems need to be turned several times to facilitate retting. The total energy consumption in stand/dew retting includes the machinery used to turn the stems and the embodied energy in the herbicides used as a dessicant. About 45% of the total mass is lost from stand/dew retting [87].

Scenario-3 is based on the fibre processing method of green scutching followed by bio-retting (biotechnological retting). The stems are left on the field for drying after the harvest and stems are scutched prior to retting (green scutching) by using standard scutching machines. The green scutching process reduces the amount of material to be retted by removing the woody part of the stem, therefore the water consumption is potentially less than the traditional warm water retting process. The principle of bio-retting is similar to warm water retting except that instead of relying on natural bacteria, an inoculum of selected pectinolytic bacteria is added to water to improve retting. The production of the inoculums is not included in the analysis. The temperature is maintained at $35^{o}C$ for 72 hours of retting. The fibre bundles need to be separated as they are glued together after retting. The retted fibre is rinsed with cold, pressurised water and dried using hot air with steam as the heating media. The dried fibre is softened by using a mechanical shaking process to remove remaining shives and short fibre [87]. It was assumed that electricity is used for bio-retting and post-retting processes of rinsing, drying and mechanical softening.

Energy consumption in different retting and subsequent scutching processes are shown in Figure 5.3.

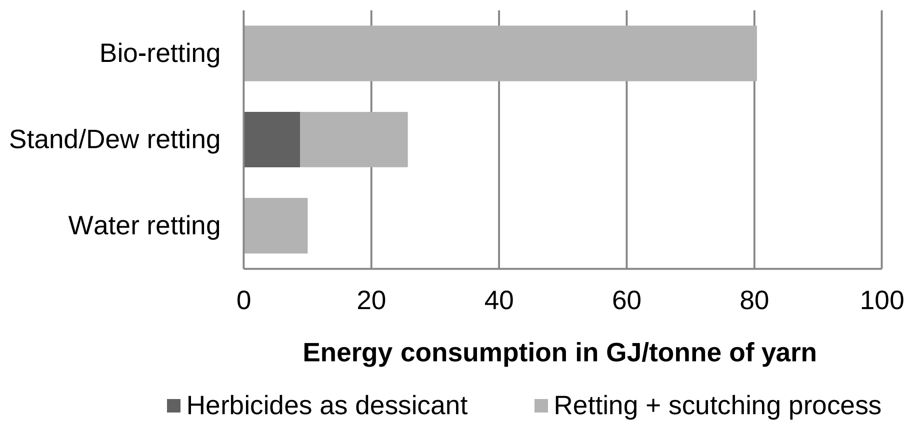

Figure 5.3 Energy consumption in retting and subsequent scutching processes GJ/tonne of yarn [86, 87]

Water retting and stand/dew retting are followed by the mechanical operation called scutching or decortication. This is done by passing the dry retted stems between rollers followed by rotating blades to separate the short fibres and shives from the long fibres [53]. The scutching described in this study was carried out by using a scutching machine, which has a capacity of one tonne of stems per hour by consuming 120kWh of electricity according to the study by Turunen & van der Werf [87]. The scutched long fibre is produced as a result from the scutching process with co-products of short fibre, shives, dust and coarse plant residues. The scutched long fibres are further refined by a process called hackling which produces unaligned fibres called "sliver" and also co-products of short fibre and dust. Fibres are combed with pinned elements (hackles) in a hackling machine. For yarn, the flax sliver is then normally spun by a wet spinning process, which is regarded as a slower and more expensive method than dry spinning [87].

By considering all the options available to produce flax fibres for reinforcement in polymer matrix composites, the LCI focuses on three scenarios.

Scenario 1: No-till and water retting (i.e. lowest energy)

Scenario 2: Conservation till and stand/dew retting (i.e. intermediate energy)

Scenario 3: Conventional till and bio-retting (i.e. highest energy)

The Appendices – D1, D2 and D3 contain the data of the complete LCIs for the production of one tonne of flax sliver and yarn for the three above scenarios respectively based on the study carried out by Turunen and van der Werf [86, 87]. The total energy consumption in the production of one tonne of flax sliver and yarn in each scenario is shown in Figure 5.4.

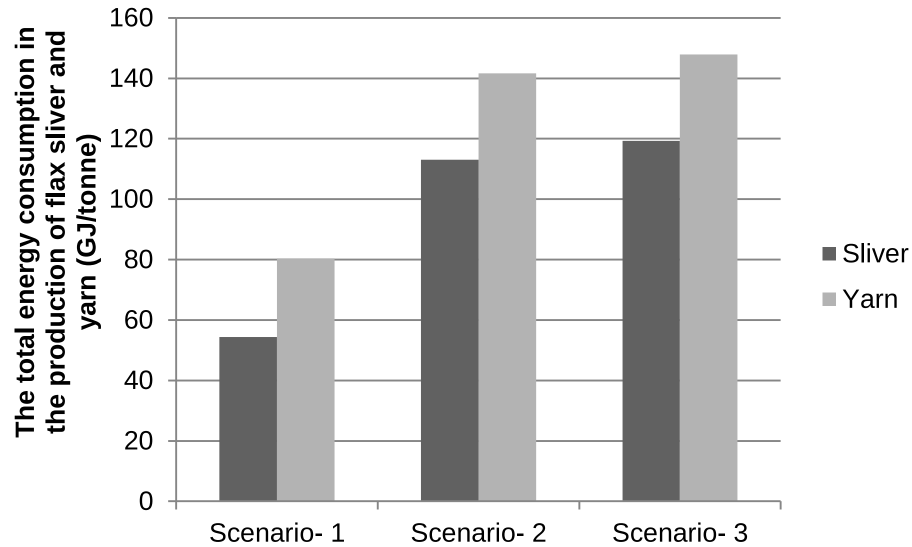

Figure 5.4 The total energy consumption in the production of flax sliver and yarn (GJ/tonne) [86, 87]

5.3 Products and co-products

Co-products such as short fibre and shives are produced from the scutching and hackling processes. These can be easily converted into pulp for production of different grades of paper that can be used for wrapping, packaging, writing and printing purposes [164]. Alternative uses include animal bedding (especially horse bedding), building particle boards and production of cellulosic ethanol [165]. Dust and coarse plant residues are also produced from the above processes that can be collected and consolidated as biomass fuel. The long fibre remains the high value product. Approximately 20% of the mass of green flax stems are lost in the water retting process and 46% in stand/dew retting process. Only 5% of the mass is lost from the bio-retting process and post-retting processes of rinsing, drying and mechanical softening in scenario-3. The mass of the co-products and mass as a percentage of green stems from three scenarios are given in Table 5.2. The final mass as a percentage of green stems does not add up to a total of 100%. The reasons for the unexplained wastage is mainly from handling, storage and operational faults.

Table 5.2 Mass of co-products

(Note that no seed is produced as the plant is harvested while still flowering)

Co-products	Mass per tonne of yarn (kg)	Post-scutching mass as a % of green stems	Final mass as a % green stems
Scenario 1			
Yarn	1000	6	4.5
Short fibre	4496	25	20.4
Shive	7104	40	32.3
Dust	2672	15	12.1
Coarse plant residues	2288	13	10.4
Scenario 2			
Yarn	1000	4	2.3
Short fibre	6157	27	14.4
Shive	9235	40	21.6
Dust	3474	15	8.1
Coarse plant residues	2974	13	7
Scenario 3			
Yarn	1000		5.1
Short fibre	2850		14.6
Shive	8840		45.4
Dust	2335		12
Coarse plant residues	3502		18

The detailed mass loss at each stage in all three scenarios is given in Appendix H [86, 87].

5.4 Emissions from crop production and fibre processing

Primary emissions from the crop production phase are caused by diesel used in agricultural equipment and also from agro-chemicals. The emissions associated with diesel combustion are CO, CO_2, NO_x, SO_2 and NMVOC. Diesel is also used to heat the water in warm water retting and for the tractors to turn the stems to improve the retting in stand/dew retting. The production and use of nitrogen and phosphate fertilisers result in emissions such as CO_2, N_2O, NO_3, NH_3, SO_2 and also nitrate and phosphate leaching causing eutrophication and acidification. Heavy metal emissions such as As, Cu, Cr, Hg, Ni and Zn also result from phosphate fertiliser production. Data associated with emissions of K fertiliser production and application could not be identified. Emissions from pesticides production in UK are used in the calculations of LCI and emissions from pesticides usage could not be identified. Emissions from pesticides production, such as chlorides, dichloride, hydrogen chloride, SO_2, chlorpyrifos, hexachlorocyclohexane and pentachlorophenol compounds are calculated using the emission factors given in Appendix E [166]. CO_2 emissions from calcination of limestone are used to calculate emissions from agricultural lime production, and CO_2 emissions from agricultural lime application are also considered. The emissions associated with diesel, N, P, pesticides and lime production and application are given in Appendix E.

The emissions from fibre processing operations such as scutching, hackling, spinning and bio-retting result from the electricity used to operate the machinery. The estimated fuel usage to produce electricity in Europe is 40% oil, 24% natural gas, 18% coal, 13% nuclear energy and 5% renewable [167] although there are major differences in the countries with a high proportion of nuclear in France and hydroelectric power in Norway. CO_2 equivalents for each of the above sources are used in calculations for the emissions from electricity generation [168] and it was taken as 59.1 g of CO_2 is emitted to the environment by using 1 kWh of electricity [169]. Emissions arising from warm-water retting and bio-retting are not considered within the analysis due to the lack of data availability.

The total emissions from crop production and fibre processing for three scenarios are given in the Appendices D1, D2 and D3 respectively.

5.5 Summary

This chapter contained the LCIs for the three selected scenarios in terms of energy used in crop production and fibre processing operations. The associated emissions in the production and mass loss (co-products) were also addressed. The complete data sets of LCIs are given in Appendices D1, D2 and D3.

The third step of the LCA is the Life Cycle Impact Assessment (LCIA) to assess the potential environmental burdens as discussed in the next chapter.

Chapter 6. Life Cycle Impact Assessment

This chapter focuses on the eight environmental impact classification factors (EICF) as listed in ISO/TR 14047:2003 [12] and more coherently defined by Azapagic [13, 14] using different terminology as given in Page 5, Chapter 1.

The eight EICFs are calculated for scenario-1 (no-till and water retting), scenario-2 (conservation tillage and stand/dew retting) and scenario-3 (conventional tillage and bio-retting) for the production of one tonne of either flax sliver or yarn.

6.1 Global Warming Potential (GWP)

The principal gases contributing to global warming/climate change are CO_2, CH_4, nitrous oxide, chlorinated hydrocarbons, trichloroethane, chlorofluorocarbons, sulphur hexafluoride and other volatile organic compounds. The following GWP results (Table 6.1 and Figure 6.1) are from diesel combustion, nitrogen fertiliser and agricultural lime production and application and electricity use in the production of flax sliver/yarn. GWP in the LCIA is calculated using the classification factors given in Appendix G in terms of CO_2 equivalent.

The impact from the agro-chemicals is dominant for GWP in scenarios 1 and 2. GWP of scenario 3 is dominated by bio-retting rather than agro-chemicals. The minimum impact is reported from water retting in scenario-1 and followed by stand/dew retting on scenario-2. Diesel is used in water retting and stand/dew retting and electricity is used in bio-retting, scutching, hackling and spinning. The lowest GWP is calculated from scenario-1 and the highest is from scenario-3. The GWP can be reduced by approximately 25% in scenario-1, 18% in scenario-2 and 15% in scenario-3 by eliminating the spinning operation.

Table 6.1 shows the values of GWP in kg CO^2Eq at each stage calculated using the data from LCI and Appendices E and G for the production of flax sliver and yarn in the scenarios defined.

Table 6.1 Global warming potential (GWP) as CO_2 equivalent in kg for the production of flax sliver and yarn at each production stage

	Global Warming Potential (GWP) in kg of CO_2		
	Scenario-1	Scenario-2	Scenario-3
Crop production	2.5	6.5	3.3
Agro-chemicals	10192	16078	8800
Retting	0.3	2.3	12228
Scutching	1618	2098	1605
Hackling	379	497	384
Spinning	4113	4111	4111
Sliver (pre spinning)[a]	**12045**	**18457**	**22744**
Yarn (post-spinning)	**16305**	**22793**	**27131**

[a] Decreased by 1.2% to correct for the mass loss from spinning operation

Figure 6.1 represents the GWP for the production of flax sliver and yarn in the three scenarios.

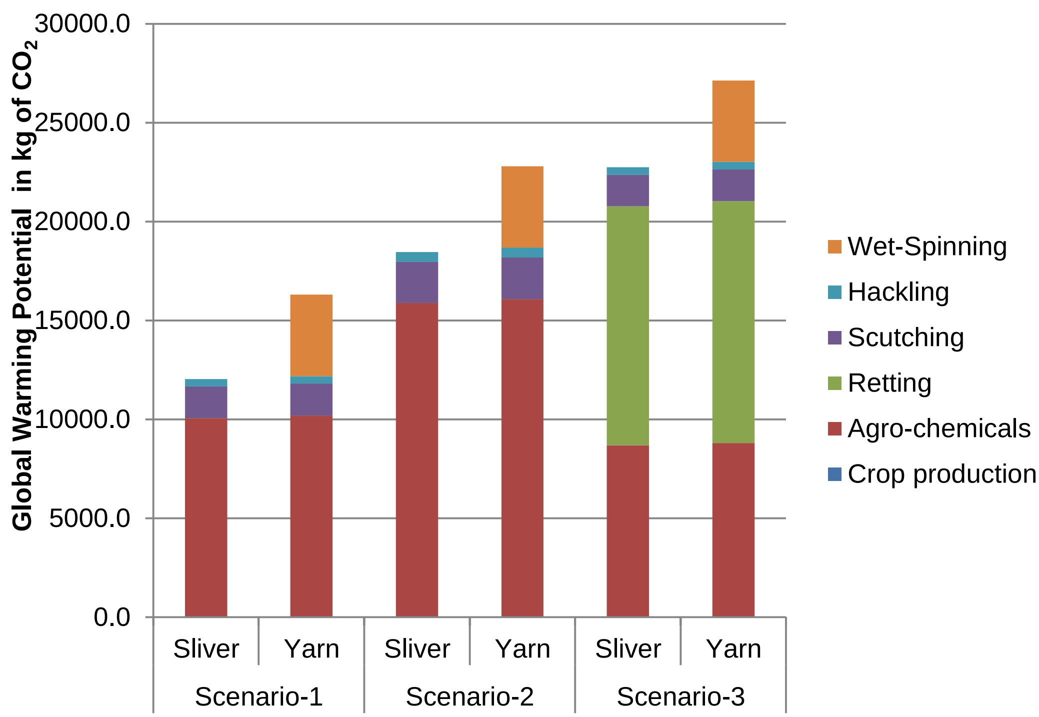

Figure 6.1 Global Warming Potential (GWP) for the production of flax sliver and yarn

6.2 Acidification Potential (AP)

Acidification potential is calculated based on the contributions of SO_2, NO_x, HCl, NH_3 and HF using the classification factors given in Appendix G. The values of AP resulting from diesel combustion, nitrogen and phosphate fertiliser and pesticides production and application are given in Table 6.2 and Figure 6.2.

Table 6.2 The contribution to the Acidification Potential (AP) as SO_2 equivalent from the production of flax sliver and yarn

	Acidification Potential (AP) in kg of SO_2		
	Scenario-1	Scenario-2	Scenario-3
Crop production (diesel)	5.5×10^{-3}	1.4×10^{-2}	7.0×10^{-3}
Retting (diesel)	6.4×10^{-4}	5.1×10^{-3}	0.0
N - fertiliser	142.3	268.6	125.9
P - fertiliser	6.1	7.0	3.2
Pesticides	2.4×10^{-5}	4.0×10^{-5}	2.2×10^{-5}
Sliver (pre spinning)[a]	**146.6**	**272.3**	**127.5**
Yarn (post-spinning)	**148.4**	**275.6**	**129.1**

[a] Decreased by 1.2% to correct for the mass loss from spinning operation

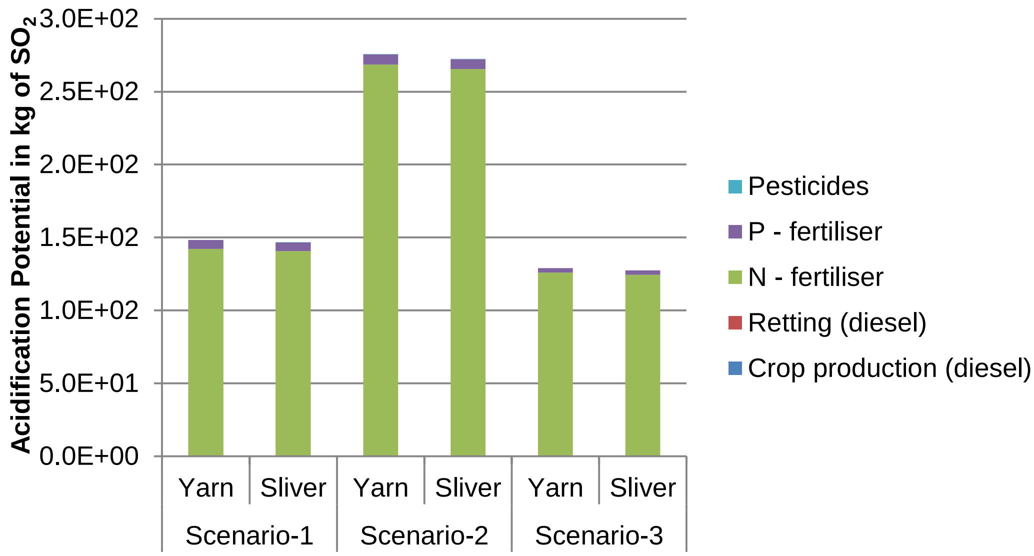

Figure 6.2 Acidification Potential (AP) for the production of flax sliver and yarn

AP is mostly dominated by N fertiliser production and application in all three scenarios. The highest total AP value is obtained in scenario-2 with increased use of agro-chemicals. The contribution to the AP from pesticides and diesel combustion in crop production and retting are insignificant. The lowest AP is reported from scenario-3 as 129kg SO_2Eq which is 13% and 53% lower than scenarios 1 and 2 for the production of flax yarn. A significant difference in AP is not noticeable between the production of flax sliver and yarn as this arises from a very small loss of material in spinning.

6.3 Eutrophication Potential (EP)

EP is calculated using the classification factors of phosphates, nitrates, ammonia, oxides of nitrogen and chemical oxygen demand (COD) as given in Appendix G.

Nitrogen fertiliser production and application is the most dominant EP contributor in all three scenarios due to nitrogen leaching and ammonia emissions. Phosphate fertiliser production and application has the next highest contribution to the EP. The impact caused by diesel emissions is negligible compared to fertiliser impacts. The highest EP value is recorded from scenario-2 which is 54% higher than scenario-3 and 45% higher than scenario-1. The scenario-3 has the lowest EP and there is no significant difference between the production of flax sliver and yarn in all the scenarios.

The main contributor for eutrophication is the production and application of fertilisers and these values are given in Table 6.3 and Figure 6.3.

Table 6.3 Eutrophication potential in kg as referenced to PO_4^{3-} for the flax fibre yarn and sliver production

	Eutrophication Potential (EP) in kg of PO_4^{3-}		
	Scenario-1	Scenario-2	Scenario-3
Crop production (diesel)	9.3×10^{-4}	2.4×10^{-3}	1.2×10^{-3}
Retting (diesel)	1.1×10^{-4}	8.5×10^{-4}	0.0
N - fertiliser	62.4	119.8	55.2
P - fertiliser	50.0	83.4	38.0
Sliver (pre spinning)[a]	**111.1**	**200.7**	**92.1**
Yarn (post-spinning)	**112.4**	**203.1**	**93.2**

[a] Decreased by 1.2% to correct for the mass loss from spinning operation

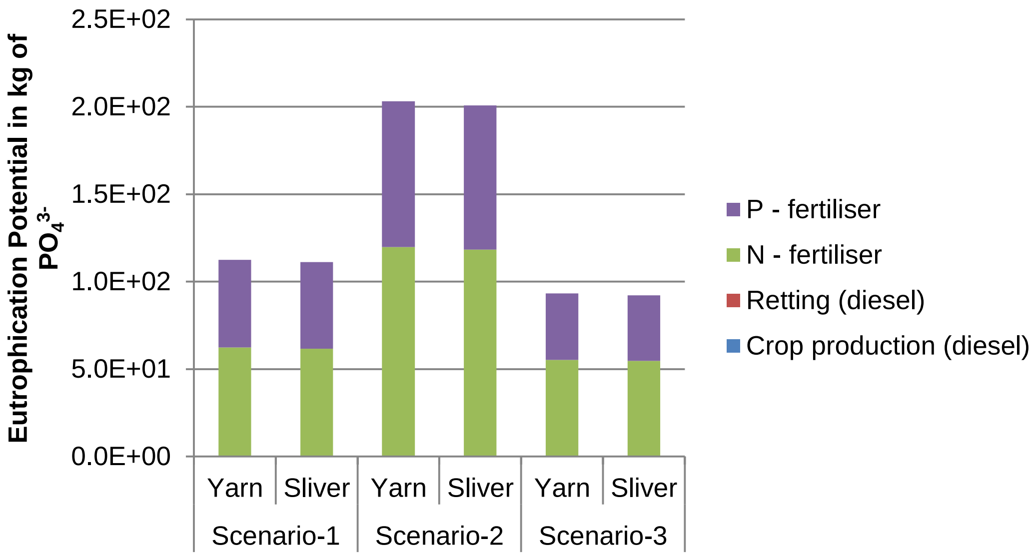

Figure 6.3 Eutrophication Potential for the production of flax sliver and yarn

6.4 Human Toxicity Potential (HTP)

Azapagic [96] recently stated that "Toxicity estimations in LCA are notoriously unreliable and difficult". The contributors for human toxicity include gases such as CO, NOx, SO_2, hydrocarbons and heavy metals such as As, Hg, Cr, Cu, Fe etc. The human toxicological factors are still at early stage of development, therefore HTP can only be taken as an indication and not as an absolute measure of the toxicity potential.

HTP is calculated according to the classification factors given in Appendix G. The values for HTP in kg for the production of flax sliver and yarn in 3 chosen scenarios resulting from diesel combustion, fertilisers and pesticides production and application are given in Table 6.4 and Figure 6.4

Table 6.4 Human Toxicity Potential (HTP) in kg for the production of flax fibre sliver and yarn.

	Human Toxicity Potential (HTP) in kg		
	Scenario-1	Scenario-2	Scenario-3
Crop production (diesel)	6.2×10^{-3}	1.6×10^{-2}	8.3×10^{-3}
Retting (diesel)	7.2×10^{-4}	5.7×10^{-3}	0.0
N - fertiliser	16.4	23.4	14.5
P - fertiliser	10.0	11.5	5.2
Pesticides	4.9×10^{-3}	9.5×10^{-3}	4.4×10^{-3}
Sliver (pre spinning)[a]	**26.0**	**34.5**	**19.5**
Yarn (post-spinning)	**26.4**	**34.9**	**19.7**

[a] Decreased by 1.2% to correct for the mass loss from spinning operation

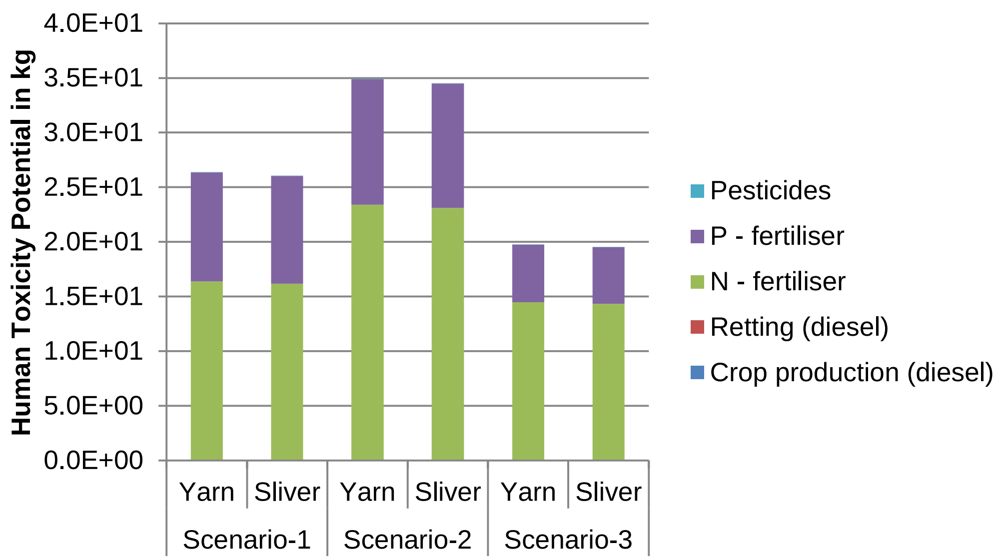

Figure 6.4 Human Toxicity Potential (HTP) for the production of flax sliver and yarn

The production and application of nitrogen and phosphate fertilisers is the main cause of HTP in all three scenarios. The values of HTP resulting from diesel combustion and pesticides are insignificant. The lowest HTP is reported from scenario-3 which is 25% lower than scenario-1 and 43% lower than scenario-2. The production of flax sliver and yarn has very similar values for HTP.

6.5 Aquatic Toxicity Potential (ATP)

As with HTP, the classification factors for are still being developed and these can only be used as indicators of potential toxicity. ATP was calculated using the classification factors given in Appendix G and the calculated values are given in Table 6.5 and Figure 6.5 for the production of flax sliver and yarn in all three scenarios.

Table 6.5 Aquatic Toxicity Potential (ATP) in $m^3 \times 10^{12}$ for the production of flax sliver and yarn

	Aquatic Toxicity Potential (ATP) in m^3x10^{12}		
	Scenario-1	Scenario-2	Scenario-3
Pesticides	1793.5	2066.9	941.6
Sliver (pre spinning)[a]	**1772.0**	**2042.1**	**930.3**
Yarn (post-spinning)	**1793.5**	**2066.9**	**941.6**

[a] Decreased by 1.2% to correct for the mass loss from spinning operation

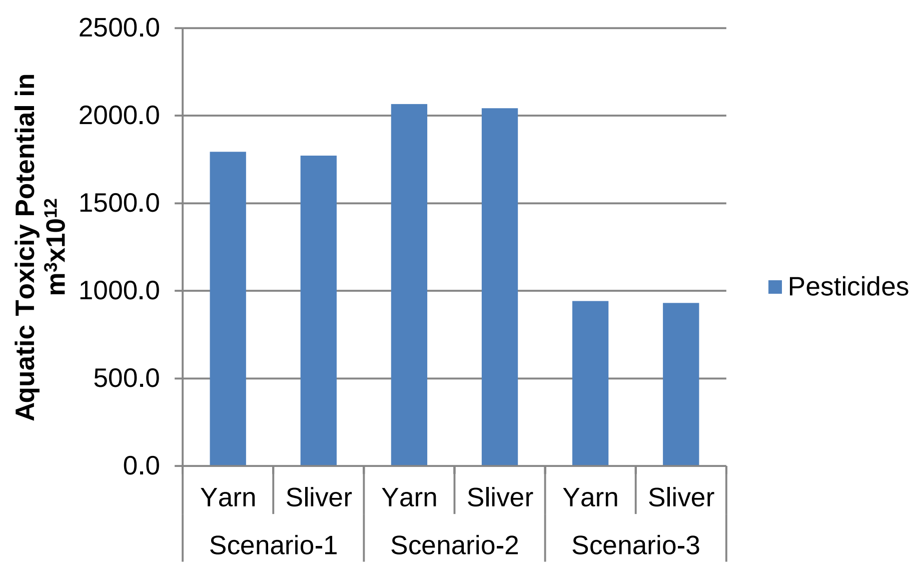

Figure 6.5 Aquatic Toxicity Potential (ATP) for the production of flax sliver and yarn

ATP results from pesticide production and application. The highest ATP is reported from scenario-2 with the highest amount of pesticides used. The lowest values are reported from scenario-3 which is 54% and 47% lower than scenario-2 and scenario-1 respectively.

6.6 Ozone Depletion Potential (ODP)

ODP is calculated based on classification factors given in Appendix G for trichlorofluoromethane (CFC-11), chlorinated hydrocarbons, chlorofluorocarbons and other volatile organic compounds. The only cause identified for ODP was the diesel combustion in the production of flax sliver and yarn as given in Table 6.6 and Figure 6.6.

Table 6.6 Ozone Depletion Potential (ODP) in kg referenced to CFC-11 for production of flax sliver and yarn

	Ozone Depletion Potential (ODP) in kg of CFC-11		
	Scenario-1	Scenario-2	Scenario-3
Crop Production (diesel)	7.4×10^{-6}	1.8×10^{-5}	9.4×10^{-6}
Retting (diesel)	8.6×10^{-7}	6.3×10^{-6}	0.0
Sliver (pre spinning)	8.2×10^{-6}	2.4×10^{-5}	9.3×10^{-6}
Yarn (post-spinning)	8.3×10^{-6}	2.4×10^{-5}	9.4×10^{-6}

[a] Decreased by 1.2% to correct for the mass loss from spinning operation

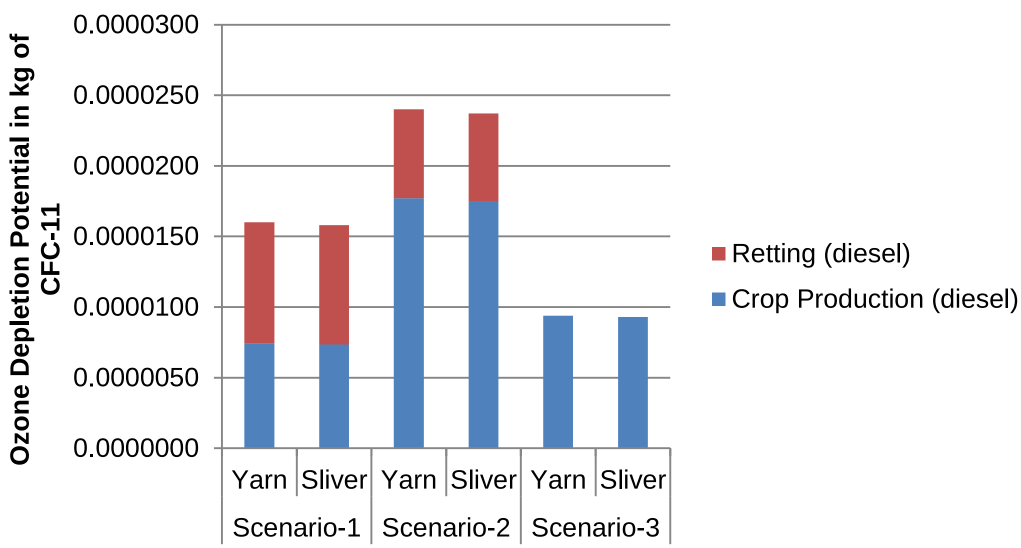

Figure 6.6 Ozone Depletion Potential (ODP) for the production of flax sliver and yarn

6.7 Photochemical Oxidants Creation Potential (POCP)

POCP is calculated according to the classification factors of ethylene, methane, other hydrocarbons, aldehydes, styrene and other volatile organic compounds as given in Apppendix G. These calculated values are given in Table 6.7 and Figure 6.7.

Table 6.7 Photochemical Oxidants Creation Potential (POCP) in kg referenced to Ethylene for the production of flax fibre sliver and yarn

Photochemical Oxidants Creation Potential (POCP) in kg $\times 10^{-6}$ of Ethylene			
	Scenario-1	Scenario-2	Scenario-3
Crop Production (diesel)	10	24	13
Retting (diesel)	1.2	8.7	0
Sliver (pre-spinning)[a]	**12**	**33**	**13**
Yarn (post-spinning)	**12**	**33**	**13**

[a] Decreased by 1.2% to correct for the mass loss from spinning operation

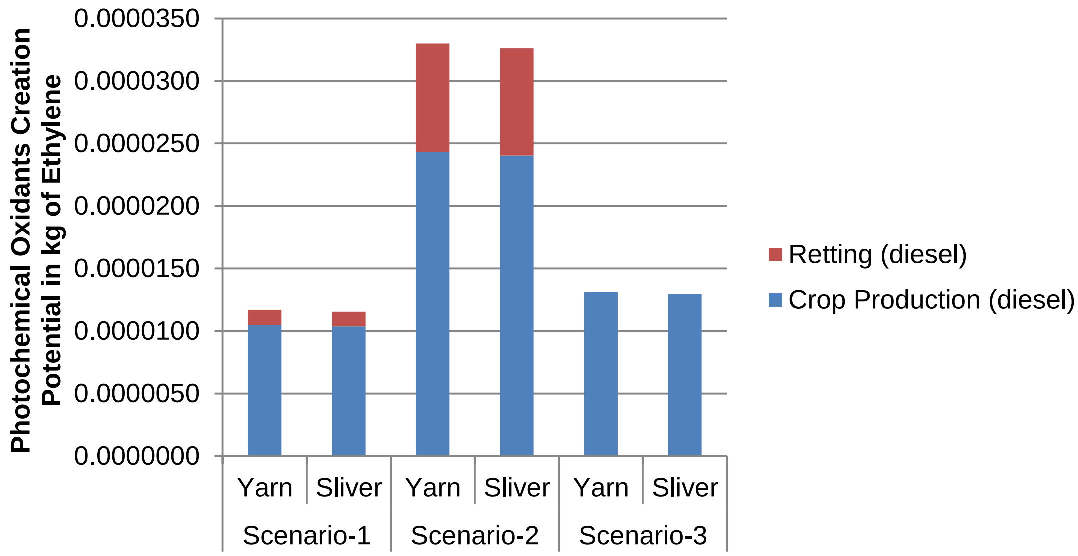

Figure 6.7 Photochemical Oxidants Creation Potential (POCP) for the production of flax sliver and yarn

POCP is resulted from diesel combustion and the lowest value is reported from scenario-1 which is 65% and 11% lower than scenario-2 and 3 respectively. The scenario-2 has reported a value of 33mg of ethylene per tonne of fibre. There is no significant difference between the POCP values for the production of flax sliver and yarn.

6.8 Non-Renewable/Abiotic Resource Depletion Potential (NRADP)

NRADP is calculated for diesel and electricity usage in the flax fibre sliver/yarn production using the classification factors for coal, oil and gas given in Appendix G. Electricity is used in fibre processing operations (scutching, hackling and spinning). The NRADP contributions for producing flax fibre sliver and yarn in three scenarios are given in Table 6.8 and Figure 6.8.

Table 6.8 Results of NRADP contribution for the production of one tonne of flax fibre sliver and yarn

		Oil/10^{-12}	Gas/10^{-12}	Coal/10^{-15}
Scenario-1	Yarn	3.9	2.0	3.1
	Sliver	2.0	0.6	1.0
Scenario-2	Yarn	6.5	2.2	3.4
	Sliver	4.5	0.8	1.3
Scenario-3	Yarn	9.6	5.9	9.2
	Sliver	7.4	4.4	6.8

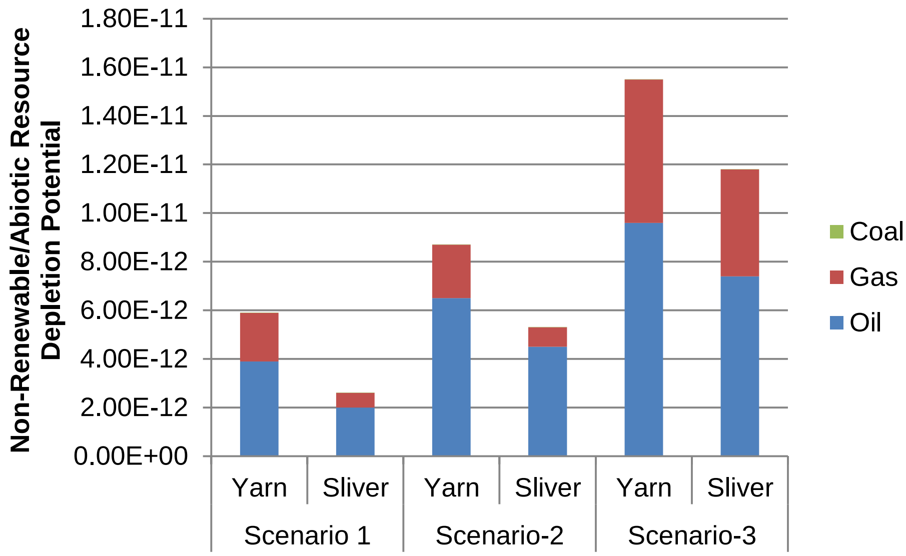

Figure 6.8 Non-Renewable/Abiotic Resource Depletion Potential (NRADP) for the production of flax sliver and yarn

Scenario-1 has reported the lowest NRADP values for oil, gas and coal for flax sliver and yarn production. The highest NRADP values are recorded from scenario-3 due to the intensive electricity use in bio-retting. The scenario-2 has reported the similar NRADP values for gas and coal as in scenario-1 but the NRADP value for oil has increased due to the high diesel consumption. The NRADP values can be reduced by using sliver as reinforcement or by using renewable energy sources in the production of flax fibre sliver and yarn.

6.9 Summary

The Table 6.9 shows the complete set of LCIA results for the production of flax sliver and yarn in all 3 of the defined scenarios as a summary.

Table 6.9 Summary of LCIA Results

		GWP	AP	EP	HTP	ATP*	ODP/10^{-6}	POCP/10^{-5}
Scenario-1	Sliver	11971	146.6	111.1	26.1	1772	8.2	1.2
	Yarn	16073	148.4	112.4	26.4	1793.5	8.3	1.2
Scenario-2	Sliver	18359	272.3	200.7	34.5	2042.1	24	3.3
	Yarn	22538	275.6	203.1	34.9	2066.9	24	3.3
Scenario-3	Sliver	22212	127.6	92.1	19.5	930.3	9.3	1.3
	Yarn	26436	129.1	93.2	19.7	941.6	9.4	1.3

*All the values are in kg of associated reference materials except ATP values which are in $m^3 \times 10^{12}$

The eight environment impact classification factors are calculated for each operation in the production of flax fibre sliver and yarn in all three scenarios. The scenario with lowest/highest potential environmental impacts can be identified from the results of the LCI and LCIA and this is discussed in the next chapter of Life Cycle Interpretation.

Chapter 7. Life Cycle Interpretation

The aim of this chapter is to discuss and draw conclusions from the findings of the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA). This is carried out by comparing the 3 chosen scenarios for the production of flax sliver and yarn.

7.1 Comparison of the three scenarios for energy use

Scenario-1, which uses the no-till and warm water retting method, has the minimum energy requirement among the three scenarios for the production of flax fibre sliver and yarn. Direct sowing and reduced or minimal tillage are the normal methods in conservation agriculture which reduce the energy consumption in crop production. Chisel ploughing (scenario-2) uses approximately 40% less energy than mouldboard ploughing (scenario-3) where drilling combined with a no-till pass consumes only 6% of the energy required for mouldboard ploughing.

Three methods of retting assumed in this analysis are warm water retting (scenario-1), stand/dew retting (scenario-2) and bio-retting (scenario-3) and in the absence of data specific to flax fibre, bio-retting of hemp and stand/dew retting of baby hemp are assumed to have similar energy requirements to flax. Herbicides used as a dessicant in stand/dew retting have contributed further 6% of energy to the total energy consumption in scenario-2. Bio-retting is the most energy intensive method of retting which also includes post harvest field operations, green scutching, rinsing, drying and mechanical softening to produce long fibres. Warm water retting is the process requiring the least energy but generates a considerable amount of waste water (approximately 94% of water used). The waste water treatment, or emissions from the retting water is not included in the analysis due to lack of available data. The water use for both irrigation and retting will be discussed in the next chapter.

The maximum energy in crop production results from the scenario-2 as over 45% of the mass of dry green flax stems is lost from the stand/dew retting process hence the increased land use and the amount of agro-chemicals. The land use is not included in this analysis and will be addressed in the next chapter. The amount of agro-chemicals used in the scenario-3 is significantly lower than the other two scenarios, due to the reduced wastage (mass loss) from the process. The energy input from agro-chemicals is dominant in both scenarios 1 and 2 for the production of flax sliver and yarn. Nitrogen fertilisers have the highest embodied energy among the other fertilisers and the effect of N, P and K fertiliser on the flax plant is analysed in Appendix J from an experiment carried out in the University of Plymouth. Flax seeds were grown, harvested and chemical analysis was carried out to determine the N, P and K levels in the flax stems. No correlation between the fertiliser input and fertiliser uptake by the plant stem was found and it was concluded that different levels of fertiliser have not contributed towards the growth of the flax plants. The growth medium used probably had adequate levels of the respective elements before the addition of fertiliser.

Bio-retting is the largest contributor to the total energy in both sliver and yarn production in scenario-3. Energy used in bio-retting and agro-chemicals adds up to about 75% of the total energy in this scenario.

The Figure 7.1 shows the energy use in various production stages for flax sliver and yarn in all three scenarios.

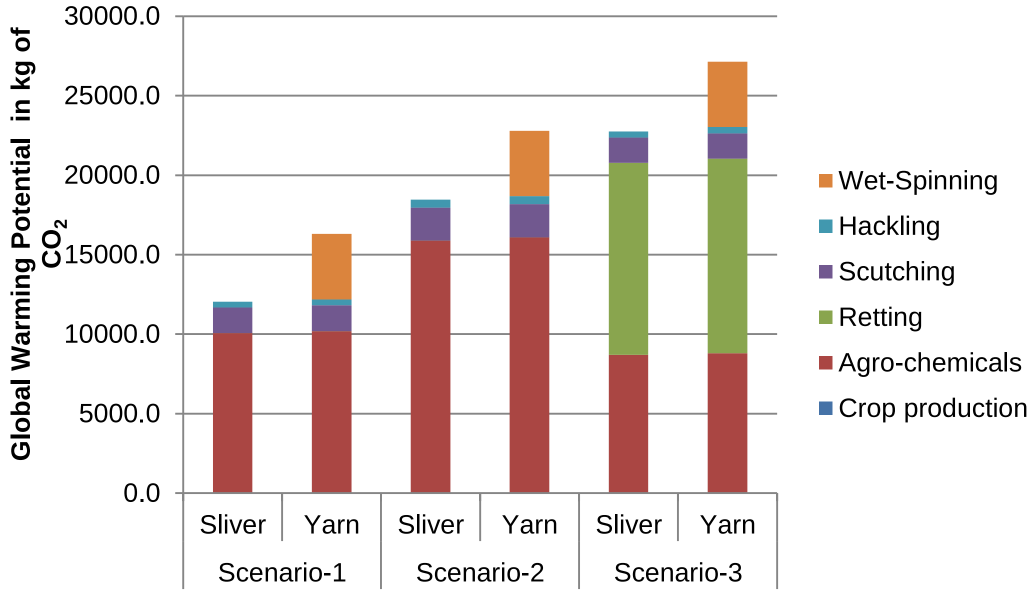

Figure 7.1 Energy use in each production stage for flax fibre sliver and yarn

Only 5%, 4.5% and 2% of the mass of dry green flax stems are converted into yarn in bio-retting, warm-water retting and stand/dew retting respectively. The remainder could be regarded as waste or the respective co-products. Short fibre and shives are produced from scutching and hackling processes. These can be used as animal bedding or in paper production. Dust is also produced from processes such as scutching and hackling and these can be collected and consolidated as biomass fuel. The long fibres are regarded as the high value product throughout this analysis. Typical masses of the co-products from the three scenarios are given in Appendix H. Reduction in total mass is noticeable at the end of each process and in the scenario-1, 22 tonnes of dry green flax stems produced 1 tonne of flax yarn. The mass of dry green flax stems required to produce 1 tonne of yarn in scenario 2 and scenario 3 are 43 tonnes and 20 tonnes respectively. The mass reduction at each stage of the production as the percentage of green stems for the three scenarios is shown in Figure 7.2.

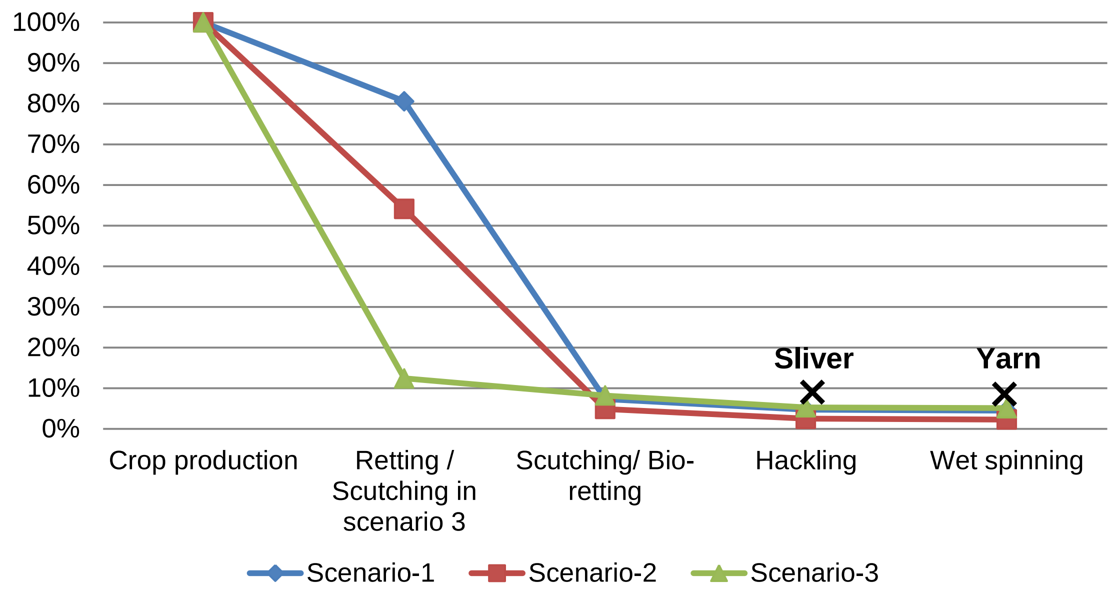

Figure 7.2 The mass reduction at each stage of the production as percentage of green stems

The minimum total energy required in production scenario-1 is 54.4GJ/tonne of sliver and 80.4GJ/tonne of yarn. The energy consumption in scenario-2 has recorded the intermediate values of 113.1GJ/tonne of sliver and 141.6GJ/tonne of yarn. The maximum energy requirement is recorded from scenario-3 as 119.3GJ and 147.9GJ for the production of one tonne of flax sliver and yarn respectively.

The energy required to spin one tonne of flax sliver is 23.9GJ and if the aligned (carded and hackled) sliver could be used for quasi-unidirectional reinforcement then the energy consumption could be significantly reduced by elimination of the spinning operation. Wet spinning increases the total energy consumption by 29% in scenario-1 and more than 16% in scenario-2 and scenario-3.

7.2 Comparison of the three scenarios for impacts

Scenario-1 has reported the lowest global warming potential (GWP), ozone depletion potential (ODP) and photochemical oxidants creation potential (POCP) relative to the other scenarios. This is directly linked with the lowest energy use in the form of diesel or electricity. The highest GWP in scenario-3 has resulted from the highly energy intensive method of bio-retting. The fibre processing operation of water retting uses the least energy. In scenario 3, the percentage of green stems converted into long fibre is higher, and the wastage during retting process is lower than scenarios 1 and 2. Hence the land use and cultivation is reduced, to achieve the same output of 1 tonne of flax sliver/yarn. Therefore, the scenario-3 has reported the lowest agro-chemical usage and the lowest acidification potential (AP), eutrophication potential (EP), human toxicity potential (HTP) and aquatic toxicity potential (ATP).

AP is mainly caused by NH_3, N_2O and NO_x emissions from agro-chemicals production and application. EP is caused by NH_3, N_2O and N leaching. Emissions from retting liquid are not included in the analysis due to lack of data availability, but this water could be used for irrigation and would thus return the biomass to the soil. The GWP of scenario-2 is lower than scenario-3 but all the other impact potentials are higher than scenario-1 and scenario-3. The herbicides, used as a dessicant prior to the harvest as a preparation to the stand/dew retting process, and over 45% of the mass loss from the retting process have resulted in increased agro-chemicals usage in the scenario-2 with highest impact potentials.

The highest diesel consumption is also reported from scenario-2 with highest impact potential values for ODP and ATP. The scenario-3 has the highest NRADP value for gas with the highest electricity consumption. The scenario-1 has the lowest NRADP values for oil, coal and gas. The NRADP values are lower for sliver production due to the lower diesel and electricity consumption than yarn production. In the production of sliver, the above differences in the three scenarios are consistent to the production of flax yarn with improved set of environmental impact potentials for all categories due to the elimination of the spinning operation.

The normalised values for environmental impact categories are presented as radar plots in Figure 7.3 and 7.4 for the flax sliver and yarn production respectively. The graphical representation using radar plots was judged to be the best means of data presentation. There is no direct comparison between the seven axes. The radar plots only present the relative magnitudes of the environmental impact potentials.

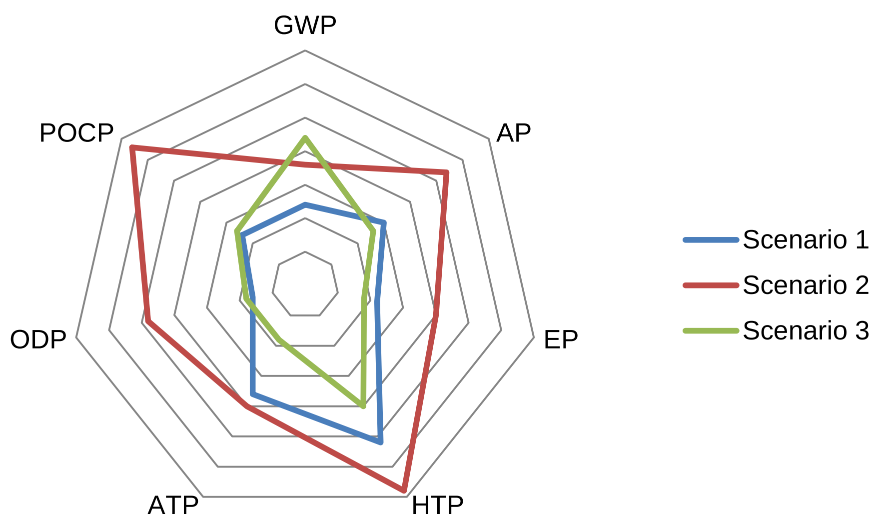

Figure 7.3 Representation of LCIA for the production of flax sliver
(Note that this data presentation uses numbers from the raw analysis and thus the relative magnitudes for each EICF do not infer proportionate environmental damage)

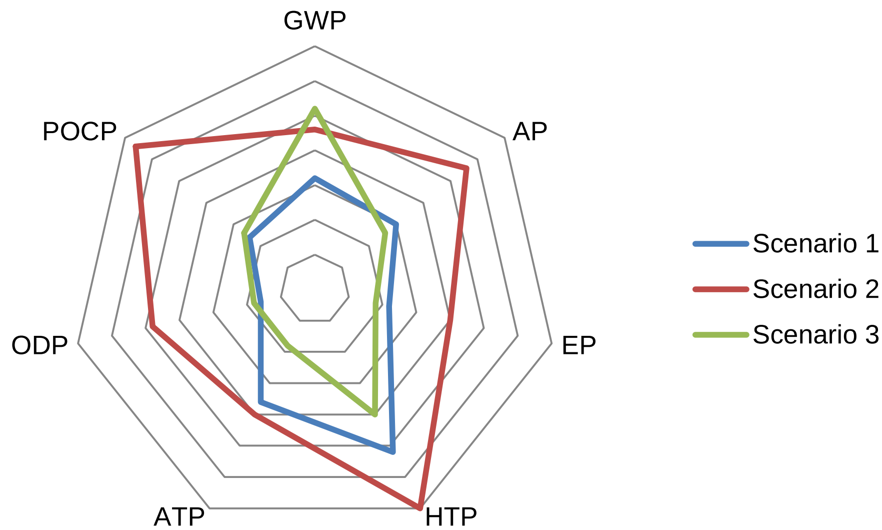

Figure 7.4 Representation of LCIA for the production of flax yarn

The above radar plots show that, the scenario-2 has the worst environmental impacts for both sliver and yarn production (except GWP). The scenario-1 and 3 are highly comparable to each other. The potential environmental impacts in the scenario-1 could be reduced by controlling fertiliser and pesticides use and scenario-3 can be improved by reducing the energy consumption in bio-retting process by adopting different technology or improving the process.

7.3 Flax fibre vs. glass fibre

The aim in this section is to compare the environmental impacts of flax fibre production with glass fibre production. A quantitative LCA for glass fibres was carried out with a limited data set as it was difficult to identify potential data sources due to the commercial sensitivity of this information. The comparison was undertaken using data from literature and LCA database (EcoInvent).

One tonne of either glass fibre or flax fibre for reinforcement are compared in this section with different reinforcement formats (glass mat vs. flax sliver or glass roving vs. flax yarn). It was assumed that, similar processing techniques are used for component manufacture to eliminate the significant differences in flax fibre and glass fibre at that stage and for the flax fibre component to be adequate for the normal lifetime of the component with no deterioration.

An underlying assumption is that equal weights of fibre will provide equal stiffness. However, at constant fibre weight fraction the flax fibre will occupy ~1.67 of the actual volume of glass fibre. Therefore the cross-sectional area of the component will be increased by 67% with a consequent increase in the quantity of the polymer matrix required.

In a study carried out in Germany in 1999, Diener and Siehler [9] reported that the energy used to produce glass fibre yarn is 31.7GJ/tonne and to produce a glass fibre mat is 54.7GJ/tonne. These values are an accumulation of energy in raw materials, mixture, transport, melting, spinning and mat production. These data were subsequently used by Joshi et al [8] to compare natural fibre composites and glass fibre composites from an environmental view point. The energy requirement for the production of glass fibre mat is given in Table 7.1 [8, 9]

Table 7.1 The energy requirement for the production of glass fibre yarn and mat

Operation	Energy Consumption GJ/tonne[a]
Raw materials	1.7
Mixture	1.0
Transport	1.6
Melting	21.5
Spinning	5.9
Mat Production	23.0
Total (yarn)	31.7
Total (mat/sliver)	54.7

[a] Source Ref [9], reproduced in Ref [8]

The embodied energy in the primary production of E-glass (0.4-12 micron monofilament) was estimated to be between 67.7 - 74.9 GJ/tonne with CO_2 footprint between 4.26-4.71 kg/kg by the Educational software CES 2010 EDUPACK [170]. That report does not clearly define the reinforcement format of the glass fibre. The embodied energy in the primary production of flax in the unwoven state is estimated to be in the range between 67.9 -75.1 GJ/tonne with CO_2 foot print between 4.27-4.72 kg/kg [171].

From the data derived in this thesis, the total energy used to produce flax sliver is 54.4GJ/tonne and yarn is 80.4GJ/tonne in scenario-1, where no-till and water retting is used (Appendix D1). Using traditional conventional method (mouldboard ploughing) and bio-retting the values are 119.3GJ/tonne of sliver and 147.9 GJ/tonne of yarn (Appendix D3). The published values [9] for glass fibre reinforcements are 31.7GJ/tonne for continuous fibre (which is equivalent to yarn) and 54.7GJ/tonne for mat (which is equivalent to sliver). Based on energy analysis, sliver from the low energy route has an embodied energy directly comparable to that for glass fibre mat. Continuous glass fibre reinforcement is superior from an environmental energy viewpoint to spun flax yarn. The CES 2010 EDUPACK embodies energy values are about 30% higher than glass fibre mat values reported by Diener and Siehler [9] and 31% higher than scenario-1 flax sliver as derived in this thesis.

The emissions associated with glass fibre production considered in this analysis include CO_2, NO_x and volatile organic compounds (VOC). The data was obtained from the Sustainability Report of Owens Corning 2008. That report does not specify the reinforcement format of the glass fibre (mat/yarn) [158]. The environmental impact potentials for LCIA were determined from above emissions and based on assumptions given in Appendix I.

The normalised values for environmental impact categories for glass fibre and flax sliver production are presented as radar plots in Figure 7.5. For two EICF (ATP and NRADP), it has not been possible to identify appropriate data for glass fibres to permit a direct comparison.

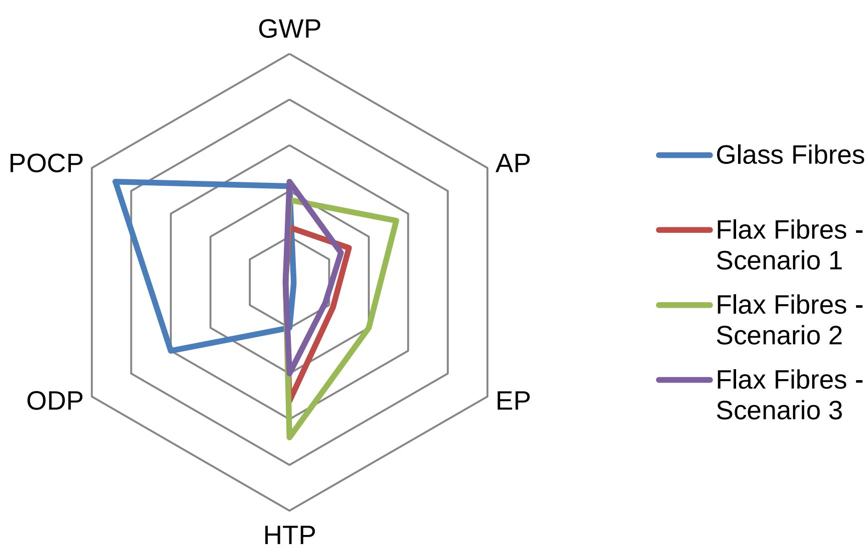

Figure 7.5 Representation of LCIA of glass fibres vs. flax fibres (sliver) production in three scenarios

Glass fibre has soaring values for ODP and POCP when compared with flax fibres due to the VOCs of glass fibre production. However, glass fibres are better than flax fibres for three other factors of AP, EP and HTP. Flax fibre has high values for acidification, eutrophication and human toxicity due to the agro-chemical usage in the production. Depending on the chosen method of flax fibre production (low energy route) and the form of reinforcement (by choosing sliver as reinforcement instead of yarn), GWP could be minimised to compete with glass fibres.

In the production of yarn, the above differences in the three scenarios are consistent with the production of flax sliver with elevated values for GWP due to the energy intensive spinning operation. By adopting the lowest energy route to produce flax sliver/yarn and minimising the agro-chemicals input in the production of flax, the environmental impacts can be reduced and lowered relative to glass fibres. Flax fibre produced by no till and warm-water retting (scenario-1) has an embodied energy of 54.4 GJ/tonne of sliver (vs. *54.7* GJ/tonne for glass mat). The spinning process raises the embodied energy for yarn to 80.4 GJ/tonne (vs. *31.7* GJ/tonne for continuous glass fibre). The values of embodied energy in the production of flax fibres are derived by considering the crop production phase including fertiliser and pesticide input and fibre processing stages of retting, scutching, hackling and spinning. Further, the validity of the “green” case for substitution of glass fibres by natural fibres is dependent on the chosen reinforcement form and associated production method. No-till method with water retting (scenario-1) is identified as the method which requires the lowest energy hence the lowest GWP, ODP and POCP. Conventional tillage and bio-retting (scenario-3) has the lowest AP, EP, HTP and ATP and the highest GWP due the highest energy consumption. To improve the case for natural fibres, the principal recommendation is for the use of organic fertiliser, biological control of pests, appropriate choice of retting method and conservation agriculture.

7.3.1 LCIA results from EcoInvent

The EcoInvent LCA database was developed by Swiss Centre for Life Cycle Inventories with many other Swiss Federal Offices. The most recent version (v2.2) contains high-quality generic LCI datasets which are based on industrial data. These have been compiled by internationally renowned research institutes and LCA consultants. The data are available in the EcoSpold data format, and they are compatible with all major LCA and eco-design software tools [84] .

The main reason to use data from an international LCA database was to compare and validate the findings of this study. Even though the EcoInvent data v2.0 comprises life cycle inventory data covering energy for various materials (on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management) the database does not include the LCI values for the production of flax fibres or glass fibres.

The LCIA data for glass fibre production was extracted from the EcoInvent v2.0 for 6 environmental impact classification factors (GWP, AP, EP, HTP, ODP, and POCP). The LCIA values for the production of one tonne of glass fibres are given in Table 7.2. The reinforcement format of glass fibres was not given in the database.

Table 7.2 The LCIA results from EcoInvent v2.0 per tonne of glass fibre production

EICF	LCIA - Results from Ecoinvent v2.0
GWP (kg CO_2-Eq)	2634.5
AP (kg SO_2-Eq)	15.66
EP (kg PO_4-Eq)	1.37
HTP (kg1,4-DCB-Eq)	8763.7
ODP (kg-CFC11-Eq)	0.00036
POCP (kg Ethylene-Eq)	0.59

The above values are normalised and plotted against the LCIA results of the three scenarios of the flax fibre sliver production. The representation of the radar plot is given in Figure 7.6.

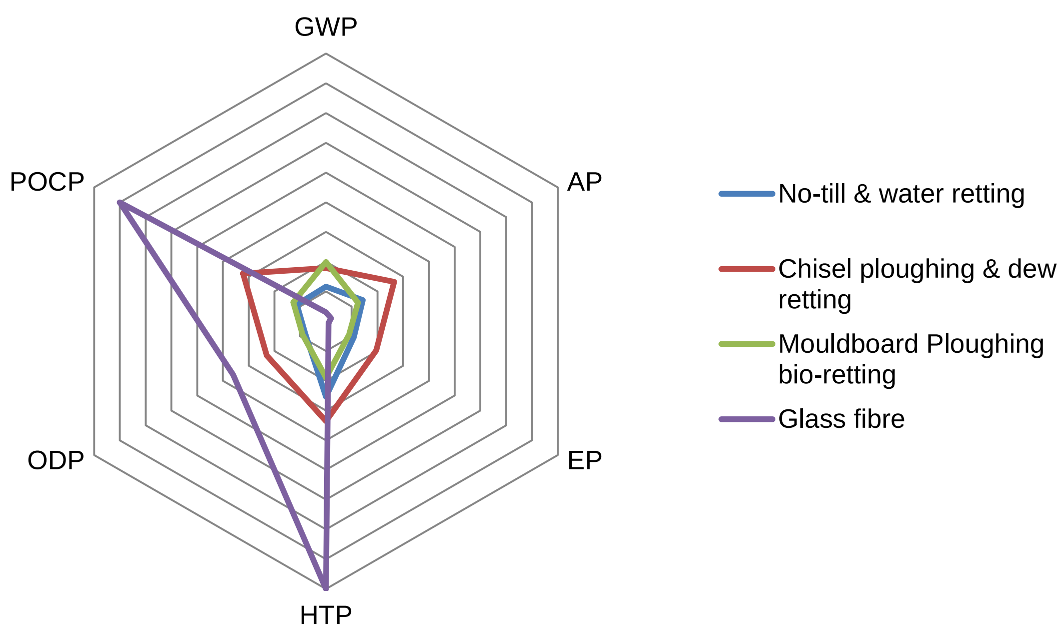

Figure 7.6 Representation of LCIA for glass fibres (EcoInvent) vs. flax sliver production

The LCIA results from EcoInvent v2.0 give higher values for POCP and HTP than the values obtained from the literature. It has also reported a very low GWP value for glass fibre production. The value for EP is similar, while the value for AP is nearly doubled. The value for ODP is lower than the figures from literature.

The differences in values could be due to the reinforcement format of glass fibres and the differences in the production methods used. These could not be found from the Owens Corning report or the LCA database. The GWP value from the literature could also include the emissions from ancillary processes such as lighting, heating storage, long distance transport etc. The limited numbers of emissions were considered from the literature (due to the lack of availability) in calculating AP, HTP and ODP hence reported lower values than the LCA database EcoInvent.

These values in EcoInvent are mainly derived from CML 2001 and values are given as mean values. The given values in the EcoInvent are for glass fibre production in a European situation and literature values are based on the Owens Corning plant in USA.

7.4 Summary

Scenario-1 used the least energy in the production of flax sliver/yarn while scenario-3 reported the highest energy use, as a consequence of the definitions of the respective scenarios. The GWP, ODP and POCP are at their lowest in scenario 1 and the lowest AP, EP, HTP and ATP were reported from scenario-3. The spinning process inevitably raises the embodied energy for yarn. In consequence, the substitution of glass fibres by natural fibres is truly dependent on the chosen reinforcement form and associated process. Flax sliver as reinforcement is comparable in energy terms to the glass fibre mat when no-till and water retting is used in the production.

The aim of the next chapter is to discuss the other potential environmental impacts which are not included in the LCIA such as land use, loss of biodiversity, noise and vibration, etc.

Some of these impacts could not be quantified but should be considered in any complete LCA study.

Chapter 8. Other Environmental Impacts

The topics discussed so far relate to the energy use and emissions in the production cycle. The environmental impacts are not addressed in the LCIA such as land and water use, impacts on biodiversity and soil fertility, soil erosion, noise and vibration. The aim of this chapter is to address the other environmental impacts which should be considered although corresponding methods of evaluation within the life cycle assessment are yet to be developed and validated [172].

8.1 Discussion – Other Environmental Impacts

Many of the environmental impacts are not measurable. For example, effects on the appearance of the landscape or implications for the bio diversity caused by agriculture could not be measured by established methods. Therefore, these potential environmental impacts are only discussed qualitatively in environmental assessments. The main environmental impacts in agriculture are caused by pesticides, nitrogen compounds and soil erosion in the United Kingdom [173]. The impacts associated with air and water can have significant effects on the area surrounding the place of the origin causing many more inter related impacts which makes the quantification very difficult to achieve.

Malthus (1798) [18] believed that increasing population growth would surpass the means of subsistence at some point. The population has grown since then; and the current resource consumption is about 30% more than the planet could replace/regenerate within that year resulting in deforestation, degraded soils, polluted air and water and dramatic declines in the numbers of fish and other species [174].

The landmark day is called the "Earth Overshoot Day", the day the human population uses up all natural resources and services for the year, which means we are borrowing resources available for the following year [175]. On average, the overshoot day or ecological debt day has fallen on an earlier day than in the previous year; the projected overshoot day for the year 2050 (based on projected resource consumption, population etc) falls in the middle of that year. Table 8.1 represents some calendar days of earth overshoot since 1987.

Table 8.1 Calendar days of Earth Overshoot since 1987 [175]

Year	Overshoot Day
1987	Dec-19
1990	Dec-07
1995	Nov-21
2000	Nov-01
2005	Oct-20
2007	Oct-26
2008	Sep-23
2009	Sep-25
2050 (expected)	Jul-01

The productive land available to support each person on this planet has decreased with the increasing population and it will reduce further unless there is an end to the population growth. A person's environmental footprint differs across the globe depending on their life styles; the biggest consumers are from UAE, US, Kuwait and Denmark consuming 8 or more "global hectares" (20 acres or more) per person. The global average consumption was 2.7 hectares a person, compared with a notional sustainable capacity of 2.1 hectares. The UK, with an average footprint of about 5.5 hectares, ranks 15th in the world, just below Uruguay and the Czech Republic but ahead of Finland and Belgium.

The ultimate aim is to use the available land for cultivation of basic food essentials such as corn, rice and wheat to cope with the increasing demand and prices. But the current agricultural practices have both negative and positive impacts on the environment. They will result in more food or fuel production to support positive development and also will result in loss of biodiversity, water and soil resources. Deterioration of soil quality by the increased use of chemical fertilisers and non-renewable energy usage are the challenges to overcome during the cultivation of any crop. Some argue that there is sufficient food supply which is unequally distributed [176] but there is growing concern that using the land for growing bio-fuels or industrial feed stocks rather than food will increase the inequality in food availability.

The UK government aims to reduce green house gas emissions by 60% by 2050, with the main focus on renewable energy sources [177]. Plant derived bio-fuel such as bio-ethanol, has direct impacts on land use and impacts on wildlife and biodiversity. The environmental impacts could only be reduced by producing bio-fuel from by-products of food cultivation where the agriculture system is strictly environmentally orientated. The important aspect is to ensure sustainable production of food, animal feed, fibre, industrial feedstocks and fuel to reduce the impacts on the environment [178].

Land use should be analysed in terms of quantity and quality (transformation and effects on biodiversity and landscape). It is not included as an environmental impact category in this study. The quantity of land use for the cultivation of flax fibres in three scenarios are calculated in LCI, which is very dependent on the yield. Land use can be reduced directly by increasing the yield, but such an increase could involve negative impacts such as increased fertiliser and pesticides application.

Pesticides used in the cultivation of flax, result in contamination of water, impacts on bio-diversity and humans. Some of these impacts were measured in terms of eutrophication, acidification, human toxicity and aquatic toxicity in Chapter 6, but the extension of these impacts which cause the loss of aquatic life or contamination of drinking waters are not addressed since they are very complex to quantify. The levels of pesticides were found to be generally higher in surface waters than ground waters and the chemicals can be absorbed or degraded in soils [173]. Pesticide uptake occurs through the skin, eyes, lungs or intestinal tract causing human poisoning. The Health and Safety Executive in UK reported 196 incidents in 1992/1993 caused by pesticides poisoning [173]. The indirect impacts of pesticides such as loss of habitats and human poisoning are very difficult to analyse within the scope of this study as there are few limiting factors such as the area and time period. Furthermore, some industrially produced chemicals are implicated in reduced quality of life (e.g. non-fatal cancers and heart disease) and some information may be suppressed for commercial reasons.

Crop rotation and biological control of pests would reduce the environmental impacts and emissions from agro-chemicals. Crop rotation or cropping sequence not only helps to minimise weed control but also to improve the soil quality. Biological control of pests involves the use of insects, plant diseases, nematodes, microorganisms, plants, animals, fish or birds for reducing pests or weeds. The risk of biological control is that release of an organism that may attack useful plants or animals or lack of control, could prevent farmers from using this method more widely [179].

It was reported that about 56% of the nitrogen contamination found in surface waters result from agriculture [180], which is caused by inorganic fertilisers. Acidification, eutrophication and human toxicity potentials resulting from nitrogen and phosphate fertilisers are calculated in Chapter 6. Catt [181] has found that the nitrate loss from direct drilled land was 24% less than from ploughed land. It has not been possible to measure the nitrogen loss associated with tillage regime in this study. The no-till practice uses the lowest energy and also reduces nitrate leaching and permits more timely fertiliser application with minimum soil disturbance. Goss et al [182] stated that the nitrogen losses are influenced by the soil mineral N residues present, the amount of drain flow, amount of N fertiliser applied, the amount of rainfall, N uptake by the crop, the mineralization of crop residues and the tillage regime. The nitrate run off/leaching and associated emissions can be controlled by applying the correct N fertiliser level required by the crop, using advanced fertiliser techniques (use controlled release fertilisers, place fertiliser below surface, match fertiliser for seasonal conditions, widen crop rotations) and optimising the tillage, irrigation and drainage requirements [183].

The water consumption in the production of flax fibre is not considered in this study, as Turner [50] stated in the *Linseed Law* that *"flax does not need irrigating"*. In fibre production water is generally used for warm water retting and bio-retting, but the amounts of water used and emissions associated with retting process could not be determined due the lack of data availability. Retting water could result in odour due to methane and production of other gases in the retting process. It was assumed that the water used in the retting can be recycled and reused, but the waste water treatment is not included within the scope of this study.

It is believed that there is an over consumption of water by the agricultural sector, especially in some parts of the world where water availability is low and varies from year to year. Effects of increased water abstraction include salination and contamination of water, loss of wetlands and aquatic habitats and reducing the water levels in rivers and lakes resulting in water scarcity. For example, the irrigation of cotton around the Aral Sea eventually led to the body of water being eliminated and the resulting salt sea now only has 3 of 19 fish species [184]. Using recycled waste water as a grey water system for secondary uses would reduce the strain on available ground and surface water resources.

Soil erosion and soil compaction are complications which arise from agriculture and need to be addressed. Soil erosion is mainly caused by the action of water and wind in arable lowland and by frost and animals in the uplands. The main impacts of soil erosion include reduced soil water storage capacity and loss of nutrients affecting soil fertility. It was reported that, soil erosion is significantly increased where the crops are drilled up and down a slope but this results in reduced yield [173]. No-tillage has been successfully adopted in south eastern U.S. to control soil erosion and to enhance soil water conservation, especially on the sloping lands [185]. Soil compaction can result from the use of heavy machinery in agricultural operations such as ploughing, sowing and harvesting and has effects on soil biodiversity and soil structure. Soil compaction will also lead to problems such as water logging [180].

Loss of biodiversity can result directly from pest control and inorganic fertiliser use [186] or indirectly from soil erosion/compaction, pesticides/fertiliser leaching to ground and surface waters and over abstraction of water. Loss of crop diversity results from continued specialised cultivation over a long period of time, for example loss of grass land, field boundaries and tree lines. Intensification of agricultural practices also results in loss of biodiversity and crop diversity.

Asher et al [187] have used phenograms to represent changes in the number of butterflies recorded over time. On each plot, the horizontal scale represents the days in the year from 1 January – 31 December. The vertical scale represents grid lines at 100km intervals in a northerly direction with numbering corresponding to northings on the UK Ordance Survey National Grid. Coloured dots are used to indicate, on a logarithmic scale from violet = 1 through the rainbow to red = 1000, the total number of butterflies seen on each day at each latitude. Observing phenograms for an individual species in chronological order (by year or groups of years) allows changes in distribution, in first flight and in last flight days to be visualised. This technique allows trends in butterfly occurrence to be observed with sparser phenograms suggesting potential extinction.

Noise and vibration result from the use of heavy agricultural equipment and fibre processing machinery and are not included as an environmental burden in this study. It has not been possible to collect this data since it was assumed that contemporary agricultural machines and fibre processing machinery are used for the production of flax fibres, regardless of the make, individual performance or age. Noise and vibration resulting from agricultural and fibre processing machinery would vary with factors which are not considered in this study. Noise levels greater than 70dB during the day or 45dB at night are considered to be annoying [73], but the noise levels reduce with distance from the installation. Noise levels may also have an influence on wild life and hence biodiversity. In a noisy environment an animal may be unable to attract a mate in the same way as in a quiet remote location.

The photosynthetic CO_2 fixation in natural fibre plants has a positive effect on the CO_2 balance of the environment. There are several negative contributors in the production phase e.g. fertilisers, pesticides and fossil fuel use in agricultural activities. The stored CO_2 remains locked within the fibres throughout their use phase. The end of life disposal method and the durability of the natural fibre product are critical components in assessing the sequestered CO_2 within the plant or fibre as there is a possibility of returning this CO_2 into the atmosphere [188]. In general bast crops absorb 1.7-1.9 tonnes of CO_2 per tonne of bast crop cellulose produced [189]. The sequestration of CO_2 is not included in the scope of cradle-to-gate as it has not been possible to obtain the level of CO_2 equivalent materials within the flax fibres. The sequestration of CO_2 from the atmosphere will reduce the GWP in the impact assessment and help to improve the picture of ecological friendliness of using natural fibres.

CO_2 sequestration in soil can be increased by avoiding emissions into the atmosphere. Lal [190] stated that the carbon sequestration in conservation tillage practices is higher than in the conventional tillage practices. West and Marland mentioned that, changing from conventional tillage to no-till enhances the C sequestration in soil and decreases the CO_2 emissions [60]. The no-till/minimum tillage is the best way to maintain the existing CO_2 storage in soil together with other practices such as efficient use of pesticides, irrigation and heavy agricultural machinery etc. Due to the difficulty in obtaining the data for CO_2 sequestration in soil it is not included in this study.

The data presented in this study was validated against the Life Cycle Inventories developed by Swiss Centre, named "EcoInvent". Unfortunately the database does not contain any data relating to flax fibre production. The values for LCIA of glass fibres were obtained from the mentioned database and were presented in the Chapter 7.

8.2 Summary

The factors discussed in detail in this chapter include land use, food-fuel debate, loss of biodiversity, noise and vibration, water use etc which are not considered in the LCIA. Most of these factors cannot be quantified but should be addressed at least in broad terms to understand the full environmental implications of the flax fibre production in terms of the Life Cycle study.

Chapter 9. Discussion

The aim of this chapter is to discuss the findings of the Life Cycle study of flax fibre production with some reference to glass fibre as presented in the previous chapters.

In order to achieve and complete a quantitative LCA, it was necessary to fully understand all the stages in converting seeds to fibre. Based on the flow chart (Figure 4.1, Page 81) the data required (inputs and outputs) for the analysis was identified. A comprehensive survey of available information sources was used to compile tables given in Appendices B, C, D1, D2, D3 and E. These numerical data are used to inform the analysis. The various options for production of flax fibres were considered to identify the low, medium and high burden routes which were then analysed quantitatively using a model embedded in a MS Excel spreadsheet. The resulting burdens of eight environmental impact classification factors have been presented using radar plots, which clearly show where improvements for the process might improve the environmental credentials for flax fibres as reinforcement in composites.

Scenario-1 (no-till method with warm water retting) required the least energy in the production of flax fibres when compared to other two scenarios. The total energy required to produce flax sliver is 54.4GJ/tonne and yarn is 80.4GJ/tonne when these methods were used. Scenario-1 has also reported the lowest GWP, ODP, POCP and NRADP. The amount of agro-chemicals used in scenario-1 is higher than the scenario-3 (conventional tillage and bio-retting) hence the higher AP, EP, HTP and ATP values. In terms of energy, the no-till system is better than the other systems (conservation and conventional tillage), but it requires a large amount of herbicides [191]. The traditional warm water retting has been identified as the method which requires the least energy when compared to stand/dew retting and bio-retting. The wastage from warm water retting is approximately 15% higher than the bio-retting process. The mass of green flax stems is nearly halved by the stand/dew retting process wasting nearly half of the resources which include seed, land, agro-chemicals and energy. Therefore, stand/dew retting could not be regarded as an environmental friendly method of retting. The scenario-3 has the lowest values for AP, EP, HTP and ATP due to the reduced wastage and reduced agro-chemicals use. Bio-retting consumes the most energy (more than spinning) and generates the lowest wastage. Therefore, the use of seed, land and agro-chemicals is lower than other two scenarios. The agro-chemical use in the crop production phase is the main contributor towards the environmental impacts such as global warming, acidification, eutrophication, human toxicity and aquatic toxicity.

Similar fibre processing stages were considered in all three scenarios. Spinning has been identified as the most energy intensive process among the other fibre processing operations. The energy required to convert sliver to yarn (spinning process) is about 24GJ/tonne. The spinning process accounts for about 30% in scenario-1, 17% in scenario-2 and 16% in scenario-3 of the total energy required to produce one tonne of flax yarn. This is the largest single component contributing towards the energy requirement in flax fibre yarn production. Therefore, if the sliver (pre-spun fibre) is used for reinforcement instead of yarn, the amount of energy required in the production and the associated environmental impacts will be reduced. The key consideration for reducing energy consumption would be to produce aligned fibre reinforcement without the need for the energy intensive spinning operation.

Fibre orientation distribution factors (FODF) are a weighted function of $\cos^4\theta$ [46]. FODF is an indication of reinforcement efficiency and the stiffness and the strength of the material are determined by the orientation of the reinforcing fibres. Virk [192] has studied the mechanical properties of jute fibres and their composites using sliver in epoxy resin. He has measured the orientation of the sliver fibres in an image analysis program and the preliminary results give fibre orientation distribution factors in the range 0.89 to 0.71 (arithmetic mean) and 0.87 to 0.56 (geometric mean). Measurements of the twist angles in flax yarn (given in Appendix K) show an arithmetic mean of 20.32° and geometric mean of 19.80°. The average FODF values from the range reported by Virk are compared to yarn in Table 9.1. There is obviously little benefit to the mechanical properties to be gained from spinning natural fibres. The spinning process could also introduce damage to the fibres, while it might improve the handling of fibres during composites processing. The use of sliver, rather than yarn, could significantly reduce the embodied energy in the reinforcement without compromising mechanical performance.

Table 9.1 Comparison of fibre orientation distribution factors of flax yarn and jute sliver

Fibre orientation distribution factor	Yarn (Appendix K)	Sliver [192]
Arithmetic mean	0.77	0.80
Geometric mean	0.76	0.72

The results of LCA in flax fibre production should be directly compared to the LCA of glass fibre production in order to identify the most sustainable option in composite reinforcement. The results of the LCA of flax fibres are compared with some of the glass fibre production data extracted from the literature and the LCA database (EcoInvent) as it was difficult to obtain a complete data set to carry out a complete and comprehensive LCA on glass fibre production. The comparison helps to determine the environmental credential of flax fibre production in terms of energy use and the associated emissions. The energy required to produce flax fibre in scenario-1 (no-till and warm water retting) is 54GJ/tonne of sliver is compared to 55GJ/tonne of the equivalent glass fibre mat (or estimation between 67.7 - 74.9 GJ/tonne as in CES 2010 EDUPACK). The spinning process in flax fibre production raises the total energy required for yarn to 80GJ/tonne while the equivalent is 32 GJ/tonne for continuous aligned glass fibre.

Based on the energy analysis, continuous glass fibre reinforcement appears to be superior to spun flax yarn and the gains from substitution of glass fibres by natural fibres are dependent on the chosen reinforcement form in respect of the environmental benefits. According to the LCIA carried out using the literature sources, the production of glass fibres has higher values for ODP and POCP and lower values for AP, EP and HTP than flax fibre production in any of the three scenarios. There is no agreed methodology for cross comparison of the 8 EICF, so the levels of the ODP and POCP might be excessive or negligible relative to the other 6 EICF. Eco Invent LCIA confirmed the literature findings but also reported a higher HTP value for glass fibre production than flax fibre production. This could be due to the different production technologies or reinforcement formats used in Europe and USA.

The worst case (i.e. all the burden assigned to the reinforcement fibres and none to the co-products until they become waste streams) is considered in this study to identify the best practice by choosing flax fibres as the candidate fibre. Flax requires a large amount of agro-chemicals when compared to other bast fibres such as hemp or nettle. Unlike flax, hemp and nettle are less susceptible to weeds, pests or diseases [193]. Alternative bast fibres not only require less agro-chemical input but may also yield a higher percentage of long fibre.

Therefore, the production of other bast fibres would require lower energy than flax fibres and should prove to be very competitive with glass fibres.

Compiling and analysing data in this study was not straight forward and the study needs more comprehensive data to confirm the analysis. The data presented in this study are indications in terms of energy use and potential environmental impacts of flax fibre production and should not be regarded as absolute values. The data have been compiled in this study under the assumption that the flax plants are grown in their normal range/condition where irrigation is not required.

Chapter 10. Conclusions

This chapter aims to draw conclusions from the findings of the quantitative life cycle assessment of flax fibre production.

10.1 Agricultural Operations

The best agricultural practice is identified from this study to reduce the environmental impacts in the production of flax fibres for reinforcement. This includes:

- practising no-till method in ground preparation
- using organic fertiliser, at the correct levels as required by the crop according to the soil state,
- adopting biological methods to control pests

which minimise the environmental impacts caused by agricultural operations and agro-chemicals.

10.2 Fibre Extraction

Warm water retting uses the least energy and mass loss is about 20% of green flax stems from the retting process. The bio-retting method reports the highest energy in fibre extraction. But the wastage is lower than water retting (5% of green flax stems converted to yarn in bio retting vs. 4.5% in water retting and 2% in stand/dew retting) hence the lowest values for acidification, eutrophication, human toxicity and aquatic toxicity.

The selection of retting process has an overall effect on the energy consumption and the associated environmental impacts.

10.3 Fibre Separation

Spinning is identified as the most energy intensive of the fibre processing operations. Therefore, if the sliver (pre-spun fibre) is used for reinforcement instead of yarn, the amount of energy used and the associated emissions will be reduced.

The key consideration for reducing energy consumption would be to produce aligned fibre reinforcement without the need for the energy intensive spinning operation. The energy used to produce one tonne of flax sliver is comparable for glass fibre mat production. In consequence, the validity of the “green” case for substitution of glass fibres by natural fibres is dependent on the chosen reinforcement form and associated processes.

The key conclusion is that use of sliver, rather than yarn, could significantly reduce the embodied energy in the reinforcement without compromising mechanical performance.

10.4 Overall Conclusion

Although it has been possible to identify the major environmental impacts associated with flax fibre production from this research study, they cannot be treated in isolation as they are frequently inter-related. Some of these impacts are unseen for several years and the increasing environmental pressures on agriculture means that new environmental techniques need to be adopted.

Environmentally orientated agriculture is the best way forward to reduce the potential environmental impacts, which includes: preserving and improving water quality and resources, controlling soil erosion/compaction, preserving physical/chemical/biological soil quality and air quality, preserving biodiversity and reducing energy consumption by using renewable energy sources etc.

Environmental credentials for flax fibre production can be improved by adopting no-till for preparing the ground, using organic agro-chemicals, biological control of pests with traditional water retting and using sliver as reinforcement rather than yarn.

Alternative bast fibres such as hemp and nettle not only require less agro-chemical input per tonne of green stem but may also have higher yield per hectare and higher percentage of long fibre. Therefore, other bast fibres could be “greener” than flax fibres and environmental benefits can be further improved by adopting sustainable agriculture. By considering the sliver as reinforcement in polymer matrix composites will make the natural fibres superior to manmade glass fibres.

Chapter 11. Future Work

The scope of this LCA study was cradle-to-gate, which considers flax fibre production life cycle from converting seed to fibre ready for reinforcement in composites. The initial objective was to expand this scope to cradle-to-grave, but the complexity in accumulating a reliable data set made it impossible to complete. Therefore, we believe that the expansion of scope of the LCA to include use and disposal/recycling phase would help to understand the environmental impacts in the whole product life cycle. The functional unit could be regarded as a component made from natural fibre reinforced composite. It may be necessary to factor in a shorter use phase if biodegradation or other factors shorten the component life.

By leaving flax in the field to yield seed, QLCA could also be apportioned between seed, which is used as omega-3 food supplement and fibre. However the lignification of the stem would change the fibre extraction processes such as retting, scutching/decortication as the stems will become tougher with the maturity of the plant so retting consume more energy. The agro-chemical balance will change for stand/dew retting as dessicant is not used. Considering seed and long fibres primary product co-product in the QLCA will reduce the respective energy consumption and associated environmental impact potentials.

The comparative LCA of flax fibres and glass fibres is based on the assumption that the specific tensile moduli of the composites are comparable. Even though the specific moduli of the composites made out of flax fibre and glass fibre have the same numerical values, there are a number of practical issues. An equal weight of fibre, will require a greater volume of flax fibre and at equivalent fibre volume fraction this implies a greater resin matrix. The durability of the flax fibre composites will depend on the chosen life span of the final product and the conditions where it will be used e.g. highly stressed environments chemical or high moisture contained environments. The stiffness strength degradation in various environmental conditions and susceptibility under fatigue and creep loading for both flax fibre reinforced composite product and glass fibre reinforced product should be analysed and compared.

CO_2 sequestration by the fibres and soil should also be analysed within the expanded scope. As the CO_2 sequestration of the fibre is highly dependent on the end of life treatment of the final product, it could not be analysed in this study. The CO_2 sequestration value of the fibres and soil (depending on the chosen tillage regime) would influence the total value of global warming potential and this need to be investigated further.

The standard eight environmental impact classification factors are considered in this study. There are several other environmental impacts such as land use, water use and emissions in water retting, noise and vibration which need to be addressed further. The methods to calculate impacts such as loss of biodiversity, landscape etc are still developing. All possible environmental impact potentials should be included in a future analysis. Investigating methods for increasing long fibre yield, reducing energy consumption in bio-retting, improving the process by adopting different technologies will reduce all the environmental impacts and use of resources such as seed, land, agro-chemicals etc.

The data compiled in this LCA study is subject to variability as they are extracted from different literature sources, locations, climates and cultures. The reduction in variability of the data would improve comparability and will reduce the effect of errors within the study.

The study was carried out as a first step towards understanding and establishing the best practice for the natural fibre production considering the environmental view point with reference to flax fibres. Compiling reliable data for a comprehensive and quantitative LCA was very complex and the findings of this research have opened up many avenues for further research and raised many questions.

The results for flax fibres are derived on the expectation of the worst case scenario due to high levels of agro-chemical input. A quantitative and detailed LCA study on glass fibre production will complement the study undertaken and will be able to provide a better direct comparison. This thesis presents a model which will permit growers of other fibres for example hemp or nettle, (provided that they have similar mechanical properties) to provide a quantitative LCA and their respective products should be superior to glass fibres from the environmental viewpoint.

Appendix – A (Publications)

Appendix A1

Composites Part A: Applied Science and Manufacturing, October 2010, 41(10), 1329 - 1335.

A Review of Bast Fibres and their Composites. Part 1 – fibres as reinforcements

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Abstract:
Bast fibres are defined as those obtained from the outer cell layers of the stems of various plants. The fibres find use in textile applications and are increasingly being considered as reinforcements for polymer matrix composites as they are perceived to be "sustainable". The fibres are composed primarily of cellulose which potentially has a Young's modulus of ~140 GPa (being a value comparable with man-made aramid [Kevlar/Twaron] fibres). The plants which are currently attracting most interest are flax and hemp (in temperate climates) or jute and kenaf (in tropical climates). This review paper will consider the growth, harvesting and fibre separation techniques suitable to yield fibre of appropriate quality. The text will then address characterisation of the fibre as, unlike man-made fibres, the cross section is neither circular nor uniform along the length.

Introduction
Chand *et al*, [1], Lilholt and Lawther [2], and Franck [3] have reviewed the technology of natural fibres. Bolton [4], Mohanty and Misra [5], Nabi Saheb and Jog [6], Bledzki *et al* [7], Netravali [8], Baillie [9], Mohanty *et al* [10] and Pickering [11] have reviewed the use of natural fibres in polymer composites. The intention of this paper is to review the use of bast (plant stem) fibres in the context of fibre-reinforced polymer-matrix composites. This paper will not address natural fibres from animals (*eg* silk [12] or wool [13]) or those resulting from wood, seeds (*eg* coir or cotton), leaves (*eg* abaca, pineapple [14] or sisal [15]) or grasses (bamboo, miscanthus or wheat) which have at various times been considered as reinforcements for composites. Given the broad scope of this article, it will inevitably be incomplete, but will hopefully provide a sensible overview of the topic.

The majority of plant fibres which are being considered as reinforcements for polymeric materials are bast fibres, defined as fibres obtained from the outer cell layers of the stems of various plants [16]. All the important natural fibres were in textile use thousands of years ago with flax used in Egypt at least 7000 years ago. Archaeologists have found evidence that even Stone Age man knew how to twist short lengths of fibre together to form cords and yarns, using a spinning process not very different from that used in primitive parts of the world to this day [17]. Kvavadze et al [18] have recently reported finding twisted wild flax fibres indicating that prehistoric hunter-gatherers were making cords for hafting stone tools, weaving baskets, or sewing garments around Dzudzuana Cave (Georgia) up to 30 thousand years before the present.

Temperate regions

Flax: *Linum usitatissimum* [19-23] grown for fibre and linseed grown for seed oil are cultivars (varieties of the same plant species bred with an emphasis on the required product). In the UK the flax plant is normally sown in March-May and may grow to one-metre high dependent on the variety (there are 180 species [21]). The Flax Crop Production page of the Flax Council of Canada (FCC) website [23] is an especially useful resource giving comprehensive details of the husbandry of this plant. The life cycle of the flax plant has 12 distinct growth stages [19]. In 1941, flax and hemp (with wheat and spruce pulp) fibres were used in resin matrix composites for the bodywork of a Henry Ford car which was claimed to have an "impact strength 10 times greater than steel" [24]. Flax is amongst the natural fibres now finding use in thermoplastic matrix composite panels for internal structures in the car industry (including car door panels, car roof and boot linings, and parcel shelves) [25] and [26].

Hemp *Cannabis sativa L* is an annual plant native to central Asia and known to have been grown in China over 4500 years ago [21]. It probably reached central Europe in the Iron Age (circa 400 BC) and there is evidence of growth in the UK by the Anglo-Saxons (800-1000 AD). It does not require fertiliser, herbicides or pesticides to grow well (and hence is potentially of great interest in the context of sustainability). In suitable warm conditions, it can grow to 4 metres in just 12 weeks. True hemp is a fine, light-coloured, lustrous and strong bast fibre obtained by retting (see below). The colour and cleanliness vary considerably according to the method of preparation of the fibre. The lower grades are dark cream and contain much non-fibrous matter. The main producing areas are Italy, Yugoslavia and Russia [16]. The fibre ranges in length from 1.0-2.5 m. The term hemp is often used incorrectly in a generic sense for fibres from different plants, e.g. abaca (manila hemp), sisal (sisal hemp) and sunn fibre (sunn hemp) [16]. Hemp, is amongst the natural fibres now finding use in thermoplastic matrix composites for internal structures in similar automotive applications to those for flax fibres.

Nettle: European nettle *Urtica dioica* [27-29] and Himalayan nettle *Girardinia diversifolia* [30]. Nettle is another plant-stem fibre which may find application as a reinforcement. The yield of nettle fibre ranges from 335 to 411 kg/ha in the second year and from 743 to 1016 kg/ha in the third year [31]. The fibres are far stronger than cotton but finer than other bast fibres such as hemp. They are a much more environmentally friendly fibre crop than cotton, which requires more irrigation and agrochemical input. Lewington [21] states that "during the Second World War ... Britain's Ministry of Aircraft Production experimented with the use of a very strong, high-grade paper made from nettle fibre for reinforcing plastic aircraft panels as well as gear wheels and other machine parts".

Tropical regions

Jute: *Corchorus capsularis* (white jute) and *Corchorus olitorius* (dark jute) fibre is obtained from the bast layer of the plants. Each of the above classes is further sub-divided into numerous grades denoting quality and other characteristics. Jute is the second most common natural fibre (after cotton) cultivated in the world. It is an annual plant that flourishes in monsoon climates and grows to 2.5-4.5 m [21]. It is primarily grown in Bangladesh, Brazil, China, India and Indonesia. Jute-based thermoplastic matrix composites find a substantial market in the German automotive door-panel industry (growing from 4000 tonnes in 1996 to over 21000 tonnes in 1999 and rising) [21]. Typical fibre length and cross-sectional area distributions for jute fibre are given in Figures 1 and 2 respectively.

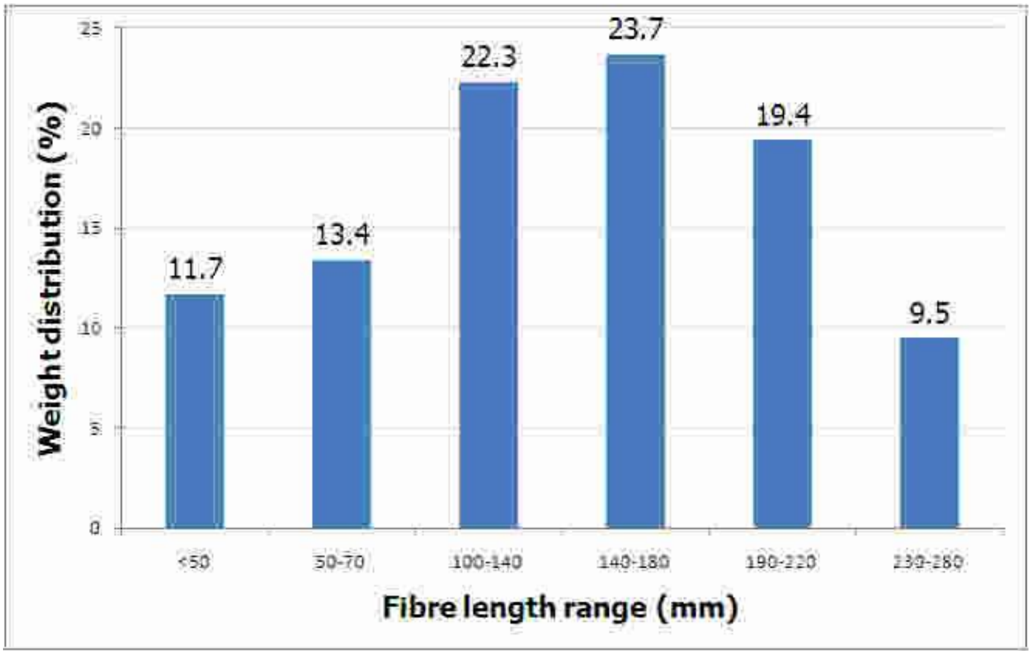

Figure 1: Fibre length distribution from 100g of jute fibres (courtesy of Richard Cullen)

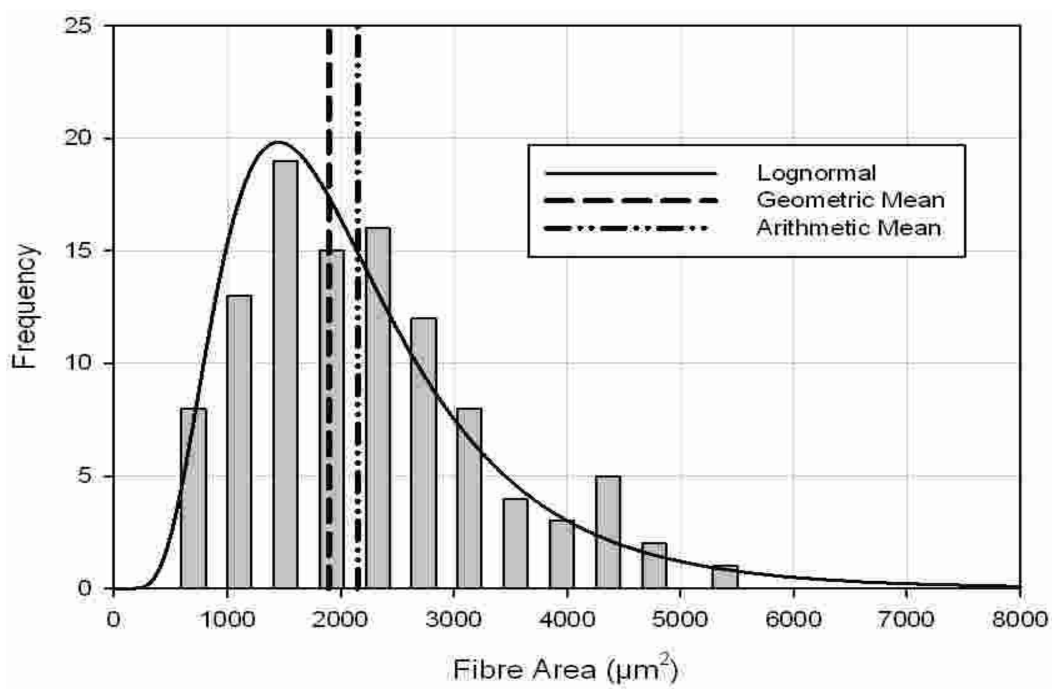

Figure 2: Distribution of fibre cross-sectional areas for jute fibres (Virk data)

Kenaf: *Hibiscus cannabinus,* is a warm season, short-day, annual herbaceous fibre plant native to central Africa, and a common wild plant of tropical and subtropical Africa and

Asia. It has been cultivated since around 4000 BC for food and fibre. It is known as *mesta* in India and Bengal, as *stockroot* in South Africa, as *java jute* in Indonesia and as *ambari* in Taiwan. The plant has a unique combination of long bast (about 35% of the stalk dry weight) with short core fibres in place of the hollow core [16] and [32]. Kenaf belongs to the Malvaceae, a family notable for both its economic and horticultural importance. Kenaf has a high growth rate, rising to heights of 4-6 m in about 4-5 months. Strong interest is being shown in this plant in Malaysia as it is fast growing and can yield two crops/year in the local climate. It can then yield a dry weight of 6000-10000 kg/ha.year (new varieties may reach 30000 kg/ha.year). It is similar to jute in many of its properties and may be used either as an alternative to, or in admixture with, jute.

Fibre growth and processing

The typical production cycle for flax is given below.

Tillage is the preparation of land for cropping by ploughing, harrowing or similar operations. Conventional tillage is preferred in flax cultivation which is primary tillage followed by early spring tillage and planting. No-till methods have been trialled by some growers with no significant change in flax yield [33]. Agricultural lime ($CaCO_3$) may be applied to maintain soil pH. For flax grown in the UK, typical levels of fertiliser are 40 kg/ha of nitrogen (N), 50 kg/ha of phosphorus (P) as P_2O_3 and 50 kg/ha of potassium (K) as K_2O [34], while for flax grown in Northern Ireland (NI), the suggested levels of fertiliser are 20 kg/ha N, 20 kg/ha P_2O_5 (equivalent to 15.5 kg of P_2O_3) and 80 kg/ha K_2O [19].

Drilling (planting) the seed usually starts at the end of February in Belgium, France and the Netherlands and ends in early April in NI. Flax is planted in narrow rows (150-200 mm apart) using similar equipment to that used for cereals. Optimum seed depth is 25-40 mm and optimum seeding rates are 35-50 kg/ha [33].

Weed control: Flax is a poor competitor with weeds which can contaminate the scutched (i.e. decorticated - see below) flax fibres. Herbicides are usually applied to control the growth of undesirable species.

Plant growth for flax consists of a 45-60 day vegetative period, a 15-25 day flowering period and a maturation period of 30-40 days and is well illustrated in Turner [19].

Dessication (drying) of the crop has numerous advantages over field retting (see below) including earlier harvesting, elimination of the need for swathing (lying after being cut), reduction in combining time and less wear and tear on machinery. A glyphosate chemical treatment is typically applied 10-14 days after full flower (at about mid-July in NI). Glyphosate is only used where stand retting (see below) is adopted followed by direct combine harvesting of the crop.

Harvest is normally in August or September by either combine harvester or pulling, The latter is more labour intensive but yields fibre with less damage.

Rippling is the removal of flax seed capsules by drawing stems through a coarse steel comb.

Retting is the subjection of crop or deseeded straw to chemical or biological fermentation treatments to make the fibre bundles more easily separable from the woody part of the stem. Flax can be stand-retted (before harvest), dew-retted (cut and left in in the field), water-retted (immersed in tanks) or chemically–retted (in process tanks). Enzymes (*e.g.* pectinase digests the pectin binder [35]) may be used to assist the retting process. Termination of the retting process may be a problem and failure to achieve this can result in reduced fibre properties. Pre-harvest stand-retting of flax, when glyphosate is applied at the mid-point of flowering, depends on uniform desiccation of the entire stem and is difficult to achieve during a dry season [36]. Both dew-retting and stand-retting of the desiccated flax in the field rely on invasion by natural microorganisms and are dependent on the vagaries of the weather.

Decortication [37, 38] is the mechanical removal of non-fibrous material from retted stalks or from ribbons or strips of stem to extract the bast fibres. This is usually achieved by a manual operation, hammer mill, inclined plane/fluted rollers or willower. Specifically for flax, the process is often referred to as “scutching”

Hackling is the combing of long (line) flax fibres in order to remove short fibres, to parallelise the remaining fibres and also to remove any extraneous matter (shive).

Carding is a process to disentangle and align fibres by working them between two closely spaced, relatively moving surfaces clothed with pointed wire, pins, spikes or saw teeth. The product is known as **sliver**.

Gilling (or pin drafting) is combing of the sliver to decrease the mass per unit length.

Spinning is the drafting and twisting of natural (or man-made) fibres to produce **yarn** (also known as filaments). In the bast-fibre industry, the terms ‘wet spinning’ and ‘dry spinning’ refer to the spinning of fibres in the wet state or in the dry state respectively.

A similar growth and processing route to that described above is followed for the production of the other bast fibres. Flax is probably the most labour and agrochemical intensive of the bast fibres [16], The other natural fibres normally have reduced agro-chemical inputs and will thus impose a lower environmental burden.

Subsequent treatment of natural fibre textiles [16] may include:

Acetylation: the process of introducing an acetyl radical into an organic molecule. The term is used to describe the process of combining cellulose with acetic acid (or precursors for the acid). The reduced number of hydroxyl groups after acetylation confers a more hydrophobic character to the fibres.

Bleaching: any procedure (other than scouring alone) of improving the whiteness of textile material by decolorizing it from the grey state, with or without the removal of natural colouring and/or extraneous substances. The removal of colour from dyed or printed textiles is usually called “stripping”.

Grafting: the incorporation of monomers (e.g. cyanoethylation: reaction with acrylonitrile) or oligomers (short chain polymers) at the fibre surface by chemical reaction.

Mercerisation: the treatment of cellulosic textiles in yarn or fabric form with a concentrated solution of caustic alkali [soda], whereby the fibres are swollen, the strength and dye affinity of the materials are increased, and their handle is modified. The process takes its name from its discoverer, John Mercer (1844).

Scouring (solvent treatment): the treatment of textile materials in aqueous or other solvents in order to remove natural fats, waxes, proteins and other constituents, as well as dirt, oil, and other impurities.

Kalia [39] has recently reviewed pretreatments for natural fibres intended to improve their effectiveness when used as the reinforcement in polymer composites.

Characterisation of the fibres

Chemical and physical structure

The principal components of the fibre cell walls are cellulose, hemicelluloses and lignin with pectin normally considered to be the main binder (Table 1).

Component	***Minimum proportion***	***Maximum proportion***
Cellulose	67.0%	78.3%
Hemicellulose	5.5%	16.1%
Lignin	2.9%	3.3%
Pectin	0.8%	2.5%

Table 1: Proportions of the principal components of raw hemp bast – data from [40].

Cellulose is the most important structural component of nearly all green plant cell walls, especially in many natural fibres (flax, jute, hemp, cotton, *etc*). The *cellulose* polymer is composed entirely of carbon, hydrogen and oxygen (the molecular formula can be written as if it consisted of only carbon and water, hence the name *carbohydrate*). Cellulose is a polysaccharide $(C_6H_{10}O_5)_n$ which can be degraded to give only glucose $(C_6H_{12}O_6)$. The smallest repeat unit is cellobiose $(C_6H_{11}O_5)_2O$ formed by the condensation of two glucose units and hence is also known as *anhydroglucose* (glucose minus water). Cellulose is a strong, linear (crystalline) molecule with no branching. Cellulose has good resistance to hydrolysis although all chemical and solution treatments will degrade it to some extent. Resources on cellulose can be found at references [41-44].

Hemicelluloses are lower molecular weight polysaccharides, often copolymers of glucose, glucuronic acid, mannose, arabinose and xylose, which may form random, amorphous branched or nonlinear structures with little strength. Hemicellulose is easily hydrolyzed by dilute acids or bases, but nature also provides an arsenal of hemicellulase enzymes for its hydrolysis. These enzymes are commercially important because they open up structure bound cellulose materials [45-47].

Lignin [47] is formed by non-reversible removal of water from sugars (primarily xylose) to create aromatic structures. Lignification progresses as the plant matures conferring mechanical stability to the plant. As lignin becomes more rigid, it is localised away from the lumen surface and porous wall regions to maintain wall strength and permeability and help with the transport of water [48]. Lignin resists attack by most microorganisms as the aromatic rings are resistant to anaerobic processes while aerobic breakdown of lignin is slow.

Vincent [49] states that the elementary fibril of cellulose is about 3.5 nm diameter and contains about 40 molecules. The cellulose elementary fibrils can be arranged into larger fibrils of 20-25 nm diameter. They are formed by neighbouring cellulose chains forming hydrogen bonds leading to partially crystalline regions (micelles). These form a strong structural framework in the cell walls. Cellulose found in plants as microfibrils may be 2-20 nm diameter and 100 nm - 40 μm long) [42].

Mechanical properties

Cellulose has been estimated to have a modulus of 140 GPa when using X-ray diffraction to determine the strain [49]. A slightly higher figure has been obtained by calculation from the chemical structure of the crystal with consideration of the straightening of the covalent bonds and stretching of the interchain hydrogen bonds. If hydrogen bonding is not included in the calculation, then the modulus drops by a factor of ~8. Experimentally measured moduli will inevitably be lower than theoretical values (due to <100% crystallinity and off-axis fibre orientation). Nevertheless, Vincent has reported values of 100 GPa for dry flax and ~80 GPa for wet flax. As water penetrates the amorphous regions of cellulose, the stiffness can drop by a factor of 2-4 as the contribution of the hydrogen bonding is progressively removed. Table 2 presents some mechanical property data for bast fibres.

Properties	**Fibre**					
	E-glass[50]	**Flax[51]**	**Hemp [50]**	**Jute[50]**	**Kenaf**	**Nettle [54]**
Density kg/m^3 (ρ)	2550	1530	1520	1520	1193 [52]	-
E-modulus (GPa)	71	58 ± 15	70	60	14-38 [53]	87 ± 28
Tensile strength (MPa)	3400	1339 ± 486	920	860	240-600 [53]	1594 ± 640
Specific modulus (E/1000ρ)	28	38	46	39	12-32	-
Elongation at failure (%)	3.4	3.27 ± 0.4	1.7	2	-	2.11 ± 0.81
Moisture absorption (%) [55 via 56]	-	7	8	12	-	-

Table 2: Typical properties of some bast fibres, with comparative values for E-glass

Plant/technique	θ° (range)	θ° (average)	Source
Cannabis sativa (hemp)			
optical microscopy: major extinction position	0.0 - 5.0	2.3 ± 0.3	[58] (Kundu and Preston, 1940)
striations	0.0 - 6.0	2.0 ± 0.3	[58] (Kundu and Preston, 1940)
Corchorus capsularis (jute)			
optical microscopy: major extinction position	0.0 - 23.0	7.9	[59] (Preston, 1941)
Agave sisalana (sisal leaf fibre)			
optical microscopy: major extinction position	8.0-32.3	20.4 ± 7.2	[60] (Preston and Middlebrook, 1949)
x-rays		18	[60] (Preston and Middlebrook, 1949)

Table 3: The angle between the cellulose chains and cell length [57]
(extracted from RD Preston, *The Physical Biology of Plant Cell Walls*, 1974, page 293)

Table 3 presents the winding angle of the cellulose molecule relative to the principal axis for some natural fibres. Figure 3 presents reported elastic moduli against winding angle for several plant fibres. The Krenchel [62] equation permits calculation of the effectiveness of a mis-aligned fibre reinforcement, as a fibre orientation distribution factor, using the proportions of fibre at each angle and the fourth power of the cosine of the angle between the fibre and the reference direction. The $\cos^4\theta$ line is forced through the data point for cotton (seed fibre) in the Figure to indicate the applicability of this model to the molecular winding angle in the fibre for this limited data set regardless of the source of the fibre.

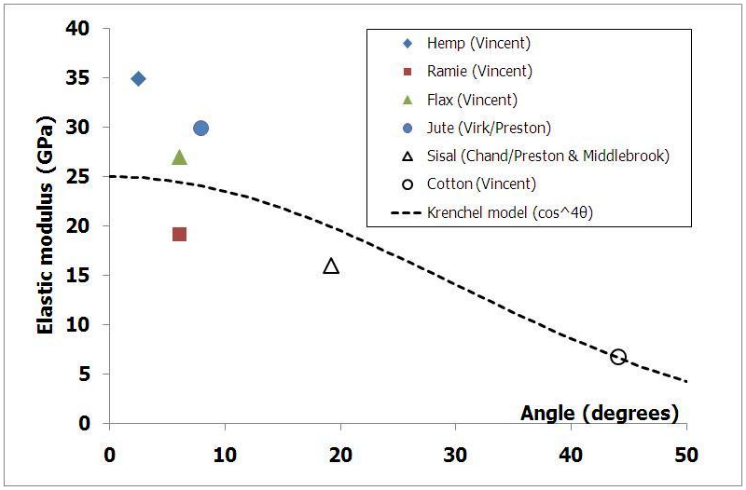

Figure 3: The dependence of the elastic modulus of plant fibres on the angle between the cellulose molecules and the fibre principal axis for bast fibres (solid markers), leaf fibres (sisal) and seed fibres (cotton): data from Chand *et al* [1], Vincent [49], Preston [59] and Preston and Middlebrook [60] and Virk [61] with the Krenchel [62] $\cos^4\theta$ dependence on the orientation forced though the cotton data.

Fibre Quality

Unlike synthetic reinforcement fibres, the natural fibres are perceived to have significantly greater variability in their mechanical properties as a consequence of the conditions experienced in the field and the potential damage arising from the above processes, especially over-retting. The harsh conditions during harvest may introduce damage and it is common to see mechanical damage in extracted fibres.

The textile industry, and many researchers in the composite field, assume that fibres are of a regular circular cross-section and use microscopy transverse to the principal axis to determine a characteristic dimension (incorrectly referred to as the diameter). Figure 4 is a confocal scanning laser microscope image of a cluster of elementary jute fibres: these fibres (which are typical of bast fibres) are clearly not round. Further the dimensions of each cell in the fibre will change along the length.

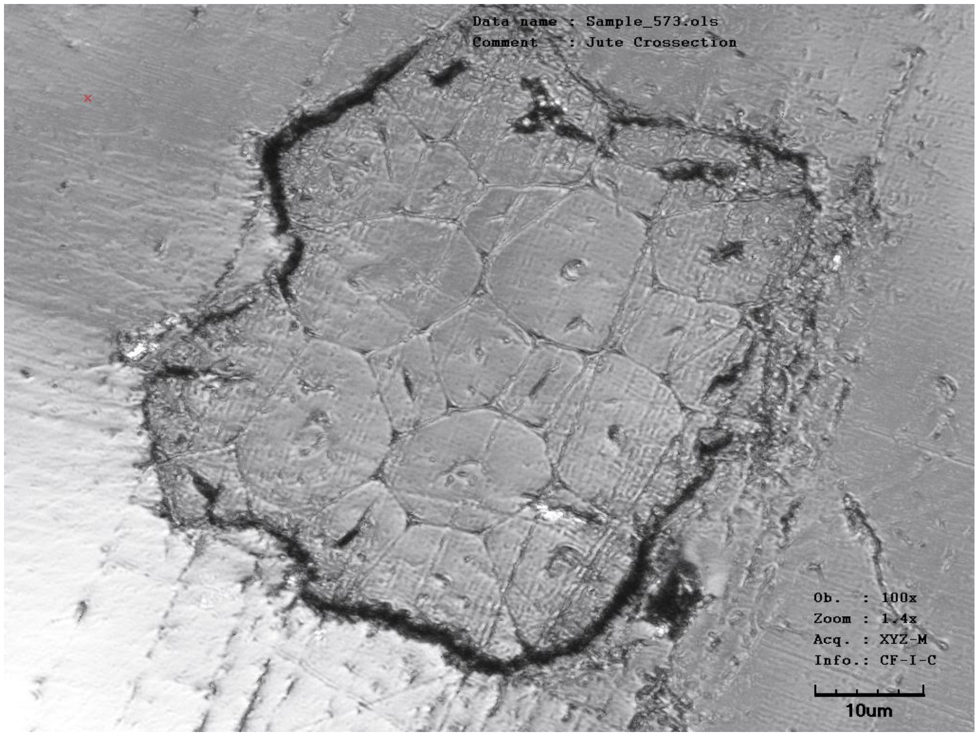

Figure 4: Confocal Scanning Laser Microscope (CSLM) image of a cluster of elementary jute fibres, (image acquired by Amandeep Singh Virk).

Figure 4 also shows that each elementary fibre normally has a central hollow channel (the lumen). This feature will introduce additional porosity into the composite (voids within synthetic fibres are comparatively rare) and will reduce the cross-section of fibre material available to carry load.

The elastic modulus (and ultimate tensile strength) of the individual filaments can be determined by ASTM D3379-75 (now withdrawn), Grafil Test Method 101.13 [63] for 50 mm fibres or the French norm NFT25-704. The corresponding values for fibre tows can be determined by Grafil Test Method 103.22 [63]. However, these methods tend to assume that the fibre has a regular cross-section with no lumen.

Virk et al [61] undertook one hundred tensile tests at each of five distinct fibre lengths (6, 10, 20, 30 and 50 mm) on a single batch of jute fibres. The Young's modulus was found to be 30 GPa while the ultimate strength and fracture strain fell from 558 to 336 MPa and from 1.79 to 1.11 % respectively as the length increased from 6 to 50 mm.

Virk et al [64] studied the mechanical characteristics of 785 jute technical fibres in batches of at least 50 at each of 10 lengths ranging from 6 mm to 300mm. Fracture strain was found to be a more consistent parameter than strength (fracture stress). Coefficients of variation (COV) for each batch were in the range 0.19-0.35 for fracture strain and in the range 0.33-0.46 for strength, with the mean COV for strain reduced by at least 25% relative to that for strength. Note that failure strain is independent of the fibre cross-sectional area while the strength relies on an accurate determination of the cross-sectional area. The variability in the strength of natural fibres arises from the methods used for determination of cross-sectional area especially where an effective diameter is derived from linear measurements.

Research opportunities

Stochastic variation

Kittl and Diáz [65] have reviewed the state of the art in probabilistic strength of materials and Weibull fracture statistics. In [66], van der Zwaag reviewed the concept of filament strength and the Weibull modulus. However, these papers are now twenty years old and it would timely to see a new review specific to the application of statistical techniques to natural fibres and their composites.

Fibre degradation

The thermal decomposition temperature of cellulose fibres is generally regarded as being around 200ºC, although this response is obviously a function of time at temperature, and will limit the choice of the polymer matrix system for composites. Initial decomposition of cellulose fibres occurs primarily in the amorphous regions. Table 4 summarises the data reported for thermal degradation of flax fibres. Ray et al [67] reported that the decomposition temperature for crystalline α-cellulose in untreated jute fibres was 362.2 ºC, but fell to 348 ºC after mercerisation. Kim et al [68] studied three forms of α-cellulose and found that the decomposition began at 285 ºC (Funacel microcrystalline cellulose), 305 ºC (cotton) and 325 ºC (*Holocynthia*) with rapid weight loss at 315-360 ºC, 340-380 ºC and 370-410 ºC respectively. The activation energy was in the range 159-166 kJ /mol regardless of the type.

Temperature (°C)	Time (minutes)	Decrease in strength (%)	Reference
170	120	0	72 Gassan
180	60	24	73 Wielage
200	30	36	73 Wielage
200	60	47	74 Kohler
210	120	50	72 Gassan
220	60	62	73 Wielage
250	4	20	75 Mieck
250	12	57	75 Mieck

Table 4: Thermal degradation of flax fibres

The cellulose molecule is hydrophilic and hence the fibre properties are sensitive to the relative humidity of the environment in which they are processed and/or used. This topic deserves a review paper in its own right.

The fibre-matrix interface

The realisation of the full mechanical performance of the reinforcement is critically dependent on the effective load transfer by shear over the “half critical length” at each fibre end, which in turn is a function of the chemical and physical bonds between the fibre and the matrix. The main approaches to enhancement of the interaction between the fibre and the matrix are surface modification of the fibre (grafting or other chemical/physical treatments), application of coupling agents to the fibre surface and/or the use of compatibilisers in the matrix. George et al [69] have critically reviewed the physical and chemical treatments that may improve the fibre-matrix adhesion. They conclude that good compatibility between cellulose fibres and non-polar matrices is achieved using polymers that favour entanglement and interdiffusion with the matrix. A new review to update that by George et al [69] would be timely.

Xie et al [70] have reviewed the use of silane coupling agents in natural fibre/polymer composites. They concluded that proper treatment of fibres with silanes can increase the interfacial adhesion and improve the mechanical and outdoor performance of the resulting composites. However, the Si-O-C bonds in natural fibre composites are less stable under hydrolysis than the Si-O-Si bonds in glass fibre composites [71].

Reinforcement Forms for Composites

The effective utilisation of the properties of a fibre as a reinforcement is a function of the fibre length and the fibre orientation with respect to the stress (see Prediction of mechanical properties in Part 2 of this review). These two fibre parameters are generally present with a statistical variation and hence are measured as the fibre length distribution factor (η_l) and the fibre orientation distribution factor (η_o). Both parameters range between 0 (short fibres or alignment transverse to the stress respectively) and 1 (continuous fibres or aligned with the stress respectively). Typical reinforcement forms are unidirectional (η_l =1 and η_o =1 when continuous fibres are aligned with the stress), woven fabrics (η_l =1 and η_o = 0.5 when one set of fibres is aligned with the stress) and random chopped strand mats (η_l <1 and η_o = 3/8).

Increasing alignment of the fibres enables more fibre to be incorporated into the composite. For practical purposes, the limiting fibre volume fractions are around 75% (unidirectional), 65% (woven) or 30% (random orientation). A major constraint on the effective use of natural fibre reinforcements is that the materials supply chain has not had a cost-effective environmentally-friendly methodology for the production of woven or otherwise aligned fabrics.

SUMMARY

This review paper has considered the growth, harvesting and fibre separation techniques suitable to yield bast fibre of appropriate quality for use as the reinforcement of polymer-matrix composites. The text then addressed the characterisation of the fibre. Bast fibres have weight specific properties which may be superior to the corresponding properties of glass fibre reinforcements and are perceived as being less problematic in the context of environmental burden. However, there are a number of factors which could constrain the commercial adoption of these fibres as reinforcements:

- Plants grown in temperate zones are normally harvested in late summer or autumn which has significant implications for the supply chain.
- Fibre properties are dependent on the weather during the growing season
- Fibres may suffer mechanical damage during mechanised harvesting.
- Fibres are extracted from the plant stem by retting, but it is difficult to determine the correct point at which to terminate the process and over-retting can reduce the fibre properties.

- The proportion of fibre extracted from a stem may be <10% by weight and the co-products are of low commercial value (short fibre for paper or animal bedding, or compressed dust as a fuel).
- Fibre as sliver could replace random mat reinforcements, but it is necessary to spin the fibres to produce continuous yarns for the production of reinforcement fabrics.
- Fibres have an irregular cross section with a central void (lumen) which makes the determination of their mechanical properties more complex than for solid circular glass fibres.
- Cellulose is a hydrophilic molecule, so the fibres have properties which are dependent on the water content.
- Fibres degrade over time at temperatures of ~200ºC or higher, so the choice of matrix system for the composite is limited.

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Appendix A2

Composites Part A: Applied Science and Manufacturing, October 2010, 41(10), 1336 - 1344.

A Review of Bast Fibres and their Composites. Part 2 – composites

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Abstract:
Bast fibres are defined as those obtained from the outer cell layers of the stems of various plants. The fibres find use in textile applications and are increasingly being considered as reinforcements for polymer matrix composites as they are perceived to be "sustainable". The fibres are composed primarily of cellulose which potentially has a Young's modulus of ~140 GPa (being a value comparable with man-made aramid [Kevlar/Twaron] fibres). The plants which are currently attracting most interest are flax and hemp (in temperate climates) or jute and kenaf (in tropical climates). Part 2 of this review will consider the prediction of the properties of natural fibre reinforced composites, manufacturing techniques and composite materials characterisation using microscopy, mechanical, chemical and thermal techniques. The review will close with a brief overview of the potential applications and the environmental considerations which might expedite or constrain the adoption of these composites.

Prediction of Mechanical Properties
The elastic modulus of a composite material can normally be predicted using the standard rule of mixtures (Equation 1) [1]:

$$E_c = \eta_l \eta_o V_f E_f + V_m E_m \qquad \textbf{Equation 1}$$

where η_l is the fibre length distribution factor, η_o is the fibre orientation distribution factor, E_f is the elastic modulus of the fibre (Vincent [2] has estimated a modulus of up to 140 GPa for cellulose fibres), E_m is the elastic modulus of the matrix, V_f is the fibre volume fraction and V_m is the matrix volume fraction (assuming $V_f + V_m = 1$, i.e. no voids or other inclusions). At this stage in the review, we have neglected the void which occurs within the fibre on the expectation that it will not influence the above. There is an interdependency within $V_f E_f$ given that the fibre cross-section and modulus could be calculated on the gross area or the net area after taking the lumen into consideration. The previous assumption would then become $V_f + V_m + V_v + V_l = 1$, where V_v is the volume fraction of voids in the matrix and at the interface and V_l is the volume fraction of lumen as a proportion of the whole composite.

Effect of voids

Madsen et al [3] have developed a model to predict the volumetric composition (volume fractions of fibres, matrix and porosity) and density of composites as a function of the fibre weight fraction. The model is particularly aimed at plant fibre composites, but is also valid for all other composites. The porosity is initially divided into three parts associated with the fibre, the interface and the matrix. Madsen et al [4] have presented a modified rule of mixtures to include the influence of porosity on the composite stiffness. The model (Equation 2) integrates the volumetric composition of the composites with their mechanical properties.

$$E_c = (\eta_l \eta_o V_f E_f + V_m E_m)(1 - V_p)^n \qquad \textbf{Equation 2}$$

where V_p is the volume fraction of porosity derived from weight fractions of the other components and n is a *porosity efficiency exponent* quantifying the effect of porosity which gives rise to stress concentrations in the composites. When $n = 0$, the porosity in the composite has no effect beyond lowering the load bearing volume. The model was validated with experimental data for volumetric composition and stiffness for several (plant) fibre composites.

Effect of fibre diameter

Lamy and Baley [5] conducted tensile tests on flax fibres of different diameters, d_i, and found that the Young's modulus for each class, E_i, decreased with increasing fibre diameter, where i is the class number (Table 1). They have proposed Equation 3 for the longitudinal elastic modulus, E_L, of a unidirectional flax-fibre composite material:

$$E_L = V_f \sum_{i=1}^{n} \frac{n_i d_i^2}{\sum_{i=1}^{n} n_i d_i^2} E_i + V_m E_m \qquad \textbf{Equation 3}$$

where n_i is the number of samples (in classes of width 2.5 µm for diameters between 5-35 µm) and E_i is the Young's modulus of fibres in the range i. For the sample of fibres tested, K_i is the contribution of n_i fibres of mean diameter d_i to an effective elastic modulus E_f of 59 GPa which in turn gave a reasonable prediction of the composite modulus.

Table 1: Dependence of properties of flax fibre on fibre diameter

(Tables 1/2 of Lamy and Baley [5])

Class i	1	2	3	4	5	6	7	8	9	10	11	12
$\mathbf{n_i}$	6	44	84	136	170	143	121	83	45	25	7	5
$\mathbf{d_i}$ **(µm)**	6.8	8.8	11.2	13.9	16.2	18.8	21.2	23.6	26.2	28.6	32.1	34.5
$\mathbf{E_i}$ **(GPa)**	79	76	72	69	65	62	58	55	51	47	43	39
$\mathbf{K_i}$ **(MPa)**	73	860	2530	5990	9670	10350	10520	8400	5230	3230	1020	770

Table 1: Dependence of properties of flax fibre on fibre diameter (Tables 1/2 of Lamy and Baley [5])

The dependence of the modulus of the composite, calculated using Equation 3, against fibre volume fraction correlated well with the experimental results. It was noted that selection of fibre diameters could be a route to improvement of the elastic properties of flax fibre reinforced epoxy resin composite materials. Baley [6] reported a decrease in the Young's modulus with increasing fibre diameter for flax fibres (Fig.1a). Bodros and Baley [7] found that the Young's modulus and the stress at break of nettle fibres decreased when the fibre diameter increased (Fig. 1b).

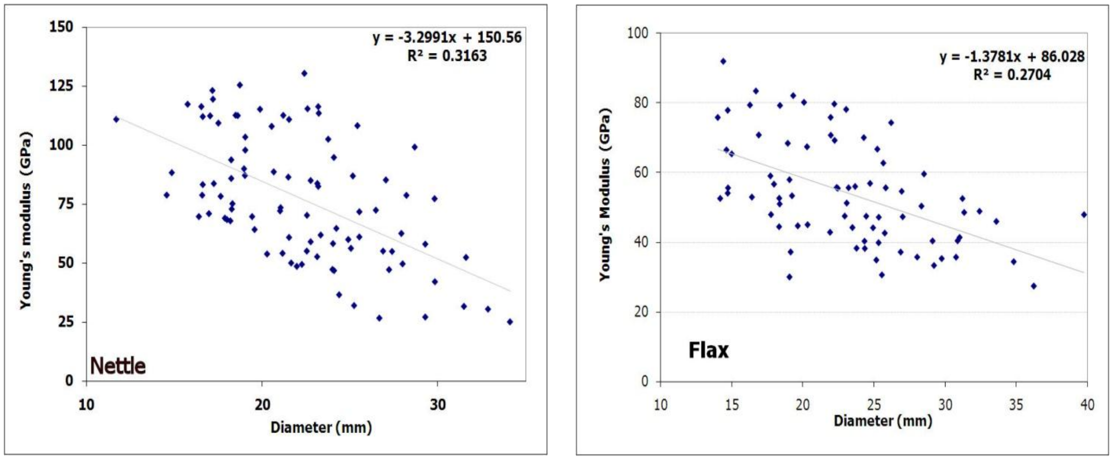

Figure 1: Young's modulus as a function of fibre diameter for (left) flax and (right) nettle
(reproduced from data, published in [5] and [7] respectively, kindly provided by C Baley with permission for use here)

The authors of this review propose a modification of the rule of mixtures through the use of a fibre diameter distribution factor, η_d, (with values in the range 0-1) to produce Equation 4. This fibre diameter distribution factor will be related to the probability density function for the fibre diameter, which could be obtained from a comprehensive study of the chosen fibre and may well correlate to the factor given in Equation 3. Derivation of that parameter is beyond the scope of this review.

$$E_c = \eta_d \eta_l \eta_o V_f E_f + V_m E_m \quad \textbf{Equation 4}$$

This equation might be modified to incorporate the *porosity efficiency exponent* above.

Composites Processing

The techniques for the manufacture of fibre-reinforced polymer matrix composites have been reviewed by Åström, Gutowski , Davé and Loos and Campbell [8-11], albeit that their emphasis is very much on synthetic fibres and thermosetting resins. Thermoset processes have been considered in greater detail:

- vacuum bagging, including autoclave cure [12-14]
- Compression moulding [no key text]
- Liquid Moulding Technologies (LMT) or Liquid Composite Moulding (LCM), including Resin Transfer Moulding (RTM) [15-21].
- Resin Infusion under Flexible Tooling (RIFT) [22-25].

- Filament winding [26].
- Pultrusion [27, 28].

The latter two processes will require that the natural fibres be spun to form a continuous yarn

For thermoplastic matrix composites, there are additional processes including extrusion (for constant cross section) and injection moulding. LMT and RIFT are possible only with a few thermoplastic systems supplied as low viscosity monomers and these are normally polymerised in-process. Vacuum bagging, filament winding and pultrusion are also possible.

Glass fibres are generally assumed to be homogeneous and isotropic, although Stockhorst and Brueker [29] have shown a very small preferred orientation through stress optical investigation. Bast fibres are generally heterogeneous and anisotropic and thus closer to the structure of carbon and especially aramid fibres. Pinzelli [30] reviewed the state-of-the-art in cutting and machining of composite materials based on aramid fibre reinforcements, and recommended that a band-saw with a fine tooth blade (14-22 raker-set or straight-set teeth/inch [~5-9 teeth/cm]) operating at high surface speeds with the running blade teeth pointing upwards (reverse) should minimise the production of fuzz and keep the teeth from snagging fibres. Cullen [31] machined flax/jute epoxy composites using a band saw with 7 teeth/cm (18 teeth/inch) running in either the forward or the reverse direction. The reverse configuration cut the fibres much more cleanly than when running with the teeth facing forwards. The Pinzelli report considers other aspects of machining aramid composites which may be relevant to natural fibre composites.

Materials characterisation

The determination of the parameters required for the rule-of-mixtures can be achieved in a variety of ways, including the Grafil [32], Composite Research Advisory Group (CRAG) [33] or (inter-)national standard procedures. Optical or electron microscopical techniques with image analysis [34-36] may be used to determine η_d, η_l, η_o and volume fractions of the components (fibre, matrix and voids including lumen) in the composite materials. For natural fibres in a resin matrix, it will normally be necessary to enhance the contrast between the components (by *e.g.* polarising filters, fluorescence or staining techniques - Dubot [37] used methylene-blue as a stain for linseed fibres). Grafil Test Method 102.13 uses microscopy with an image splitting eyepiece to determine individual fibre diameters.

Optical coherence microscopy (OCM, also known as optical coherence tomography (OCT)) is a novel imaging technique which permits the acquisition of tomographic images with high resolution (~15 μm in three dimensions) and a high dynamic range (>100 dB). . Reeves *et al* [38] have applied OCM to visualise the cellular and subcellular structures within intact *Arabidopsis* plants (including leaves, flowers, ovules and seeds).

Thumm [39] has used confocal microscopy to determine the interfacial behaviour and (non-) interactions in plant fibre composites. Labelled dyes were added to the polymer matrix to enhance the fluorescence. The extent of interaction was indicated by line profiles of the fluorescence for each component.

The determination of volume fraction of the composite is problematic and will be dependent on the moisture level and any consequent changes in the dimensions and weight of hygroscopic natural fibres (and will be a function of changes in the ambient relative humidity and of diffusion rates). A graph of fibre density against moisture content would provide useful data. Subject to the constraints above, the fibre volume fraction of composite materials may be obtained by appropriate manipulation of data from the following methods [32, 33]:

- tow counting for unidirectional composites in an open-ended mould (Grafil Test Method 302.24) or from fabric areal weight in a moulding of known thickness (CRAG method 1000-2).
- direct weighing (Grafil Test Method 302.13) when a closed mould is used and no fibre is lost in the moulding flash. The mass fraction is then the mass of fibre divided by the mass of the composite after fabrication. Accurate values of the density of the components are necessary to convert the mass fraction to a fibre volume fraction.
- density gradient column (Grafil Test Method 301.12) which is based on observing the level to which the test specimen sinks in a column of liquid when the density of liquid changes uniformly with height. The absorption of liquid by the test specimen may complicate the analysis for this technique when natural fibres are under test.
- Archimedes principle (Grafil Test Method 301.21. CRAG methods 800/1000-1) using weight measurements in air and in water. The absorption of liquid by the test specimen may complicate the analysis for this technique when natural fibres are under test.
- resin burn-off (CRAG method 1000-3c) in an oven at 580-600°C. This method is inappropriate for natural fibre composites as both components of the composite will burn. It may be possible to use Thermo Gravimetric Analysis (TGA, possibly in combination with both normal and inert atmospheres) to determine the volume fraction if the two components have clearly differentiated decomposition temperatures. The technique has been used by Sharma *et al* [40-42] to characterise the components of flax fibres.
- chemical digestion using sulphuric acid and hydrogen peroxide (Grafil Test Method 302.56. CRAG method 1000-3a) or nitric acid (CRAG method 1000-3b). It may be necessary to select different chemicals for natural fibre composites. Green [43] has proposed the use of a microwave acid digestion bomb for the determination of fibre volume fraction of carbon-epoxy composites. This may be suitable for natural fibre composites. The "bomb" is a sealed chemically-inert vessel in which microwave heating can be used for rapid sample dissolution. These bombs can be placed directly in a microwave oven for specific, high speed heating to drastically reduce the time required to dissolve or digest an analytical sample [44].

An even more challenging task is the determination of porosity levels. For high performance composites, voids are assumed to be randomly distributed and to occur only in the matrix. The resolution of void volume fraction is normally taken to be no better than ±0.5%. However, with plant fibre reinforcements, porosity may be found in any of the components of the composite. The Grafil test method 303.14 [32] (intended for hydrophobic carbon fibres) has a Standard Density Method for Void Content determined from the mass of fibre in a mass of composites when the density of the fibre and the resin are known and the density of the composite is determined experimentally. CRAG test method 1001 [33] (again intended for man-made fibre composites) describes an ultrasonic scanning technique and requires appropriate calibration blocks.

Typical mechanical properties for natural fibre reinforced polymer matrix composites are given in Table 2 and plotted against predictions using the rule of mixtures (Equation 1) in Figure 2.

Fibre	**Matrix**	**Configuration**	**% fibre**	**E (GPa)**	**σ' (MPa)**	**ε' (%)**	**Ref**	**Source (NB: this column is to ensure reference numbers are correct – it should not be published)**
Flax	Epoxy	unidirectional	40	28	133	n/a	45	Van der Wegenberg et al (2003)
Flax	PLLA	aligned roving	40 v/o	7.3±0.5	44.1±7.2	0.9±0.2	46*	Oksman et al (2003)*
Flax	PLLA	random mat	30 v/o	9.5	99	1.5	47*	Bodros et al (2007)*
Hemp	UP resin	mat	44 w/o	6.2±0.6	53.0±6.0	1.39±0.26	48	Yuanjian & Isaac (2007)
Hemp	PP	injection moulded	40 w/o	5.3	50.5	n/a	49	Beckerman & Pickering (2008)
Jute	PP	injection moulded	50 w/o	5.5±0.3	32.0±0.5	n/a	50	Karmaker & Schneider (1996)
Jute	PP/MAPP	injection moulded	50 w/o	5.4±0.4	57.9±0.4	n/a	50	Karmaker & Schneider (1996)
Nettle	Epoxy	unidirectional	24 v/o	9	91	n/a	51	Merilä (2000)

Nettle	Phenolic	unidirectional	23 v/o	5	13	n/a	51	Merilä (2000)

Table 2: Typical properties of natural fibre reinforced polymer matrix composites (nb: specific results* reported here are for the composite with highest elastic modulus reported in each paper)

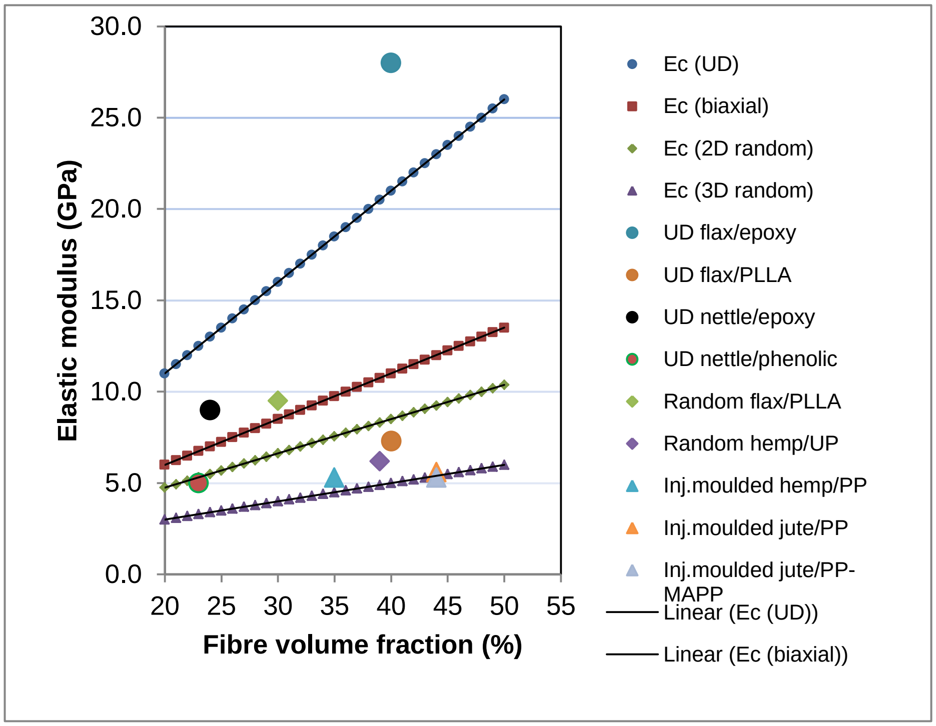

Figure 2: Variation of Young's modulus with fibre orientation plotted against fibre volume fraction (a constant fibre modulus of 50 GPa has been assumed for the trendlines)

Effect of water

A potential problem with natural fibre reinforced polymer matrix composites is the hydrophilic nature of the cellulose fibres and hence the moisture sensitivity of the resulting composites. Khalil et al [52] have studied the acetylation of plant fibres in the context of improvement of the mechanical properties of composites. Bast fibres from jute and flax were considered (along with coconut fibre (coir), oil palm empty fruit bunch (EFB) and oil palm frond (OPF)). The two bast fibres were found to be the least reactive of the five fibres studied.

Costa and D'Almeida [53] studied the effect of water absorption on the flexural properties of jute or sisal fibre reinforced polyester or epoxy matrix composites. The diffusion behaviour in both composites could be described by the Fickian model. Of the four systems studied, the jute-epoxy composites showed the best mechanical properties and still had superior performance after exposure of the composites to distilled water (Figure 3). This behaviour was attributed to a better fibre-matrix interface and better moisture resistance of jute fibres.

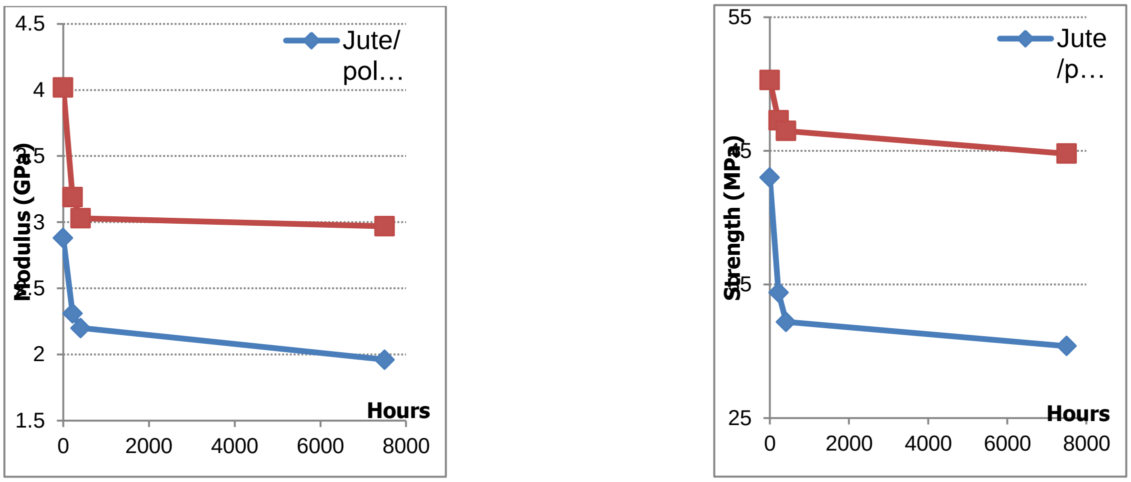

Figure 3: The deterioration of flexural modulus and strength for jute fibre composites exposed to distilled water for 0, 220, 410 or 7500 hours (data from Costa and D'Almeida [53])

Markets and Current Applications

The world market for composites was 7 million tonnes in 2000, and projected to reach 10 million tonnes in 2010 [54]:

- the North American market accounts for nearly half of world-wide composites (3.4 million tonnes – 47%),
- Europe follows at 2 million tonnes – 28%,
- Asia is the third major market at 1.6 million tonnes – 23%.

The principal European producers are Germany, Italy, France, UK and Spain. Thermoset composites account for roughly 70% of the composites processing industry in Europe.

There is a wide range of user industries for composites in all the international markets, including mechanical structures, chemical plant and electrical insulators. It should be noted that although automotive and aerospace applications account for over half the value, the volume consumption is only 26%. Whilst composites for these industries (and medical and sports applications) are often based on high cost carbon and aramid fibres, there is a mass market for low cost composites – the GRP industry, based predominantly on glass fibre reinforcement and polyester resins.

By Western standards, the Indian composites industry is relatively small at 17000 tonnes in 2001 compared to France at 295000 tonnes [55]. After a period of exceptional growth up to 1999, the Indian industry has failed to live up its growth potential in recent years, and is relatively stagnant. The industry suffers from fragmentation (over 1,700 processors), weak demand from client sectors, under-utilisation of capacity, and quality problems.
European production of natural fibre amounted to 59000–69000 tonnes of flax and 25000-30000 tonnes of hemp in 1999/2000 [56]. During the same year, world production of jute and kenaf was 2570000 tonnes, concentrated in two main producer countries, India and Bangladesh. Production of jute and kenaf declined by 49% and 19% respectively from a peak of 3860000 tonnes in 1997/8 [57].

The use of natural fibres as reinforcement for thermoplastic components is a relatively new phenomenon, dating back only to about 1995. The market has developed from pioneering work in the German automotive industry [58]. In this market, jute is in competition with the indigenous European fibres, flax and hemp, and despite being used at the outset, has consistently fluctuated in relative market share. Figure 4 shows the total consumption of natural fibres increasing to 17 thousand tonnes in 2002 [59]: estimated as flax at 9,000 tonnes and hemp at about 2,200 tonnes with the balance of 6,000 tonnes split between jute, kenaf and sisal.

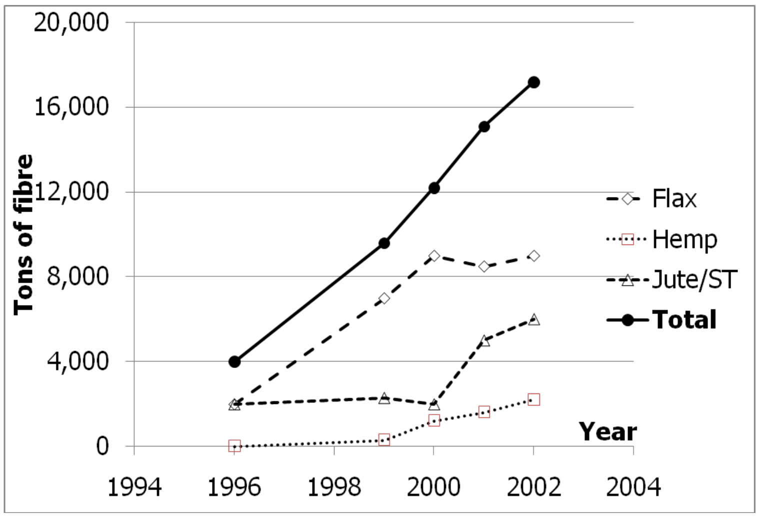

Figure 4: Use of natural fibres in the German automotive industry 1996 – 2002 (tonnes)
(after Kaup et al, 2003 [58]).

The Status Report [59] scaled down the forecast of future consumption of natural fibres. Previous optimistic estimates of up to 35000 tonnes/year were reduced to just over 25000 tonnes in 2005. An earlier report [60] indicated that Germany alone was responsible for over two-thirds of the European production of natural fibre composites, and estimated the market size to be somewhat larger than the Status study. In Germany, the natural fibre composites market has created a dedicated infrastructure of secondary suppliers (mainly non-woven producers) and is still growing strongly. The phased withdrawal of EU Common Agricultural Policy (CAP) subsidy on flax and hemp fibre crops may retard the growth of this new industry.

Ellison and McNaught [60] have identified established commercial uses in:

- automotive interior components (Germany 70%). Natural fibre panels are now in common use as door and boot liners and parcel shelves. Every Mercedes and BMW model now features such components, and the technology has been taken into the Fiat group, Ford and the volume French marques by Tier One suppliers. Current use amounts to about 10kg per car, with a potential for double this consumption.
- domestic insulation (Germany 30%) – tow or sliver bound lightly with polymers.

Established benefits for the automotive industry include good mechanical properties, fewer occupational health issues in handling and lack of splintering in accidents. A review of relevant properties demonstrated the potential for competition with GRP (Glass Reinforced

Plastics) [59]. However, the principal drivers are the potential for weight reduction (10–30%) and the consequent cost advantage of natural fibre composites.

Further, they established that two processes were dominant:

- Compression moulding: Thermoplastic mouldings usually comprise natural fibre/polypropylene blended needle-felt substrates. Thermosets consist of 100% natural fibre needle-felts impregnated with resin by processes such as RTM and S-RIM. The market is dominated by fibre carded sliver or tow chopped to a staple length of 80–90 mm.
- Co-extruded granulate for injection moulding is now under development on several fronts (Daimler Benz ASG in Germany, Collins & Aikmann Automotive Systems AB (formerly Perstorp) in Sweden, ATO-DLO Agrotechnological Research Institute in the Netherlands), and already has an estimated 4.7% share of automotive processing technology in Germany [59]. Short chopped sliver of 4–6 mm is now being used for co-injection.

Low fibre prices remain an obstacle to investment in the natural fibre supply chain. The Ellison and McNaught study in early 2000 [60] found benchmark prices for jute, flax or hemp to be in the range € 0.46-0.61/kg (converted from DM 0.90-1.20/kg using the irrevocably fixed conversion rate of € 1 = 1.95583 DM from 1 January 1999 [61]), and three years later (after the introduction of the Euro), wholesale price levels remained in the € 0.55-0.62/kg range. Prices were set at a low level in the mid-1990s and the automotive industry remains a stringent taskmaster.
The major constraints on the application of natural fibres as reinforcements include

- batch-to-batch inconsistency and other fibre quality considerations.
- performance limitations, notably tensile strength and impact strength.
- susceptibility to moisture absorption.
- odour and fogging.
-

Disposal of natural fibre composites
Conroy et al [62, 63] and Halliwell [64] have reviewed the end-of-life options for composites waste using the waste hierarchy:

- Waste reduction > re-use > recovery > disposal.

Rathje and Murphy [65] have divided recycling into four categories:

- Primary: reprocessing waste to obtain product comparable to the original version,
- Secondary: recovery of waste material with lower performance when compared to virgin materials,
- Tertiary: decomposition of materials to recover monomers, feedstock materials or fuels,
- Quaternary: recovery of the embedded energy in the materials.

An important consideration in the manufacture of any composites is the minimisation of waste associated with the manufacturing process. This waste has the advantage over post-consumer waste that it will normally be well characterised, whereas end-of-life waste is more likely to consist of a mixture of component materials. For thermosetting matrix composites, the only options for re-use or recovery would be in the second-hand spares market or as fillers respectively. For thermoplastic matrix materials, there is the additional option of granulation and reuse in, for example, the extrusion or injection moulding processes. However, this will expose the composite to a further heat-form-cool cycle and could impose additional thermal damage on the fibres.

The options for fibre and feedstock recovery for composites in general include:

- incineration [66]: this destroys the resin, but can leave usable carbon or glass fibres albeit with a reduction in the fibre mechanical properties.
- pyrolysis [67, 68]: heated to temperatures of typically 400-600ºC in an oxygen-free atmosphere.
- catalytic transformation [69], acid digestion or solvolytic/solvothermal processes (including hydrolysis and glycolysis).
- sub-, near- and super-critical fluids: this normally includes water (at 300-500ºC) or carbon dioxide. Piñero-Hernanz et al [70] recycled carbon fibre using a batch-reactor in the temperature range 250-400ºC with pressures from 4 to 27 MPa and residence times up to 30 minutes. Iwaya et al [71] have depolymerised glassfibre/polyester composites to separate the fibre, filler and polymer using sub-critical diethyleneglycol monomethylether (DGMM) or benzyl alcohol (BZA) in a batch reactor at 190-350 ºC for 1-8 hours.

However, the cellulosic bast fibres will probably be consumed along with the resin in these processes.

There are two disposal methods especially suited to natural-fibre and bio-based resin composites:

Composting

A biodegradable material is expected to reach a defined extent of degradation by biological activity under specific environmental conditions within a given time under standard test conditions [72]. Krzan et al [73] have recently reviewed the standards and certification appropriate to environmentally degradable plastics. The EU Directive on Packaging and Packaging Waste (94/62/EC) criteria for biodegradability are set out in BS EN 13432:2000 while the criteria in North America are set out in ASTM D6400-99. The requirements of the standard include:

- biodegradation: over 90% relative to the standard (cellulose) in 180 days under conditions of controlled composting using respirometric methods (ISO14855),
- disintegration: over 90% in 3 months (ISO FDIS 16929),
- ecotoxicity: test results for aquatic and terrestrial organisms (*Daphnia magna*, worm test, germination test) as for reference compost,
- absence of hazardous chemicals (included in a reference list).

The biodegradation of a polymeric materials under controlled composting conditions can be determined using standard methods including ASTM D 5338 [74] or ISO 14852 [75]. There are essentially two options (a) aerobic: carried out either in open air windrows or in enclosed vessels, or (b) anaerobic: required when animal by-products or catering wastes are included [76]. A demonstration-scale anaerobic digestion (AD) plant is operating at Dufferin (Toronto) solid waste transfer station with a mass balance (based on 100 metric tonnes/day) of 50% biogas and effluent, 25% digestate and 25% residue [77]. The biogas varies due to the batch operation but is typically 110 m^3/tonne with an average of 56% methane (ranges from 45-73%) by volume. Jana et al [78] suggest that the biogas is typically 60-65% methane, 35% carbon dioxide and a small amount of other impurities". Greenham and Walsh [79] state that "pure landfill gas" can contain up to 65% methane, 35% carbon dioxide and no oxygen. The Global Warming Potential (GWP) for methane is >20 times that of CO_2 (over a 100 year timescale), so composting should be carried out with the methane collected and burnt to produce energy. This will reduce the requirement for fossil fuels and hence limit the climate change effects.

Organisms that possess cellulase (the enzyme which cleaves sugar from the cellulose molecule) include bacteria, some flagellate and ciliate protozoa, and fungi [80]. Milner et al [81, 82] have reported a new strain of thermophylic bacteria that can break down cellulose waste to produce useful renewable fuels for the transport industry. The Geobacillus family normally synthesise sugars and produce lactic acid as a by-product when they break down biomass in a compost heap. The re-engineered TM242 strain is claimed to produce ethanol more efficiently (yields of 10 to 15%) and cheaply than in traditional yeast-based fermentation.

Incineration with energy recovery [83]

Considerable energy is used in the production of polymers (embodied energy of plastics in general is given as 90 MJ/kg [84]), but as in many other systems that energy is not lost and can be recovered at a later stage. Halliwell [64] quotes a figure of 36 MJ/kg as the energy value for ground composite containing man-made fibres. The cellulose in bast fibres will provide additional energy. During recovery of the energy content of the materials, it will be necessary to comply with the Waste Incineration Directive (WID, agreed by the European Parliament and the Council of the European Union on 4 December 2000). The Commission Directive 2000/76/EC aims to "prevent or limit, as far as practicable, negative effects on the environment, in particular pollution by emissions into air, soil, surface and groundwater, and the resulting risks to human health, from the incineration and co-incineration of waste". It sets and seeks to maintain stringent operational conditions and emission limit values for (co-)incineration plants throughout the European Community [85].

Environmental Considerations

The End-of-Life Vehicle (ELV) Directive was enacted by the European Commission (EC) during 2002 to address pollution resulting from vehicles that have reached the end of their useful life. It aimed to significantly reduce the 8 million tonnes of waste generated each year by the 12 million cars that have reached their end of life. In phase one of the directive, car makers were responsible for the disposal of all new production that would eventually become ELV. In 2007, they became responsible for all the vehicles they had ever produced. The legislation also stipulates that car-makers must re-use or recover 85% of ELVs by weight. At least 80% of that weight must be re-used or recycled while up to 5% can be dealt with through other recovery operations such as incineration. In 2015, this target will rise to 95% of ELVs by weight, 85% of which must be re-used or recycled.

The new directives on landfill and ELV, encourage industry to move away from landfill and energy recovery towards mechanical recycling or reuse. Customers (especially in the automotive sector) are increasingly asking the composites industry to accept responsibility for recycling the end-of life waste. In the context of the EC directives, it will be necessary to make a strong case for disposal by incineration or by composting. Composites, based on natural fibre reinforcements, could prove to be more beneficial in the environment than “recyclable” materials but there is a need for quantitative life cycle analysis to clearly demonstrate that this is indeed the case.

Joshi et al [86] reviewed comparative life cycle assessment studies to conclude that natural fibres would be environmentally superior to glass fibre reinforced composites. The key drivers in favour of natural fibres were:

- natural fibre production has lower environmental impacts compared to glass fibre production,
- natural fibre composites have higher fibre content for equivalent performance, reducing the more-polluting polymer content,
- the light-weight natural fibre composites improve fuel efficiency and reduce emissions in the use phase of the component (especially in automotive applications), and
- end-of-life incineration results in recovered energy and carbon credits.

However, the conclusions are tempered by two caveats:

- fertiliser use in natural fibre cultivation results in higher nitrate and phosphate emissions which can lead to increased eutrophication in local water bodies, and
- the environmental superiority of natural fibre composites may be negated if the operating lifetime is significantly reduced compared to the glass fibre composites.

Reed and Williams [87] have examined the potential for waste biomass (in the form of natural hemp, flax, jute, coir or abaca fibres) to produce activated carbon. After pyrolysis in a fixed bed reactor and steam activation, the yield of activated carbon was 20% by weight of the original biomass and surface areas were in the range 770-879 m^2/g.
The environmental impact of natural fibres in industrial applications has been reviewed by van Dam and Bos [88]. They include quantitative data and suggest that:

- natural fibre production requires < 10 percent of the energy used for production of PP fibres (around 90 GJ/tonne).
- the total energy input for jute fibre cultivation (excluding field labour, retting and decortication) was calculated at 3.8-8.0 GJ/tonne when grown by numerous small farmers utilising labour and animal power with limited use of agrochemicals and machinery.
- the energy input from inorganic fertilisers, based on the energy content of the substance and the energy required for production, transport, storage and application is 17 GJ/tonne for potassium (K), 26 GJ/tonne for phosphorous (P) and 128 GJ/tonne for nitrogen (N).
- the energy input from pesticides, based on the energy content of the substance and the energy required for production, transport, storage and application is 320-476 GJ/tonne for fungicides, 461-568 GJ/tonne for insecticides and 467-622 GJ/tonne for herbicides.

In an independent analysis, Khan [89] calculated that the total energy consumed, including the embodied energies of fertilisers and pesticides would be 18-20 GJ/tonne of jute fibre.

Dissanayake et al [90-92] have begun to undertake a Quantitative Life Cycle Assessment (QLCA) to compare flax fibres and E-glass fibres as the reinforcement for composites within an ISO 14040 framework. They are considering all eight environmental impact classification factors (EICF) identified by Azapagic [93, 94], ISO 14047 [95] and the European Environment Agency [96] (Table 3). The total energy required [97, 98] using low energy agricultural processes was found to be 54.2 GJ/tonne for flax sliver and 80.5 GJ/tonne for yarn (Table 4). Traditional mouldboard ploughing and bio retting was found to require 118 GJ/tonne for sliver and 146 GJ/tonne for yarn. Fibreglass (insulation) and fibreglass reinforcement mats are reported to have embodied energies of 30 GJ/tonne [99] and 54.7 GJ/tonne [88] respectively! The analysis for the full set of EICF is on-going.

Azapagic et al [69, 70]	**ISO/TR 14047:2003(E) [71]**	**European Environment Agency [72]**
Acidification Potential (AP)	Acidification	Acidification
Aquatic Toxicity Potential (ATP)	Ecotoxicity	Ecotoxicity
Eutrophication Potential (EP)	Eutrophication/Nitrification	Eutrophication
Global Warming Potential (GWP)	Climate change	Climate change and global warming
Human Toxicity Potential (HTP)	Human toxicity	Human toxicity
Non-Renewable/Abiotic Resource Depletion (NRADP)	Depletion of abiotic/biotic resources	
Ozone Depletion Potential (ODP)	Stratospheric ozone depletion	Stratospheric ozone depletion
Photochemical Oxidants Creation Potential (POCP)	Photo-oxidant formation	Photochemical ozone formation (summer smog)

Table 3: A correlation of the eight environmental impact classification factors

Table 4: Energy consumption (GJ/tonne of processed fibre) at the various stages of fibre production

Sliver	Cultivation	Agrochemicals	Retting	Textile processes	TOTAL
No till + water retting	4.9	37.5	0.6	11.2	**54.2**
Conservation tillage + stand/dew retting	12.8	78.3	4.6	14.5	**110.1**
Conventional tillage + bio-retting	6.6	31.7	77.3	2.1	**117.8**
Yarn	**Cultivation**	**Agrochemicals**	**Retting**	**Textile processes**	**TOTAL**
No till + water retting	5.1	39.2	0.6	35.5	**80.5**
Conservation tillage + stand/dew retting	13.3	81.2	4.7	39.0	**138.1**
Conventional tillage + bio-retting	6.9	33.0	80.4	26.1	**146.4**

Table 4: Energy consumption (GJ/tonne of processed fibre) at the various stages of fibre production

SUMMARY

Part 1 of this review paper has considered the growth, harvesting and fibre separation techniques suitable to yield bast fibre of appropriate quality for use as the reinforcement of polymer-matrix composites. The text then addressed the characterisation of the fibre. Part 2 of this review considered the use of the basic rule-of-mixtures in the context of natural fibre reinforced composites and addressed the characterisation of composite materials using microscopical, mechanical, chemical and thermal techniques. The text closed with a brief overview of some potential applications and the environmental considerations which might expedite or constrain the adoption of these composites. There are a number of factors which could constrain the commercial adoption of these fibres as reinforcements for composites:

- Unlike man-made fibres, the fibre cross section is neither circular nor uniform along the length which leads to increased complexity in the calculation of fibre volume fraction and hence in the prediction of the mechanical properties.
- It may be necessary to determine a fibre diameter distribution factor and how that factor might be incorporated into the rule-of-mixtures.

- The interface between the hydrophilic fibre and a hydrophobic matrix may need special fibre surface treatments or compatibilisers in the matrix.
- The fibres degrade over time at 200ºC of higher, so the choice of matrix system for the composite is limited.
- Cellulose fibres have similar characteristics to aramid fibres and hence specialised cutting and machining technologies may be needed.
- The “green” claim for natural fibre composites may only be appropriate when best practice is adopted in the growth, separation and processing of the fibres and where the durability of the composite component is comparable to that of glass fibre composites.

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Appendix A3

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Appendix A4

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Appendix A5:

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Quantitative Life Cycle Analysis for Flax Fibres

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SUMMARY

Natural fibres are perceived as a sustainable alternative to glass fibres for the reinforcement of polymer matrix composites. This paper reports a Quantitative Life Cycle Analysis for flax fibres (to be judged against glass fibres) using the eight environmental impact classification factors identified in ISO/TR 14047:2003.

Keywords: life cycle analysis, flax, reinforcement

INTRODUCTION

Environmental concerns have resulted in a renewed interest in sustainable composites focusing on bio-based fibres and resins. The fibres most likely to be adopted as reinforcement are bast (stem) cellulose fibres from plants such as flax, hemp, kenaf and jute. However, it is timely to consider whether the claimed benefits of the materials can be justified. The long term aim of this study is to carry out a quantitative and comparative Life Cycle Assessment (LCA) of natural fibres compared with glass fibres as reinforcement for polymer composites to establish the most sustainable option.

This paper presents the quantitative Life Cycle Assessment (LCA) of flax fibres for reinforcement in polymer matrix composites. Life Cycle Assessment (LCA) is an environmental assessment method which, according to ISO 14040:2006(E), "considers the entire life cycle of a product from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal"[5]. The outline methodology is defined by the international standards for Environmental Management Systems [5, 12, 76-78]. An LCA study has four phases:

- **The goal and scope definition –** establishing the aim and scope of the study and defining the function or functional unit of the product under examination.
- **Life Cycle Inventory analysis (LCI)** – compilation and quantification of inputs and outputs for a product through its life cycle.
- **Life Cycle Impact Assessment (LCIA)** - understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product, and

- **Life Cycle Interpretation** – the findings of the LCI or LCIA or both are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

The goal and scope definition

The main objective for carrying out the study is to determine whether the substitution of glass fibres with natural fibres is truly environmentally beneficial. Flax is chosen as the candidate fibre in this study because it is a temperate zone plant and one of the most agro-chemical intensive among the other bast fibres. Therefore the other bast fibres would be “greener” provided the yield/hectare and performance are satisfactory. The product system under investigation includes agricultural operations from preparing the ground to harvest, fibre extraction (retting and decortication), fibre preparation (hackling and carding) and processing (spinning or finishing) operations of flax fibres. For this study, the functional unit is defined as “one tonne of flax fibres ready for reinforcement in polymer matrix composite”.

The scope of the study is cradle-to-gate and the agricultural boundary ideally starts from the farm gate and stops at the factory gate (Figure 1). The production of agricultural products such as fertiliser (N, P and K) and pesticides is included within the system boundary. The agricultural machinery/equipment constructions, production of seed, transportation, storage and man power are not considered within the scope of this study. It was assumed that there is no difference in soil quality and quantity between the beginning and the end of the study. The location, land use and effects of crop rotation are not included in the analysis. The flax long fibre remains as the high value product through the analysis and co-products such as short fibre, shive, dust and coarse plant residues are assumed to have economical value which simply covers their processing costs after separation from the reinforcement fibres. In consequence, disposal costs for these elements are not included.

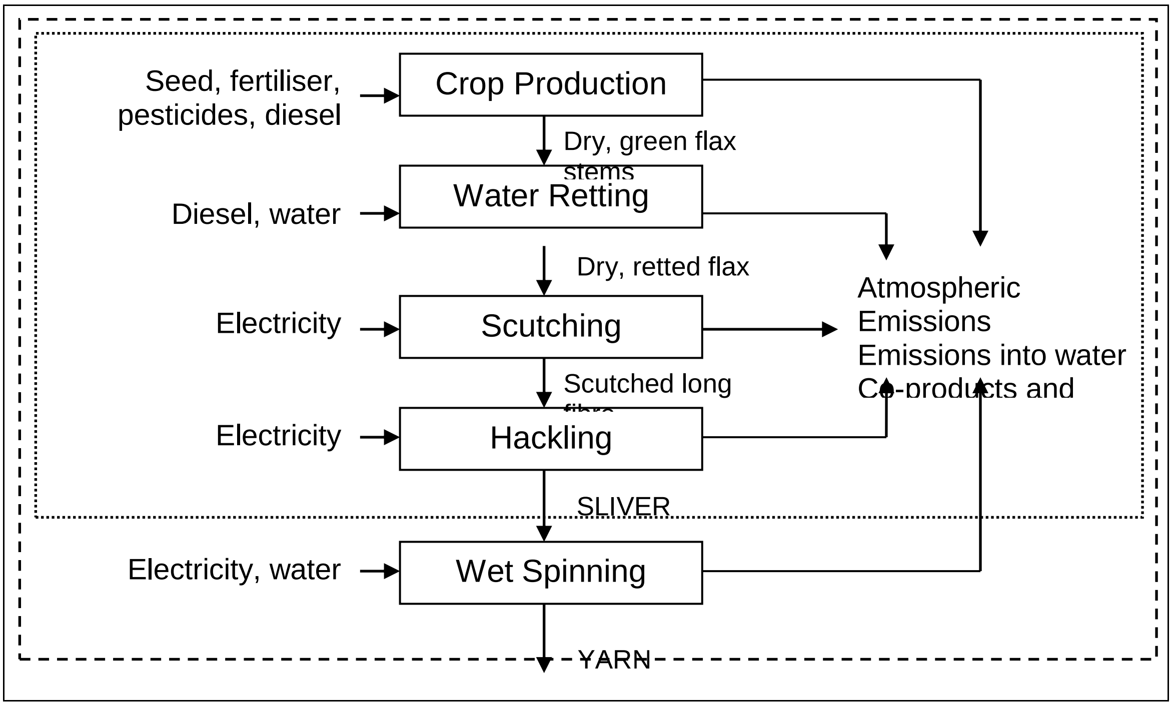

Figure1. System boundaries for flax sliver and yarn production [86, 87]

METHODOLOGY: LIFE CYCLE INVENTORY ANALYSIS (LCI)

The inventory data for the production of flax fibre has been obtained from the literature, considering various agricultural operations and inputs – fertiliser, pesticides and fibre processing techniques.

Crop Production

Agricultural operations such as ploughing, harrowing, cultivating, applying fertiliser, pesticides and dessicant and harvesting are considered. Three different methods of ploughing (tillage) practices are identified as conventional tillage, conservation tillage and no-till with different energy demands in the production flax fibres (Figure 2).

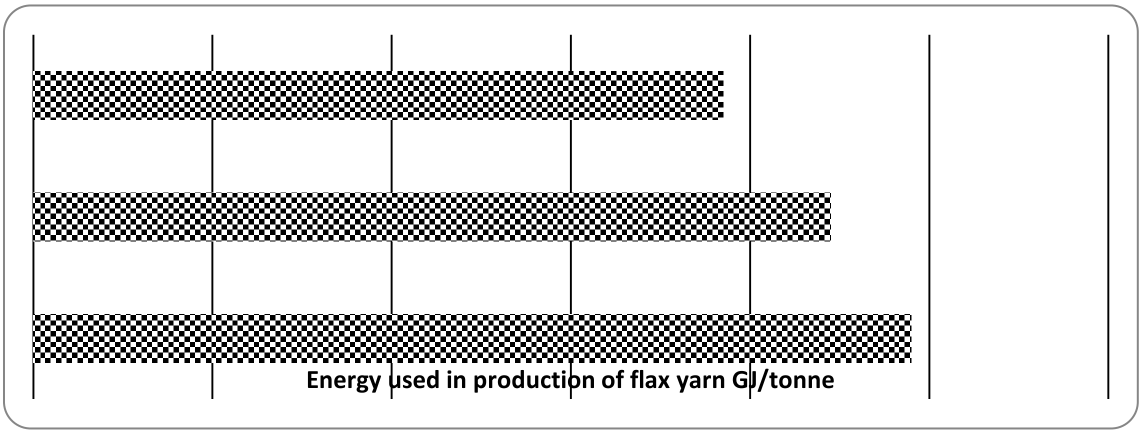

Figure 2. Energy used in the production flax yarn by different tillage practices [194]

Fibre Processing Operations

Normally, after the crop is harvested, fibre processing is retting followed by scutching/decortication. Scutching is followed by hackling and/or carding which produces sliver. Sliver will be finally spun to produce yarn. Three methods of retting considered in the analysis are warm-water retting, bio-retting and stand/dew retting. The values of energy consumption for retting followed by scutching are shown in Figure 3. In the absence of data specific to flax fibre, bio-retting of hemp and stand/dew retting of baby hemp are considered to have similar energy requirements to flax.

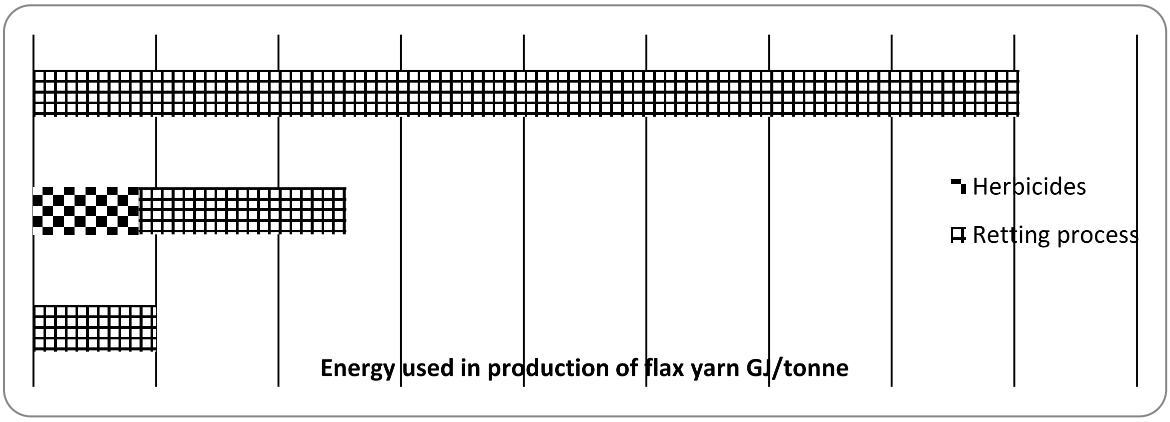

Figure 3. Energy consumption in different retting and subsequent scutching processes [86, 87]

The inventory data for the production of one tonne of flax fibre yarn is summarised in Table 1 from a report [194] based on several original references given therein.

Table 1. Inventory data for the production of flax fibre yarn using no-till practice and warm water retting

INPUTS		
Materials	**Value**	**Units**
Seed	497	kg/tonne of yarn
Lime	2445	kg/tonne of yarn
Ammonium nitrate (N)	445	kg/tonne of yarn
Triple superphosphate (P)	238	kg/tonne of yarn
Potassium chloride (K)	368	kg/tonne of yarn
Pesticides	9.4	kg/tonne of yarn
Diesel	9.49	GJ/tonne of yarn
Electricity	35.52	GJ/tonne of yarn
OUTPUTS		
Yarn	1000	kg
Co-products : Short Fibre	4497	kg/tonne of yarn
Shive	7104	kg/tonne of yarn
Dust	2824	kg/tonne of yarn
Coarse plant residue	2304	kg/tonne of yarn
Direct Emissions : CO_2	9334[113,	kg/tonne of yarn
NH_3	166, 168,	kg/tonne of yarn
N_2O	195]	kg/tonne of yarn
NO_X	68[166,	kg/tonne of yarn
SO_2	196]	kg/tonne of yarn
NO	14[166,	kg/tonne of yarn
NO_3	196]	kg/tonne of yarn
NMVOC	6[166]	kg/tonne of yarn
	3[166]	
	2[196]	
	0.1[166]	
	0.002[166]	

RESULTS: LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Eight Environmental Impact Classification Factors (EICF) are listed in ISO/TR 14047:2003 [159] and more coherently defined by Azapagic [13, 14] using different terminology:

- Global Warming Potential (GWP)
- Human Toxicity Potential (HTP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Aquatic Toxicity Potential (ATP)
- Non-Renewable/Abiotic Resource Depletion Potential (NRADP)
- Ozone Depletion Potential (ODP)
- Photochemical Oxidants Creation Potential (POCP)

In the impact assessment interpretation of the LCI data, the inventory data are multiplied by the appropriate characterisation factor to calculate the environmental impact potential, E_x , for each factor, x [13, 14].

$$E_x = \sum_{j=1}^{n} ec_{1.jx}\, B_{jx}$$ Eq. (1)

B_{jx} = burden (release of emission *j* or consumption of resource *j* per functional unit), and ec_1 = characterisation factor for emission *j*

The characterisation factors represent the potential of a single emission or resource consumption to contribute to the respective impact category [78]. Acidification, eutrophication, global warming and human toxicity potentials are calculated using Eq. (1).

Environmental impact potentials are calculated for the production of one tonne of flax silver and one tonne of yarn in 4 scenarios considering possible tillage and retting options available.

(1) No-till with warm water retting

(2) Conservation tillage with stand/dew retting

(3) Conventional tillage with bio-retting

(4) No-till with bio retting

The Tables 2 and 3 show the results of Life Cycle Impact Assessment in the production of flax yarn and sliver respectively.

Table 2. Results of the LCIA for the production of one tonne of flax fibre yarn

Scenario	GWP	AP	EP	HTP	POCP	ODP	ATP*
No-till & water retting	15873	146	123	22	0.000012	0.000008	1067
Conservation & dew retting	22586	276	203	35	0.000026	0.000018	2067
Conventional & bio-retting	26576	129	90	20	0.000013	0.000009	941
No-till & bio-retting	26557	129	90	20	0.000010	0.000007	942

Table 3. Results of the LCIA for the production of one tonne of flax fibre sliver

Scenario	GWP	AP	EP	HTP	POCP	ODP	ATP*
No-till & water retting	11062	141	102	22	0.000011	0.000008	1027
Conservation & dew retting	17889	265	195	34	0.000025	0.000018	1986
Conventional & bio-retting	18570	121	89	15	0.000012	0.000009	905
No-till & bio-retting	18549	121	99	15	0.000010	0.000007	905

Units given in above tables are kg/tonne of yarn

* Unit used in ATP is $m^3 \times 10^{12}$ per tonne of yarn, “Aquatic Toxicity estimations in LCA are notoriously unreliable and difficult” [96]

Non-renewable/abiotic resource depletion potential is calculated using Eq. (2).

$$NRADP = \sum_{j=1}^{n} \frac{B_j}{ec_{1,j}}$$ Eq. (2)

B_j = burden (consumption of resource *j* per functional unit) and, ec_1 = estimated total world reserves of resource *j*.

Non-Renewable/Abiotic Resource Depletion Potential (NRADP) was calculated for diesel and electricity usage at each stage of production of flax fibres. Electricity is used for the fibre processing operations (scutching, hackling and spinning). The electricity generation in UK is from 33% of coal 150g/kWh, 40% of natural gas 0.09m^3/kWh, 1% of oil 86g/kWh, 19% of nuclear, and 7% of other resources [195, 197] . The NRADP contributions for producing flax fibre yarn and sliver in above 4 scenarios are shown in Table 4.

Table 4. Results of the NRADP contribution for the production of one tonne of flax fibre sliver and yarn (multiplied by 10^{15})

Scenario	*Production*	Oil	Coal	Gas
No-till & water retting	*Yarn*	1200	5.6	3.3×10^6
	Sliver	1100	1.8	1.0×10^6
Conservation & dew retting	*Yarn*	2600	6.2	3.6×10^6
	Sliver	2500	2.3	1.3×10^6
Conventional & bio-retting	*Yarn*	1500	17	9.9×10^6
	Sliver	1400	13	7.3×10^6
No-till & bio-retting	*Yarn*	1200	17	9.9×10^6
	Sliver	1100	13	7.3×10^6

LIFE CYCLE INTERPRETATION

Minimal or shallower ploughing reduces the energy input considerably and especially on a sloping field it reduces the soil erosion or run off of soil sediments. Traditional or conventional tillage methods of mouldboard ploughing drastically affect the soil structure, breaking up its natural aggregates and burying the residues of the previous crop. Therefore the bare soil becomes unprotected and exposed to the action of wind and rain [150]. Chisel ploughing uses ~40% less energy than mouldboard ploughing where drilling combined with a no till pass uses only 6% of the energy required for mouldboard ploughing.

Herbicides applied as dessicant in stand/dew retting have contributed almost 36% of the total energy consumption at this stage. Bio-retting is the most energy intensive method of retting which also includes post-harvest field operations, scutching, rinsing, drying and mechanical softening to produce long fibres. Warm water retting is the process requiring the least energy but also generates a considerable amount of waste water (~94% of water used).

Co-products such as short fibre and shives are produced from the scutching and hackling processes. These can be used as animal bedding or in paper production. Dust is also produced from processes such as scutching and hackling. The dust can be collected and consolidated as biomass fuel. The long fibre remains the high value product. The mass reductions (as a % green stems) at each stage of the production of flax fibre yarn using 3 different retting methods are shown in Figure 4.

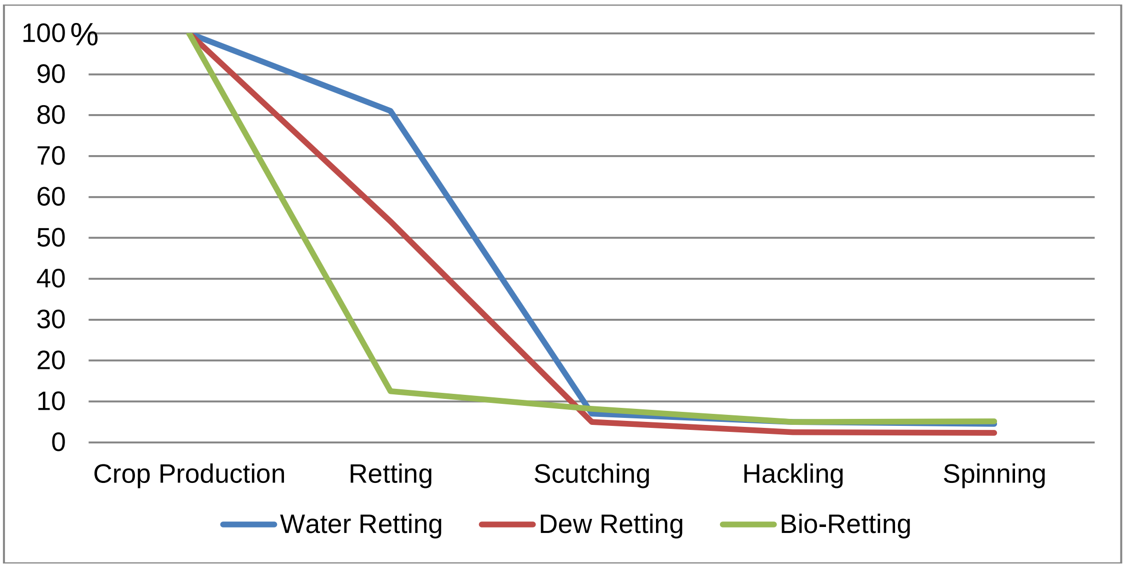

Figure 4: Remaining mass (as % of green stems) at each stage of the production of flax fibre yarn using different retting methods [86, 87]

Total energy used to produce one tonne of sliver is 59.3GJ and one tonne of yarn is 85.4GJ when no-till and water retting is used. Using traditional conventional method (mouldboard ploughing) and bio retting the values are 199GJ/tonne of sliver and 231GJ/tonne of yarn [194]. Published values [9] for glass fibre reinforcements are 25.8GJ/tonne for continuous fibre, which is equivalent to yarn and 54.7GJ/tonne for mat, which is equivalent to sliver. Based on energy analysis, sliver from the low energy route has an embodied energy directly comparable to that for glass fibre mat.

In the production of flax yarn, no-till and water retting has lower environmental impact potentials in global warming and eutrophication than other scenarios. Conservation tillage methods with dew retting has a lower global warming potential than conventional tillage with bio retting and no-till with bio-retting while having the highest impact potentials for all other categories. This is due to using herbicides as a dessicant in stand/dew retting process. Global warming potential is higher when the bio-retting is used but all the other impact potentials are slightly improved. The remaining mass after spinning process is 5.1% of green flax stems when bio-retting is used while 3.9% and 2.3% for water retting and dew retting respectively as shown in Figure 4.

In the production of sliver, the above differences in the four scenarios are consistent to the production of flax yarn with improved set of impact potentials for all categories due to the elimination of the spinning operation. The values from Table 2 and 3 are normalised and presented as radar plots in Figure 5 and 6 for the flax yarn and sliver production respectively.

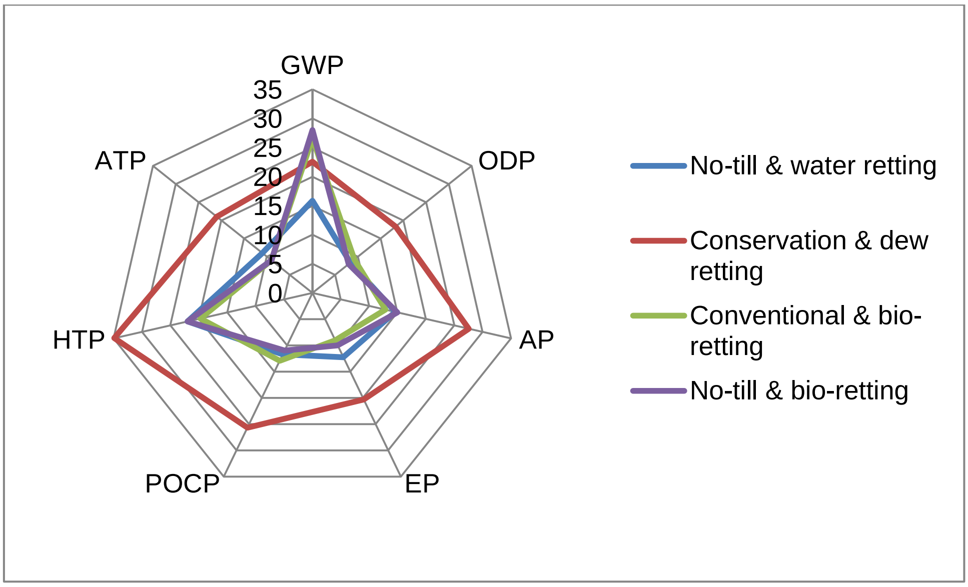

Figure 5. Representation of LCIA for production of flax yarn

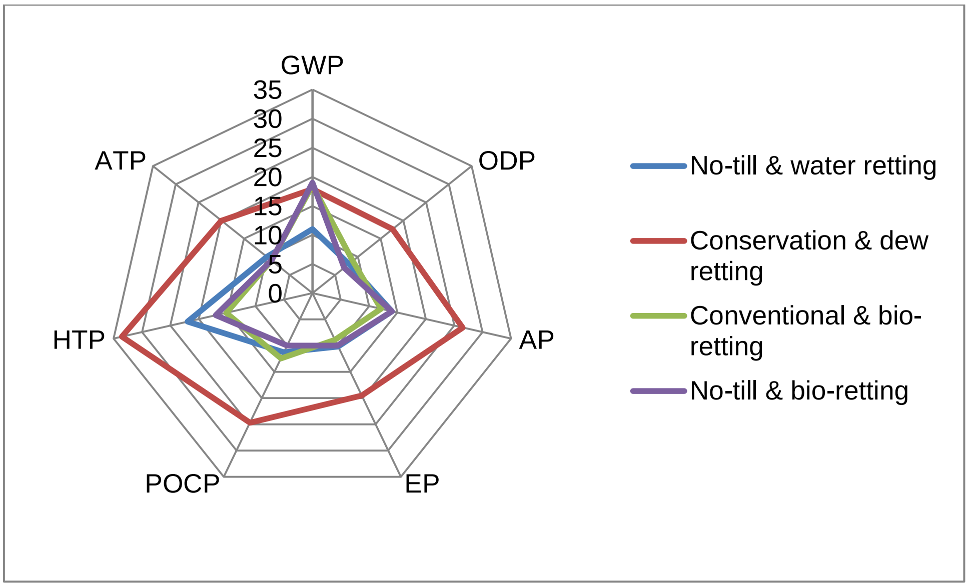

Figure 6. Representation of LCIA for production of flax sliver

The NRADP is not included in the above radar plots and using sliver as reinforcement reduces the NRADP potentials significantly in all four scenarios due to the absence of spinning operation. No-till and water retting process is the best option in terms of reduced NRADP potential followed by no-till and bio-retting.

CONCLUSION

The quantitative Life Cycle Assessment is carried out for the production of flax fibre yarn using published data and calculations where necessary within the scope of cradle-to-gate. Flax fibre produced by no till and warm water retting has an embodied energy of 59 GJ/tonne of sliver (*vs* 55 GJ/tonne for glass mat). The spinning process raises the embodied energy for yarn to 86 GJ/tonne (*vs* 26 GJ/tonne for continuous glass fibre). Flax sliver as a reinforcement is comparable in energy terms to glass fibre mat. For the other EICF, it has not been possible to identify appropriate data for glass fibres on which to base a comparison. Continuous glass fibre reinforcement appears to be superior from an environmental energy viewpoint to spun flax yarn.

In consequence, the validity of the “green” case for substitution of glass fibres by natural fibres is dependent on the chosen reinforcement form and associated processes. No-till method with water retting is identified as the most environmental friendly option for seven out of eight impact classification factors. Human toxicity potential associated with no-till and water retting is slightly higher than when bio-retting is used. To improve the case for natural fibres, the principal recommendation is for the use of organic fertiliser, biological control of pests and conservation agriculture.

A key consideration for reducing energy consumption and impact potentials associated would be to produce aligned fibre reinforcement without the need for the energy intensive spinning operation. Alternative bast fibres which are less agro-chemical intensive may justifiably be claimed to have lower environmental burden provided they have equivalent yields of fibre/hectare and similar properties (or performance for the full component life cycle). While spinning will permit the use of textile/continuous yarn processes, it will not significantly change fibre orientation distribution factor relative to aligned sliver. The high energy consumption in spinning will need to be balanced against any performance/manufacturing gains from the process.

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Appendix A6

Presented at *2nd International Conference on Innovative Natural Fibre Composites for Industrial Applications, Rome (April 2009)*
International Conference on Manufacturing of Advanced Composites, Belfast (March 2009)

Life Cycle Impact Assessment of Flax Fibre for the Reinforcement of Composites

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ABSTRACT

The long term aim of this study is to carry out a comparative quantitative Life Cycle Assessment (QLCA) of natural fibres compared with glass fibres when used as reinforcement for polymer composites to confirm or refute that the "green" fibres are the more sustainable option. As flax fibres are perhaps the most agro-chemical intensive bast fibres then, if flax is proven to be the better option, the other bast fibres (e.g. hemp or jute) may be shown to have even lower environmental burdens. Life Cycle Impact Assessment (LCIA) is used here to quantify the environmental impacts in the production process of converting flax fibres from plant stem to reinforcement for composite materials (cradle-to-gate). Life Cycle Inventory Analysis (LCI) for energy use has been completed using compiled data from a number of published sources. This conference paper reports on the Life Cycle Impact Assessment (LCIA) considering environmental categories as listed in ISO/TR 14047:2003.

KEYWORDS: flax, energy, reinforcement, life cycle assessment

INTRODUCTION

Life Cycle Assessment (LCA) is an environmental assessment method which, according to ISO 14040:2006(E), "considers the entire life cycle of a product from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal" [5]. The outline methodology is defined by the international standards for Environmental Management Systems [5, 76-78, 159]. A LCA study has four phases:

(1) The goal and scope definition – establishing the aim and scope of the study and defining the function or functional unit of the product under examination.

(2) Life Cycle Inventory analysis (LCI) – compilation and quantification of inputs and outputs for a product through its life cycle.

(3) Life Cycle Impact Assessment (LCIA) - understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

(4) Life Cycle Interpretation – the findings of the LCI or LCIA or both are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

Flax (*Linum usitatissimum)* is a temperate zone plant which grows to about 80-120 cm in height. Flax is also known as linseed when grown for seed. Dual-purpose varieties also exist. Almost the entire plant (seed, fibre, chaff, shive and retained dust) can be used when grown as flax [50].

The functional unit analysed in this study is one tonne of flax fibre in the form of reinforcement by considering the fibre as the main and only high value product.

Figure 1 shows the stages of fibre production included in this study.

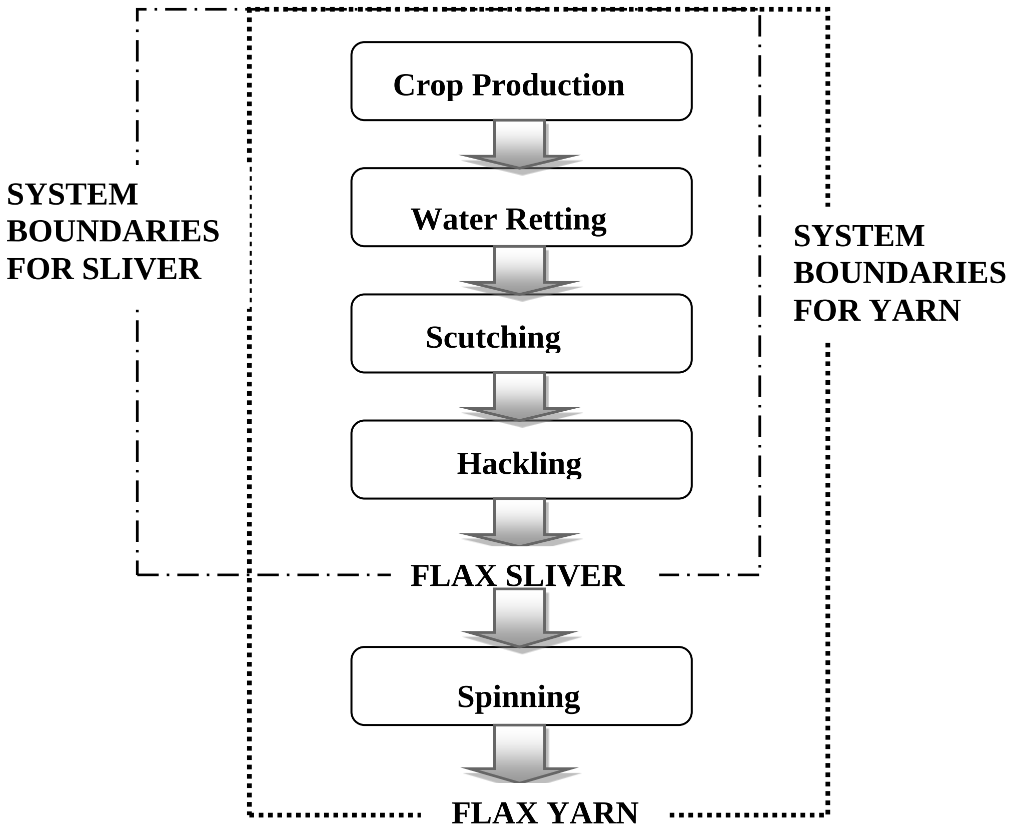

Figure 1. Flow chart for flax fibre production

LIFE CYCLE INVENTORY ANALYSIS

The inventory data for the production of flax fibre has been obtained from the literature, considering various agricultural operations and inputs – fertiliser, pesticides and fibre processing techniques. The inventory data for the production of one tonne of flax fibre yarn is summarised in Table 1 from a report [194] based on several original references given therein.

Table 1. Inventory data for the production of flax fibre yarn

INPUTS		
Materials	**Value**	**Units**
Seed	497	kg/tonne of yarn
Fertilisers: Lime	2445	kg/tonne of yarn
Ammonium nitrate	445	kg/tonne of yarn
Triple superphosphate	238	kg/tonne of yarn
Potassium chloride	368	kg/tonne of yarn
Pesticides	9.4	kg/tonne of yarn
Diesel	9.49	GJ/tonne of yarn
Electricity	35.52	GJ/tonne of yarn
OUTPUTS		
Yarn	1000	kg
Co-products : Short Fibre	4497	kg/tonne of yarn
Shive	7104	kg/tonne of yarn
Dust	2824	kg/tonne of yarn
Coarse plant residue	2304	kg/tonne of yarn
Direct Emissions : CO_2	5682 [198-	kg/tonne of yarn
NO_X	201]	kg/tonne of yarn
SO_2	8.7 [202]	kg/tonne of yarn
NH_3	0.004 [203]	kg/tonne of yarn
Particulate matter (PM)	0.062 [204]	kg/tonne of yarn
	0.3 [202]	

LIFE CYCLE IMPACT ASSESSMENT

The Environmental Impact Classification Factors are listed in ISO/TR 14047:2003 [159] and more coherently defined by Azapagic [13, 14] using different terminology:

- Global Warming Potential (GWP)
- Human Toxicity Potential (HTP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Aquatic Toxicity Potential (ATP)
- Non-Renewable/Abiotic Resource Depletion Potential (NRADP)
- Ozone Depletion Potential (ODP)
- Photochemical Oxidants Creation Potential (POCP)

In the impact assessment interpretation of the LCI data, the inventory data are multiplied by the appropriate characterisation factor to calculate the environmental impact potential, E_x , for each factor, x [13, 14].

$$E_x = \sum_{j=1}^{n} ec_{1.jx} B_{jx}$$ Eq. (1)

Where: B_{jx} = burden (release of emission *j* or consumption of resource *j* per functional unit), and ec_1 = characterisation factor for emission *j*

The characterisation factors represent the potential of a single emission or resource consumption to contribute to the respective impact category [78]. Acidification, eutrophication, global warming and human toxicity potentials are calculated using Eq. (1). Non-renewable/abiotic resource depletion potential is calculated using Eq. (2).

$$NRADP = \sum_{j=1}^{n} \frac{B_j}{ec_{1,j}}$$ Eq.(2)

Where: B_j = burden (consumption of resource *j* per functional unit) and, ec_1 = estimated total world reserves of resource *j*.

RESULTS AND DISCUSSION

Environmental impact potentials are calculated according to the emissions of the inputs such as diesel, electricity, fertiliser and pesticides at each stage of flax fibre production. Diesel usage leads to direct emissions into atmosphere (CO_2, NO_x, SO_2) and fertiliser emissions include ammonia and nitrogen oxides for both atmosphere and ground water. Table 2 shows the environmental impact potentials for global warming, human toxicity, acidification, eutrophication and aquatic toxicity.

Table 2. Results of the LCIA in the production of flax yarn at each stage (For energy sources only- agro chemicals are not included in the analysis)

	GWP (kg)	HTP (kg)	AP (kg)	EP (kg)	ATP[a] (m^3)
Crop Production	3396	8.11	6.21	1.16	1.11×10^{16}
Water Retting	232	0.61	0.42	0.078	
Scutching	1317				
Hackling	313				
Spinning	3353				
Sliver (Pre Spinning)[b]	5192	4.88	6.51	1.22	1.09×10^{16}
Yarn (Post-Spinning)	8612	8.72	6.63	1.23	1.11×10^{16}

[a] "Toxicity estimations in LCA are notoriously unreliable and difficult" [205]
[b] decreased by 1.2% to correct for the mass loss from spinning operation

At this stage of our analysis we do not believe there is any significant contribution to ozone depletion potential from the growth and processing of natural fibres. In addition, no verifiable quantitative data has yet been identified for the analysis of POCP.

Non-Renewable/Abiotic Resource Depletion Potential (NRADP) was calculated for diesel and electricity usage at each stage of production of flax fibres. Electricity is used for the fibre processing operations (scutching, hackling and spinning). The electricity generation in UK is from 37% of coal 150g/kWh, 33% of natural gas $0.09m^3$/kWh, 2% of oil 86g/kWh, 21% of nuclear, and 7% of other resources [197, 206]. The NRADP contributions at each production stage are shown in Table 3.

Table 3. NRADP contributions at each production stage

	Crop production	**Water Retting**	**Scutching**	**Hackling**	**Spinning**
Diesel : Oil (kg)	1.75×10^{-12}	1.16×10^{-13}			
Electricity: Coal (kg) Gas (m^3) Oil (kg)			 1.67×10^{-15} 7.17×10^{-13} 3.68×10^{-14}	 3.97×10^{-16} 1.7×10^{-13} 9.02×10^{-15}	 4.26×10^{-15} 1.82×10^{-12} 9.29×10^{-14}

Agricultural activities (ploughing, sowing and harvesting) with fertiliser and pesticides dominate all environmental impact categories. This LCIA considers only direct energy sources. Agro-chemical production is not included. The above GWP value is for chisel ploughing (no-till practice can reduce to this 2930 kg, mouldboard ploughing will increase this to 3741 kg). SO_2 emissions from diesel use in agricultural operations and water retting contribute for acidification, human toxicity and non-renewable resource depletion. Fertilisers contribute to eutrophication. Nitrogen fertiliser and pesticides cause acidification, aquatic and human toxicity. Crop production contributes 39% of the GWP, 92% of the HTP and 94% of AP and EP. Emissions for P/K fertilisers and pesticides, and N/P leaching are difficult to quantify accurately. Spinning requires 39% of the total GWP (Figure 2) and 67% of NRADP. The embodied energies for flax are 59 GJ/tonne of sliver (*vs* 55 GJ/tonne for glass mat) and 86 GJ/tonne of yarn (*vs* 26 GJ/tonne for continuous glass fibre) [194]. If the sliver was used for reinforcement in composites, then the magnitude of the environmental impacts will be reduced significantly (GWP by 40%, HTP by 44%).

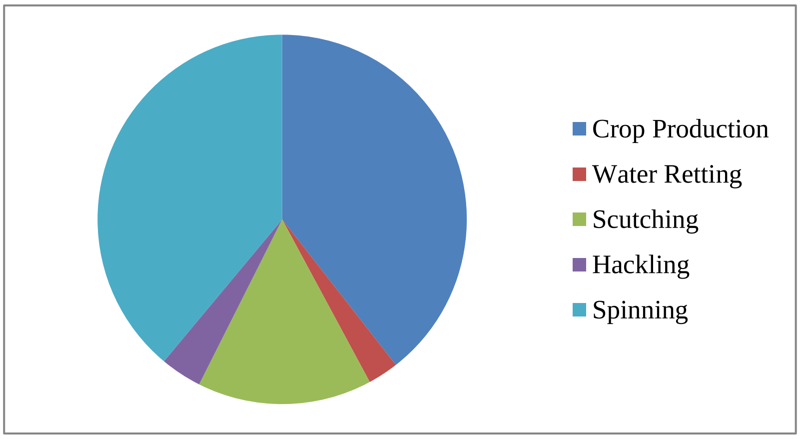

Figure 2. GWP contribution at each stage of flax fibre yarn production

CONCLUSION

The initial analysis suggests that the “green” claim for flax fibres when used as reinforcement of composites is not justified as the embodied energy is of similar magnitude to that for glass fibres. Use of conservation agriculture and organic fertiliser will improve the environmental credentials of flax. Those natural fibres which are less agro-chemical intensive may justifiably be claimed to have lower environmental burden provided they have equivalent yields of fibre/hectare and similar properties (or performance for the full component life cycle). While spinning will permit the use of textile/continuous yarn processes, it will not significantly change fibre orientation distribution factor relative to sliver. The high energy consumption in spinning will need to be balanced against any performance/manufacturing gains from the process.

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Appendix A7

Presented at *9th International Conference on Flow Processes in Composite Materials (FPCM-9), Montréal, Canada (July 2008)*

Infusion of Natural *vs.* Synthetic Fibre Composites with Similar Reinforcement Architecture in the Context of a LCA

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SUMMARY: In the context of a comparative and Quantitative Life Cycle Assessment (QLCA) of natural fibre relative to glass fibre when used as the reinforcement in composites, experiments have been conducted to study the differences in their processability and performance. Composites were manufactured from plain weave reinforcement fabrics by resin infusion under flexible tooling (RIFT). It proved difficult to get truly comparable reinforcement fabrics, but the indications are that mould filling times will be longer for natural fibres at comparable fibre volume fractions. The mechanical properties were measured in flexure and indicate that comparable panel stiffnesses are possible at equal weight.

KEYWORDS: flax fibre, glass fibre, life cycle assessment (LCA), resin infusion under flexible tooling (RIFT)

INTRODUCTION

In an environmental comparison of china reed fibre as a substitute for glass fibre in plastic transport pallets, Corbière-Nicollier et al [1] suggested that such natural fibres are less environmentally damaging than glass fibres for seven of the eight environmental impact classification factors (Table 1). The exception was eutrophication. The plants which are currently attracting most interest as sources of reinforcement are flax and hemp (in temperate climates) or jute and kenaf (in tropical climates).

Life cycle assessment (LCA) is an environmental assessment method, which "considers the entire life cycle of the product from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal" [2]. An LCA study as defined by the ISO 14040 series of standards has four phases:

- The goal and scope definition
- Life Cycle Inventory analysis (LCI)
- Life Cycle Impact Assessment (LCIA)

- Life Cycle Interpretation

The methodology for LCA is defined by the international standards for Environmental Management Systems [3]. ISO 14047 [4] defines eight environmental impacts which closely mirror the environmental impact classification factors (EICF) used by Azapagic [5, 6] shown in Table 1.

Table 1. Environmental Impact Classification Factors (EICF)

ISO/TR 14047:2003(4)	Azapagic et al (5,6)
Acidification	Acidification Potential (AP)
Ecotoxicity	Aquatic Toxicity Potential (ATP)
Eutrophication/Nitrification	Eutrophication Potential (EP)
Climate change	Global Warming Potential (GWP)
Human toxicity	Human Toxicity Potential (HTP)
Depletion of abiotic/biotic resources	Non-Renewable/Abiotic Resource Depletion (NRADP)
Stratospheric ozone depletion	Ozone Depletion Potential (ODP)
Photo-oxidant formation	Photochemical Oxidants Creation Potential (POCP)

The study reported here is part of a project which aims to carry out a comparative and Quantitative Life Cycle Assessment (QLCA) of natural fibre relative to glass fibre when used as the reinforcement in composites. Flax is the chosen fibre in this study as it is the most agro-chemical intensive of the above bast fibres. If the study demonstrates that flax is the better option, then the other bast fibres should be even more environmentally friendly than glass fibres. So far for this study, the goal and scope have been defined [7, 8, 9] and we are currently progressing towards completion of the LCI and LCIA.

The aim of this paper is to compare the processing and properties of two composite systems with similar reinforcement architecture. Producing a natural fibre laminate with identical reinforcement architecture to a glass laminate is challenging as the fibre diameters differ, hence also the surface area per tow. Typical values of (fibre modulus in GPa / fibre density in Mgm^{-3}) are ~ 42/1.5 for flax and ~70/2.5 for glass, *i.e.* 28 in both cases. For the comparison, reinforcement fabrics with areal weights pro rata to density were sought.

EXPERIMENT

Plain weave fabrics of flax fibre (areal weight = 0.25 kgm^{-2}) and glass fibre (areal weight = 0.4 kgm^{-2}) were identified. The provenance of the flax fabric (linen textile) is unknown, but was made of spun short fibre. The glass fibre mat was supplied by Carr Reinforcements Ltd, Cheshire, UK. The fabric characteristics are shown in Table 2. Laminates of similar thickness were produced, so that the span/depth ratio in bending and hence the respective contributions of flexural and shear distortion of the test beams were similar.

Table 2. Characteristics of the reinforcement fabrics

	Areal weight – kgm^{-2}	Warp - tows/m	Weft –tows/m
Flax	0.25	~ 900	~ 1200
Glass	0.4	~ 600	~ 600

Two sets of experiments were carried out (with both reinforcements enclosed by the same bag on each occasion) for woven flax and woven glass. For the first experiment, the target was a plate of at least 2 mm thickness, as required by the mechanical test standards (details below). The following equation was used with an assumed fibre volume fraction for a woven reinforcement of 0.5 for both cases to determine that seven layers of each fabric should be used.

$$n = V_f \rho_f t / A_F$$

where n = the number of layers, V_f = volume fraction of the fibres, ρ_f = density of the fibre,
t = the thickness of the laminate and A_F = the areal weight of the fabric,

Resin infusion under flexible tooling (RIFT) at ambient temperature was used to manufacture good quality composite products. Dry fibre mats were laid onto a glass plate and then covered by a peel ply and porous release film. Flow medium/transport mesh was laid over the first half of the reinforcement with a 2 cm gap from the edge (Figure 1). The whole stack was enclosed by a flexible plastic sheet (bag). The bag was sealed and put under vacuum. The resin was drawn into the mould by this vacuum to impregnate the fibre mats.

The resin used in the experiment was Sicomin SR 8100 epoxy with 22 phr (parts per hundred by weight of resin) of SD 8824 hardener. The mixed resin system has an initial viscosity of 165 mPa.s at 20ºC according to the manufacturers data sheet. The filling times (Table 3 – times to complete initial wetting of the whole reinforcement) were similar in both flax and glass laminates. Note that the range of filling times is only -15% to +9% of the average values for all experiments. The plates were cured for 24 hours at ambient temperature and then post-cured in the oven with the temperature increased from 20ºC to 60ºC over four hours, at a constant 60ºC for a further eight hours then a gradual decrease in temperature from 60ºC to 20ºC over one hour.

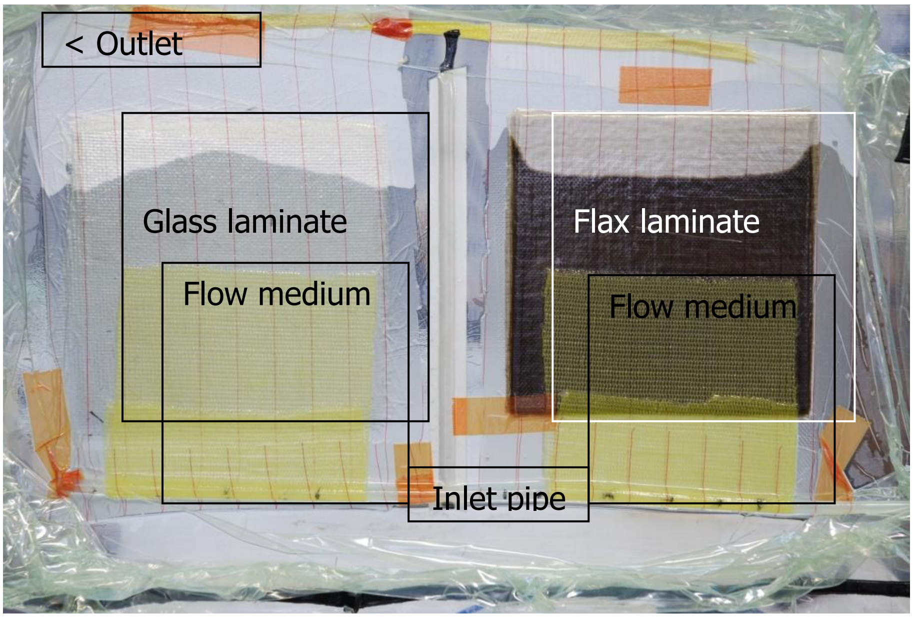

Figure 1. Photograph of experiment set up (each laminate is 200 mm square)

Table 3. Laminate filling times

Laminate	No of Layers	Bag Pressure	Filling time
First Experiment - Flax	7	1019 mbar	2min 20 sec
First Experiment - Glass	7	1019 mbar	2min 20 sec
Second Experiment - Flax	7	1012 mbar	2min 30sec
Second Experiment - Glass	11	1012 mbar	2min 42sec
		Mean:	2min 25sec

The glass composite in this first experiment was only 1.7 mm thick, while the flax composite was 2.8mm thick. The second experiment was carried out with 7 layers of flax fabric and 11 layers of glass to achieve composites of similar thickness.

RESULTS

Seven samples of 20mm × 150mm were machined from each second experiment composite panel for the three point flexural test. Samples were tested in accordance with the ISO 14125 (adapted from CRAG 200) standard using a span of 100 mm. A 500N load cell was used in the Instron 5582 machine with a cross-head speed of 5mm/min. The individual load *vs*. deflection curves for each specimen are shown in Figure 2. The flexural moduli and strengths are summarised in Table 4 and the relative magnitudes of Young's moduli are shown in Figure 3 for all the tested samples (note that the axes have different scales).

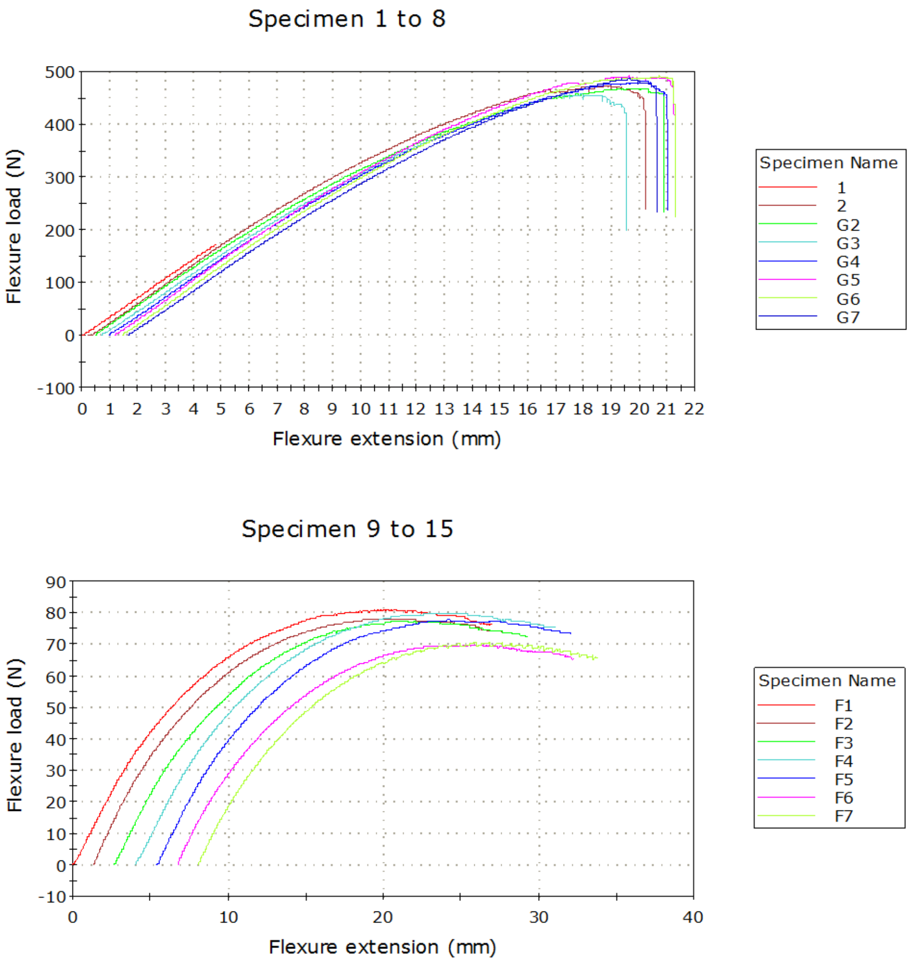

Figure 2. Load vs. deflection curves for glass fibre reinforced composite samples (specimens 1 to 8) and for flax fibre reinforced composite samples (specimens 9-15)

Table 4. Flexural testing results for glass and flax composite samples

		Thickness (mm)	Width (mm)	Volume Fraction	Flexural Modulus (GPa)	Flexural Strength* (MPa)	Flexural Strength** (MPa)
Glass	Mean	2.8	20.7	0.63	18.5	440	291
	Std Dev	0	0.1	0	0.64	12.9	5.31
Flax	Mean	2.8	20.6	0.42	4.84	74.6	59.4
	Std Dev	0.08	0.1	0.01	0.46	7.92	5.88

* Flexural strength calculated using CRAG method 200.
** Flexural strength calculated using BS EN ISO 14125:1998 with the large deflection correction equation [10]
Flexural strength for flax is calculated from the peak load as no failure was observed.

DISCUSSION

In comparing flax and glass fibre, the fibres have similar cross-sectional dimensions although the flax fibre cross section is not round and hence the fibre "diameter" is only indicative of the fibre dimensions. The short flax fibres are spun to produce a yarn for weaving hence they have lower fibre length distribution factor (glass fibres are continuous fibres) and a lower fibre orientation distribution factor (both fibres have crimp but the flax also has helical fibre orientation within the bundle due to the spinning). An ideal pair of woven fabrics for comparison would have similar number of fibres within each tow and similar tow counts in both warp and weft directions. In practice it was not possible to obtain a perfect glass fibre equivalent of the flax fabric.

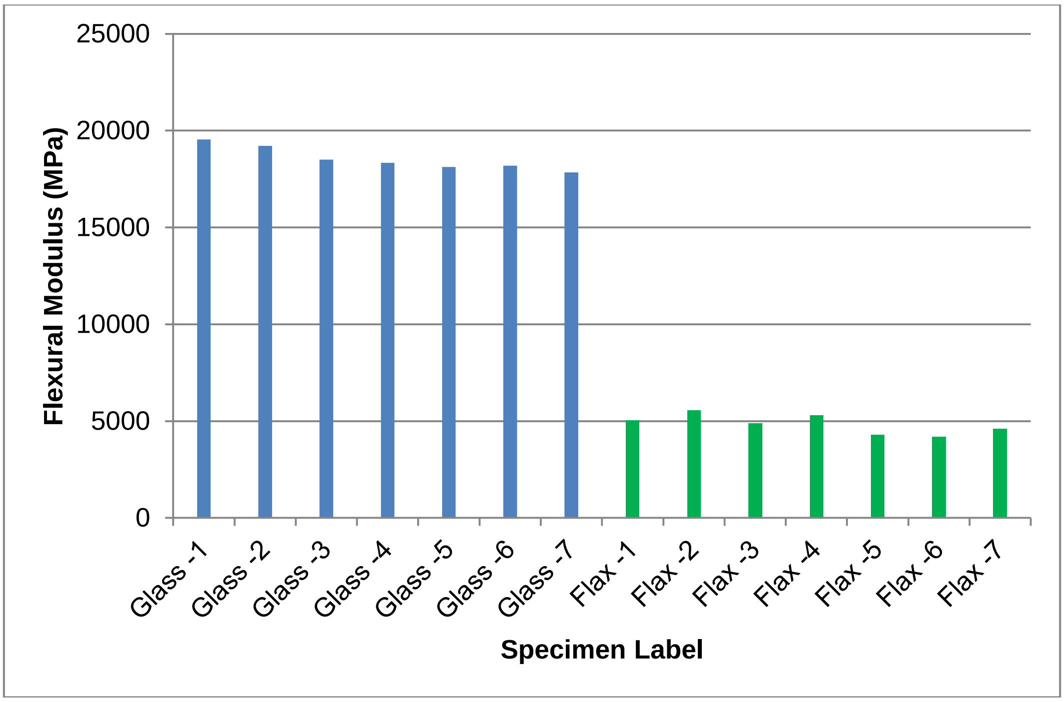

Figure 3. Comparison of flexural moduli for all glass- and flax-reinforced composites

The results indicate that for reinforcement fibres of equivalent (compensated for fibre density) areal weight, the glass fibre fabric will fill more rapidly at similar fibre volume fractions. The natural fibre composite achieves a lower fibre volume fraction, lower modulus and lower flexural strengths. Using the Kozeny-Carman-Blake analysis, the permeability, K, is a function of the porosity (ε) [11] and is proportional to either $(1-V_f)^3/(V_f)^2$ or to $\varepsilon^3/(1-\varepsilon)^2$. The permeability of flax fibre composite at a fibre volume fraction of 0.63 will thus be only 11% of a similar flax fibre composite at a fibre volume fraction of 0.42 and hence will take much longer to infuse.

Comparisons of specific modulus (E/ρ), beam stiffness ($E^{1/2}/\rho$) and panel stiffness ($E^{1/3}/\rho$) [12] are given in Table 5. The E value for the higher fibre volume fraction in flax reinforced composite was obtained using $E = \eta_o V_f E_f + V_m E_m$ when flax fibre has E_f =14.6 GPa (for the textile fabric obtained for this study) and the resin system has E_m = 2.85 GPa (manufacturers data sheet). Densities of the respective composites have been calculated using rule of mixtures with the specific gravities of 1.11 (resin), 1.5 (flax) and 2.5 (glass). The density of the resin has been calculated at 1.11 Mgm^{-3} using rule of mixtures with 27 phr by volume of hardener and densities of 1.158 and 0.942 respectively for the resin and hardener (from manufacturers data sheet) and assuming no shrinkage during cure.

Table 5. Calculations of the composite properties

		V_f %	E/GPa	ρ/Mgm^{-3}	E/ρ	$E^{1/2}/\rho$	$E^{1/3}/\rho$
Flax	Measured	42	4.8	1.274	3.77	1.72	1.32
Flax	Calculated	63	5.7	1.356	4.20	1.76	1.32
Glass	Measured	63	18.5	1.986	9.32	2.17	1.33

When comparing the mechanical performance of the materials, the three parameters (E/ρ, $E^{1/2}/\rho$ and $E^{1/3}/\rho$) are all lower for flax than for glass composites. For panels, the composites are effectively equivalent if judged using $E^{1/3}/\rho$. For panels in flexure, no weight saving is achieved by increasing the fibre content (values of $E^{1/3}/\rho$ are virtually independent of V_f). In respect of the LCA, a panel of equivalent stiffness could be produced if a fibre volume fraction of 63% can be achieved at the same thickness, or at the same weight for a fibre volume fraction of 42%. In the latter case, there will be a significant increase in the polymer content (which is the component with the higher embodied energy). If the higher fibre volume fraction route is followed, then the process times will be extended.

CONCLUSION

These preliminary experiments suggest that panels of equivalent stiffness can be produced at identical weight with broadly similar process times. However, the experiments conducted here indicate that, at the same fibre volume fraction, a flax laminate will have a lower permeability and hence it will be significantly slower to fill. A thicker beam (for flax) will require more resin and this component of the composite is environmentally less desirable as it is of higher embodied energy.

The authors would be most grateful to know of any results for studies similar to the one reported here that might inform the ongoing LCA.

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Appendix – A8

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Optimisation of Energy Use in the Production of Flax Fibre as Reinforcement for Composites

Abstract #10

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Abstract

Global warming has become a worldwide concern over the past few decades. This study aims to identify whether the use of natural fibres as reinforcement for composites is truly environmentally beneficial when judged against manmade fibres with respect to energy consumption (leading to carbon emissions). Energy used by agricultural equipment in ploughing, sowing, applying fertiliser, pesticides, desiccation and harvesting and is used to produce fertiliser, pesticides and desiccant. Energy is also used in fibre processing stages of rippling, retting, decortication, carding and spinning. These processes are carried out using heavy machinery. The aim is to determine the total energy consumption in obtaining 1 tonne of flax in a form that can be used as reinforcement for composites and to establish best practice in each stage of the agricultural process. If alternative minimum impact methods were to be adopted, how great a reduction could be achieved?

Keywords: flax, energy, reinforcement, life cycle assessment

INTRODUCTION

Environmental concerns have resulted in a renewed interest in sustainable composites focusing on bio-based fibres and resins. The fibres most likely to be adopted as reinforcement are bast (stem) cellulose fibres from plants such as flax, hemp, kenaf, jute and sisal. However, it is timely to consider whether the claimed benefits of the materials can be justified. The long term aim of this study is to carry out a quantitative and comparative Life Cycle Assessment (LCA) of natural fibres compared with glass fibres as a reinforcement for polymer composites to establish the most sustainable option. Life Cycle Assessment (LCA) is an environmental assessment method which, according to ISO 14040:2006(E), "considers the entire life cycle of a product from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal" [1]. The outline methodology is defined by the international standards for Environmental Management Systems [1-5]. An LCA study has four phases:

- The **goal and scope definition –** establishing the aim and scope of the study and defining the function or functional unit of the product under examination.
- **Life Cycle Inventory analysis (LCI)** – compilation and quantification of inputs and outputs for a product through its life cycle.
- **Life Cycle Impact Assessment (LCIA)** - understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product, and
- **Life Cycle Interpretation** – the findings of the LCI or LCIA or both are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

In the context of a quantitative LCA, the objective of this paper is to determine the energy consumption of fibre production processes for reinforcement in composites as a part of a LCI. A comparative study by van Dam et al [6] on environmental implications of polypropylene (PP), high density polyethylene (HDPE) and polyurethane (PU) relative to natural fibre based products concluded that natural fibre production requires less than 10% of the energy used for PP fibres (around 90GJ/tonne). When the use of fertiliser was included in the calculations, fibre production energy requirement increased to about 15% of those for PP fibres. However the data are for jute fibres produced without powered mechanical assistance. It is important to determine the value or a range of values for the total energy consumption in producing 1 tonne of flax, for the reinforcement in composites considering various agricultural operations and inputs – fertiliser, pesticides, herbicides etc as well as fibre processing techniques.

PRODUCTION OF FLAX

The typical production cycle of flax fibres [7] is:

- **Tillage:** the preparation of land for cropping by ploughing or similar operations. Convention tillage is preferred in flax cultivation which is primary tillage followed by early spring tillage and planting. No-till methods have been trialled by some growers with no significant change in flax yield [8].
- **Drilling** (planting) the seed: this usually occurs between the end of February and early April in Belgium, France and the Netherlands or in early April in Northern Ireland (NI). Flax is planted in narrow rows (15-20 cm apart) using similar equipment to cereals. Optimum seed depth is 2.5-4.0 cm deep and optimum seeding rates are 35-50 kg/ha [8]. For flax in UK, the suggested levels of fertiliser are:

nitrogen (N) - 40 kg/ha, phosphorus (P) as P_2O_3 - 50 kg/ha and potassium (K) as K_2O – 50 kg/ha [9].

- **Weed control:** Flax is a poor competitor with weeds and it is essential to minimise weeds to avoid contamination of the scutched (i.e. decorticated) flax fibres. Herbicides are applied to achieve this.
- **Plant growth:** the life cycle of the flax plant consists of a 45 to 60 day vegetative period, a 15 to 25 day flowering period and a maturation period of 30 to 40 days.
- **Dessication:** Glyphosate is typically applied 10-14 days after full flower, at about mid-July in NI. Glyphosate is only used where stand retting (see below) is adopted followed by direct combine harvesting of the crop. Chemical desiccation or drying of the crop has numerous advantages over field retting such as earlier harvesting, elimination of the need for swathing, reduced combing time, less wear on machinery etc.
- **Harvest:** by either combine harvester or pulling, in August/September.
- **Rippling:** the removal of flax seed capsules by drawing pulled stems through a coarse steel comb.
- **Retting** is defined for flax as the “subjection of crop or deseeded straw to chemical or biological treatment to make the fibre bundles more easily separable from the woody part of the stem. Flax is described as water-retted, dew-retted or chemically–retted … according to the process employed” [10]. Enzymes may be used to assist the retting process, but termination of the retting process may be a problem and failure to achieve this can result in reduced fibre properties. Pre-harvest retting of flax with glyphosate [11] applied at the mid-point of flowering depends on uniform desiccation of the entire stem and is difficult to achieve during a dry season. As in dew-retting, stand-retting of the desiccated flax in the field relies on microorganisms and is dependent on the vagaries of the weather.
- **Decortication** is the mechanical removal of non-fibrous material from retted stalks or from ribbons or strips of stem to extract the fibres. For flax, the process is usually referred to as “scutching”. This can be achieved by a manual operation, hammer mill, inclined plane with fluted rollers or willower.
- **Hackling** is the combing of line flax in order to remove short fibres, align the remaining long (line) fibres and also remove any extraneous matter (shive).
- **Carding** is defined as “the disentanglement of fibres by working them between two closely spaced, relatively moving surfaces clothed with pointed wire, pins, spikes or saw teeth” [10].
- **Spinning** is the drafting [decreasing the mass per unit length] and twisting of natural (or man-made) fibres for the production of yarns or filaments.

ENERGY USE IN FIBRE AND FERTILISER PRODUCTION

In the fibre production process, energy used to power agricultural machinery and fibre processing equipment and to produce and apply fertilisers and pesticides, are the primary sources considered in the context of this study. The use of agricultural machinery adds to production cost and the consumption of fuel. Energy use in such machinery is calculated according to the fuel consumption for various agricultural operations, where the energy density of diesel fuel is taken to be 34.92 MJ/l [12].

Flax fibre yield per hectare is assumed as 972 kg of scutched long fibre (6000 kg of dry, green stem) [13]. “Irrigation is not necessary for flax, and it can be regarded as complementary but secondary to good field planning and establishment" [7]. Nutrients N, P and K are used for fertilising flax. The Stern Review [14] lists fertiliser manufacture as the fourth most energy intensive industry consuming 13.31% of total costs (after electricity production and distribution: 26.70%, gas distribution: 42.90% and refined petroleum: 72.83%). Globally around 1.3% of all energy produced is used for fertilisers. Inorganic fertiliser use in agriculture changes the energy and nutrient cycling and storage that lead to disruption of normal ecosystem functioning and although it is an important issue to investigate the impacts related to fertiliser it is beyond the scope of this paper.

As flax does not compete well with weeds, adequate weed control is essential in obtaining high flax yields. Glyphosate, *N*-(phosphonomethyl) glycine [H_2O_3P-CH_2-NH-CH_2-COOH], is a systemic, broad-spectrum, non-selective herbicide used to kill broad-leaved grasses and sedge species. It is one of the most frequently used xenobiotics in modern agriculture [15] and is used as a dessicant for flax. Bromoxynil and Trifluralin are other common herbicides used to control weed in flax cultivation [7]. There are three different herbicide application periods for flax: pre-emergent, post-emergent and pre-harvest for the control of weeds [16]. Flax may be infested from the time of emergence to maturity by various insect pests. Insecticides are often applied to minimise the loss.

Agricultural Operations

The range of values for energy use in agricultural operations: ploughing, harrowing, cultivating, applying fertiliser, pesticides and dessicant and harvesting are considered. There are different methods of ploughing (tillage) in practice:

4) Conventional tillage: full tillage program combining primary and secondary tillage operations performed in preparing a seedbed [18]. This leaves <15% residue cover after planting and usually involves mouldboard ploughing [19]
5) Conservation tillage: reduced number of passes over the field for land preparation and increases the surface residues (15-30%) to protect soil and water loss. This includes single disking, chiseling and sub soiling.
6) No-till: leaves the soil relatively undisturbed.

Lal's review of farm operations reported that no till seed bed preparation produces only 5.8 kg carbon equivalent (CE)/hectare while mouldboard ploughing produces 35.3 kg CE/hectare [17] consequent upon energy used, but not including CO_2 released from the soil. The average energy use to prepare one hectare (1 ha) of land using the different methods are illustrated in following Figure 1.

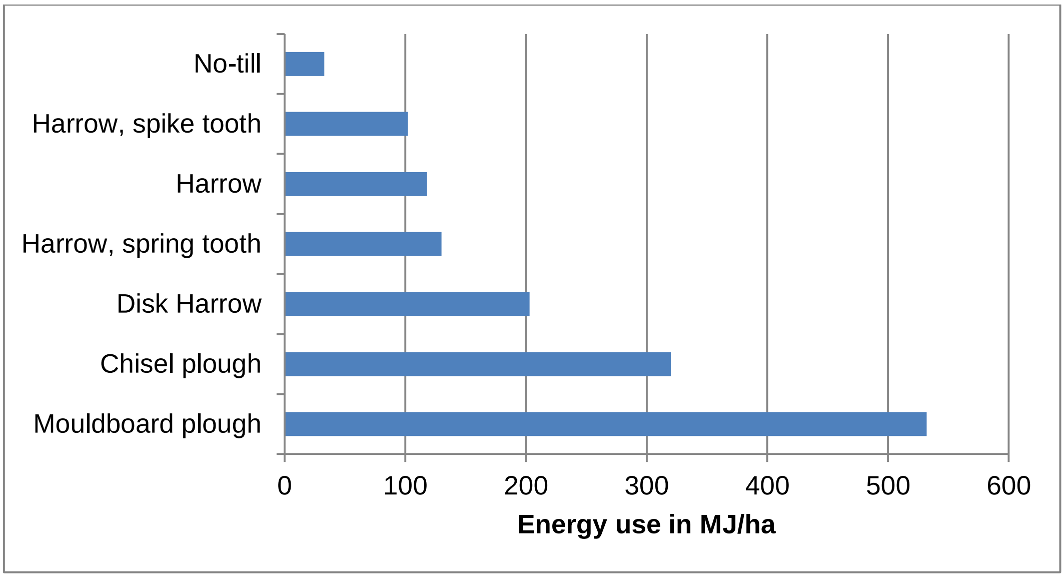

Figure 1. Average energy use in different tillage methods [18-25]

Conventional vs. Conservation tillage practices

The total energy consumed in a flax field per 1 ha using conservation tillage system is significantly less than using conventional tillage system based on the calculations [20-27]. In this example, only two passes were used on the conservation tillage system – the first is a no-till pass followed by simple harrowing (spike tooth). Rolling tines – cultivator for drilling and a cutter bar mower for harvesting was used due to the low diesel consumption. Fertiliser was sprayed 3 times (for N, P, K) using a spray/spread using a bulk cart and sprayers were used 4 times for pesticides and dessicant.

In contrast on the conventional system, two passes used including mould board ploughing and disk harrowing followed by cultivating. Fertiliser was applied 3 times using an anhydrous attachment and sprayers were used 4 times for pesticides and dessicant. Rotary mower was used to harvest.

Indirect energy – energy required for agricultural equipment construction and energy involved in seed, transportation and storage are not considered. Comparison of energy values of these two systems is demonstrated in Figure 2.

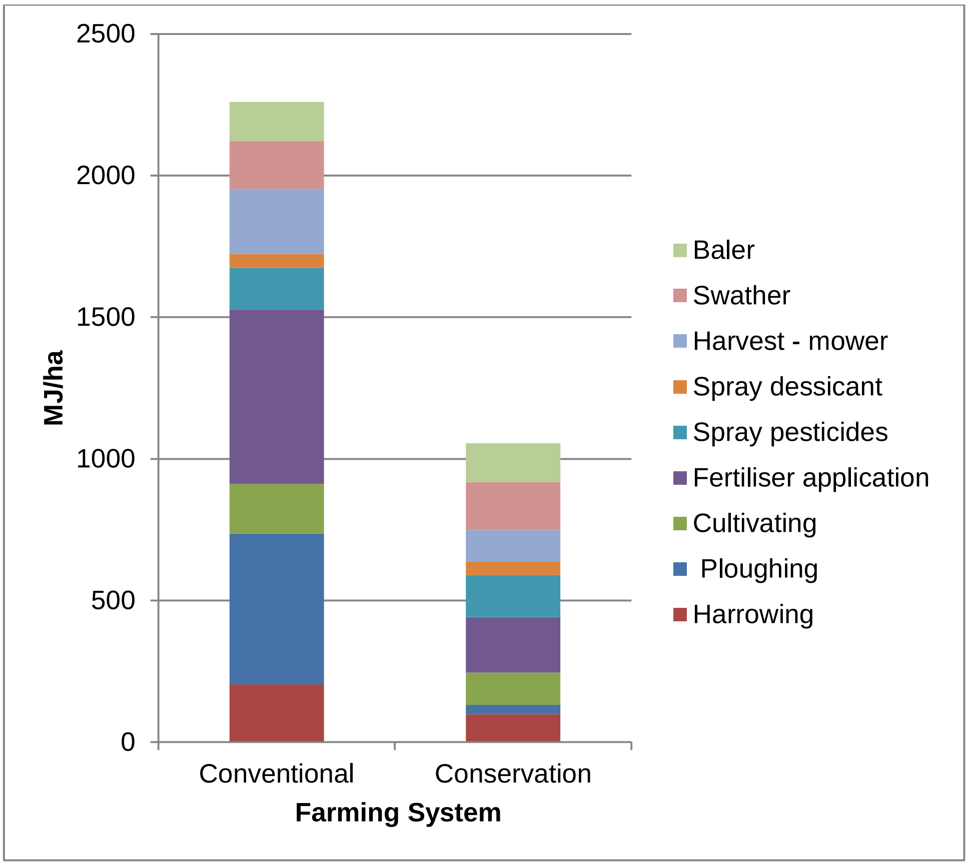

Figure 2. Energy use compared for conventional and conservation tillage system. (The above figures are indicative averages - there will be variation in each case)

The total energy to produce flax in 1 ha using conventional agricultural practice is 2.25GJ and where as conservation system only uses 0.96GJ (a 57% reduction).

Fertiliser and Pesticides

The main fertilisers used for flax are nitrogen (N), phosphorus (P_2O_3) and potassium (K_2O). Recommended levels are currently 40kg/ha of N and 50kg/ha each of P_2O_3 and K_2O in UK [9]. These fertiliser levels should be reduced if organic manure is applied. High levels of N contribute to lodging (plant collapse leading to fibre damage). Measurement of N levels prior to sowing is recommended to allow the adjustment in application rates. Routine application of secondary elements of calcium, magnesium and sulfur and trace elements of boron, copper, zinc, iron, manganese and molybdenum are also recommended for growers.

Synthetic N fertilisers are the single most energy expensive input to modern agricultural production accounting for approximately 68% of on-farm commercial energy use in less developed counties and 40% in more developed nations [28]. The average values for embedded energy in N, P and K fertilizers applied to flax are shown in Figure 3.

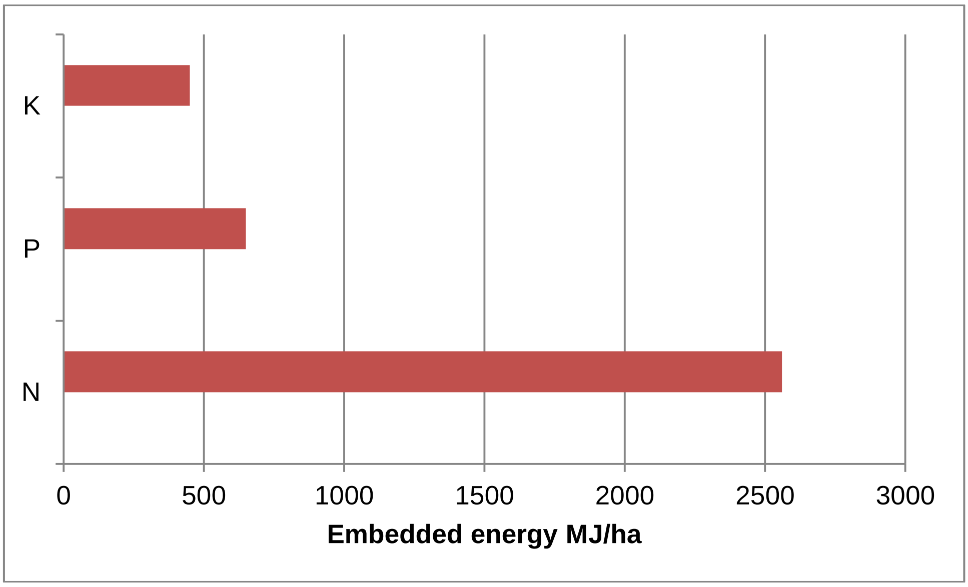

Figure 3. Fertiliser Embedded Energy [29-31]

Pesticides form a major proportion of the total agrochemicals production and usage. In flax cultivation, herbicides, insecticides and fungicides are used in small proportions after diluting with water for e.g. 500ml per 100 liters of water. The average values for embedded energy in insecticides, fungicides and herbicides in general are shown in Figure 4.

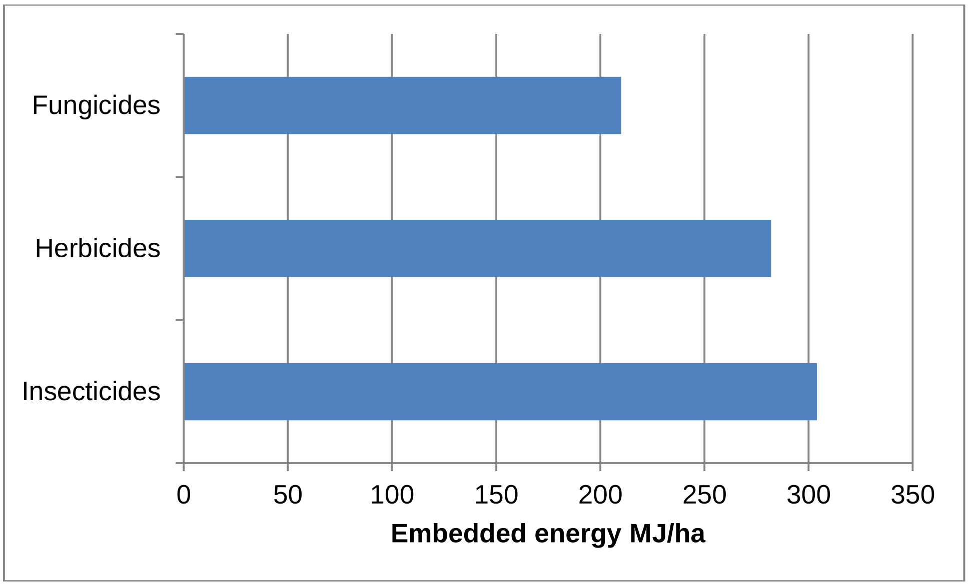

Figure 4. Embedded energy of pesticides [29-31]

Fibre Processing Operations

Generally, after the crop is harvested, the first stage of at fibre processing is retting. Rippling, which is removal of flaxseeds can be done as a part of harvesting where combine harvesting is adopted. Two methods of retting considered are bio-retting and warm-water retting. Retting is followed by a mechanical process called scutching/decortication. This includes breaking the woody core of the stems in to small pieces and separating short fibres from long fibres by beating the broken stem with rotating blades [13]. Decortication is followed by hackling, carding and spinning of the fibres. Values of energy consumption for fibre processing operations are given in Table 1.

Table 1. Energy consumption of fibre processing operations [13]

Operation	Energy Consumption – MJ/kg
Retting - Bio	0.48
-Warm water	0.03
Decortication / Scutching	0.53
Hackling	1.39
Carding	3.94
Spinning	22.9

DISCUSSION

A significant energy saving (~57%) is possible compared to conventional agriculture system in the absence of tillage, as shown in Figure 2. The total energy use to produce 1 tonne of flax scutched fibre using a conventional system is ~2.25GJ and conservation system is ~0.96GJ. Direct sowing and reduced or minimal tillage are the normal methods in conservation agriculture. Minimal or shallower ploughing reduces the energy input considerably and especially on a sloping field it reduces the soil erosion or run off of soil sediments. Traditional or conventional tillage methods of mould board ploughing drastically affect the soil structure, breaking up its natural aggregates and burying the residues of the previous crop. Therefore the bare soil becomes unprotected and exposed to the action of wind and rain [20].

Fertilisers mainly N, P and K are used in flax cultivation to maintain soil fertility levels appropriate for a reasonable yield to be produced. The energy required to manufacture nitrogen bearing materials varies from 80MJ/kg to 130MJ/kg, while the energy required to manufacture phosphorus or potassium bearing fertilisers is less per unit weight of nutrient than required for nitrogen fertilisers (Figure 3). If the recommended fertliser levels were used in 1 ha of flax cultivation, the total energy input will increase by ~3.8GJ/tonne which is 61% more than the energy required for all the agricultural operations. Apart from the high energy usage contributing to carbon emissions, the use of fertilisers in agriculture is perceived as a major cause of eutrophication. The nitrate anion, NO_3^-, has high solubility in water and is not significantly adsorbed onto most soils [32]. When both soil nitrate levels and water movement are high, leaching and run-off may be significant contributors to the nitrogen load in watercourses. However, Reddy et al [33] and Stoate [34] report that phosphorus is the nutrient which limits plant growth in most fresh (river/pond/lake) waters.

As weed control and pest control are also important in flax cultivation, the recommended level of weed control for the UK is 1.10kg/ha of Basagan SG (BASF) [9]. Assuming that herbicides, insecticides and fungicides were applied according to the recommend level, the total energy input in producing flax will increase further by ~0.8 MJ/kg. These will amount the total energy input for 6.85 MJ/kg in conventional agricultural systems and 5.56MJ/kg in conservation systems (Figures 5 and 6).

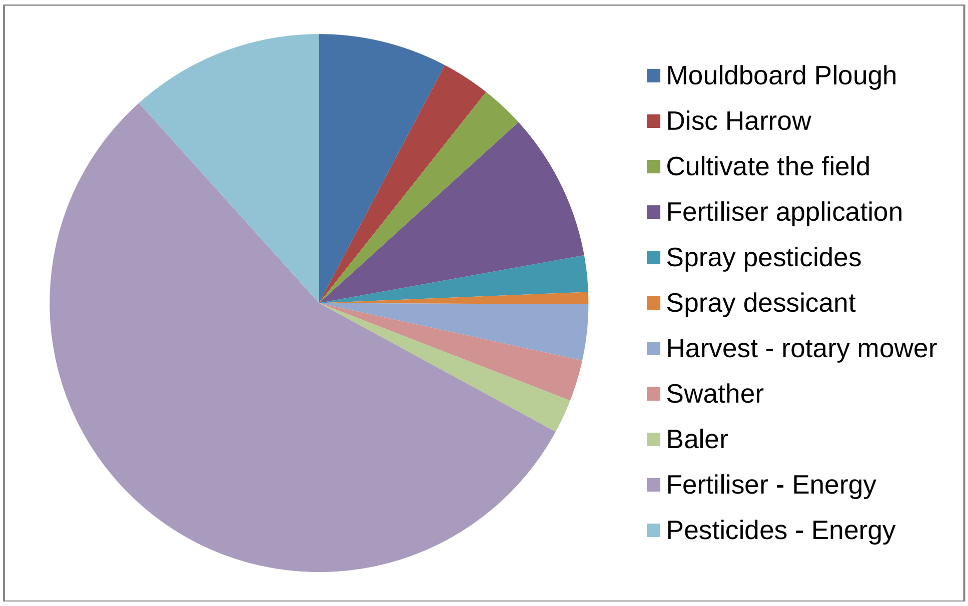

Figure 5. Energy use in a conventional agricultural system
Total Energy = 6.85 MJ/kg

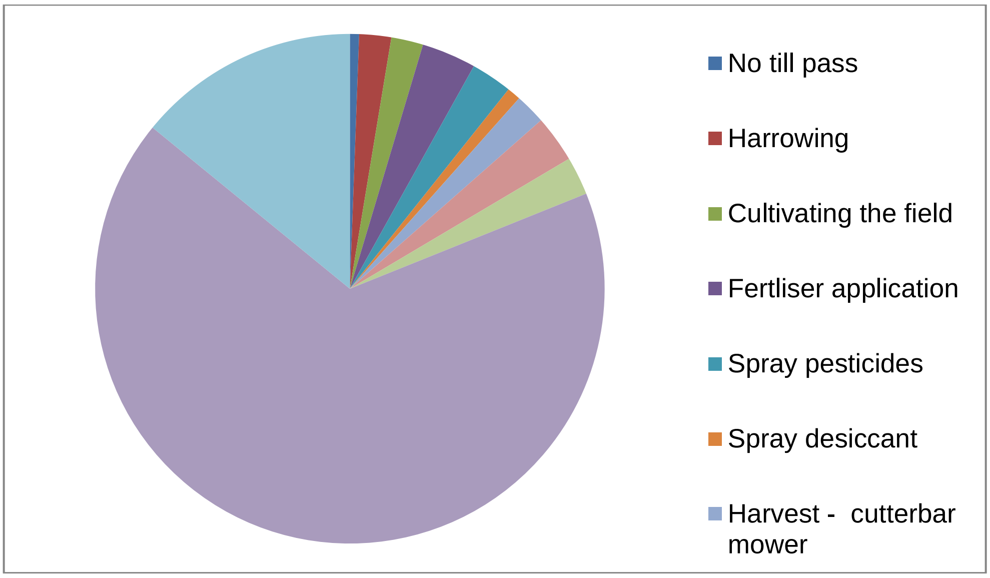

Figure 6. Energy use in a conservation agricultural system
Total Energy = 5.56 MJ/kg

Pesticides increase the eco toxicity and hence may reduce biodiversity. Eriksson et al [35] proposed a scientifically justifiable list of "selected storm water priority pollutants (SSPP)" to be used, for example, in evaluating the chemical risks posed by different water handling strategies. Glyphosate was included with the selected herbicides as it is extensively used in urban areas and along motorways in the UK, France, Denmark and Sweden.

Table 2 presents the energies used during cultivation and retting of flax fibre for one tonne of reinforcement when the high- and low-energy options are combined respectively. Conservation tillage and warm water retting requires only 76% of the energy needed for conventional agricultural practices. However, when decortication/carding and spinning of flax are included (at 6.06 GJ/tonne and 22.9 GJ/tonne respectively with only a single data point available for each) the range of energies is 34.6 GJ to 36.3 GJ per tonne which still compares favourably to the embodied energy in glass at 54.8 GJ/tonne [36].

Table 2. Total energy use to produce 1 tonne retted of flax

	GJ/tonne	GJ/tonne	
Conventional agricultural practice	2.25	0.96	Conservation tillage
Fertiliser	3.80	3.80	Fertiliser*
Pesticides	0.80	0.80	Pesticides*
Bio-retting	0.48	0.03	Warm water retting
Total	**7.33**	**5.59**	Total

*There are routes to reducing these energies (e.g. manure as fertiliser and biological control of pests) which are still to be analysed.

The two retting systems considered were bio-retting and warm water retting in the calculations. Bradshaw et al [37] reported that a major eutrophication of Dallund Sø (a lake in Denmark) occurred as a result of the changing agricultural system and the retting of flax and hemp during the Mediæval period (AD 1050-1536). This eutrophication could be significantly reduced by stand/dew retting rather than immersion/water retting and would be less energy intensive process.

From the above calculations (based on data available in the literature), it is clear that most energy use is due to the agro-chemical intensity in flax cultivation. The overall energy consumption could be reduced by adopting a minimum-tillage system which also improves the water quality, albeit that there are issues in implementing this practice with current agricultural machinery. Further, rough grass buffer strips between arable land and streams can prevent run-off from fields, especially where small pools catch the sediment before it enters the watercourse. The legally permissible buffer zones are defined in e.g. Defra/PSD documents [38]. Stoate [34] has reported that the direction of cultivation appears to be the overriding influence on how much run-off, soil and phosphorus leaves the field: cultivating across slopes (rather than up and down).

CONCLUSION

This investigation was carried out as a part of complete LCA study on flax fibres and the main focus has been the energy use in the production process with data extracted from available literature. Environmental impacts should be evaluated for each production stage to complete the analysis and there are eight Environmental impact category factors (EICF) to be considered [39, 40]. Energy use in agricultural process can be reduced or controlled by adopting sustainable agricultural practices with the development of suitable equipment. A key consideration for reducing energy consumption would be to produce aligned fibres reinforcement without the need for the energy intensive spinning operation.

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Appendix A9

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Comparative Life Cycle Assessment for Natural vs Glass Fibres as Reinforcement for Composites

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ABSTRACT

This paper considers the environmental performance of flax fibres, relative to glass fibres, when used as the reinforcement in composites. The paper seeks to identify the key environmental issues required for qualitative life cycle assessment (LCA) and to start to quantify those parameters with a view to Quantitative Life Cycle Assessment (QLCA). The scope of the study is cradle-to-gate: to identify the issues arising at every stage in flax cultivation from ploughing, sowing, use of pesticides (insecticides and herbicides), fertiliser and water, desiccation and harvest through to fibre processing into a reinforcement form for composites.

INTRODUCTION

Concern for the environment is not a new phenomenon. In the fifth century BC, Plato wrote about the effects of unsustainable practice regarding forests, referring to the deforestation of the hills around Athens as a result of logging for shipbuilding and to clear agricultural land [1]. In 1713, von Carlowitz [2] explained that if forest resources were not used with caution (i.e. planned on a sustainable basis to achieve continuity between increment and felling), then humanity would plunge into poverty and destitution. In 1798, Malthus [3] presented his Essay on the Principles of Population in which he proposed that population tends to increase faster than the means of subsistence, and its growth could only be checked by moral restraint or disease and war. In 1962, Carson [4] published Silent Spring which warned against profligate use of synthetic chemical pesticides, challenged the agricultural practices of the time and suggested that there were methods of pest control which were less damaging to the natural world. Her work is often suggested to be the primer for the rise of the environmental movement in the 1960s. In 1987, the World Commission on Environment and Development suggested that Sustainable Development should be defined as "Meeting the needs of the present without compromising the ability of future generations to meet their own needs" [5]. These few examples are not a complete record of the appropriate literature.

The composites industry has grown rapidly over the past seventy years since the introduction of commercial continuous fibre reinforcements (glass in 1937, carbon in the 1960s and aramids in 1971). Natural fibres were used in resin matrix composites in the early years of the industry including flax and hemp fibres for the bodywork of a Henry Ford car in 1941 [6], but fell from favour and are now poised for a revival. The fibres most likely to be adopted as reinforcements are bast (stem) fibres from plants including flax and hemp (in temperate zones) or jute and kenaf (in tropical zones). These cellulose fibres may match man-made glass fibres on elastic modulus, but typically suffer from having finite length (i.e. not continuous filaments unless spun into that form), lower strengths, higher variability in many properties relative to synthetic fibres and more rapid degradation in hot and/or wet environments.

Fibres like flax/linseed and hemp are currently grown commercially in UK/Europe and such natural fibre composites are used for wide range of automotive applications such as interior panels of passenger cars and truck cabins, door panels and cabin linings as substitutes for glass fibre composites. The study will help to identify whether the substitution of glass fibres with natural fibres is truly environmentally beneficial.

Life Cycle Assessment is an environmental assessment method, which normally focuses on the entire life cycle of a product from raw material extraction and acquisition, through energy and material production and manufacturing and the use phase, to end-of-life treatment and final disposal [ISO, 2006]. The environmental impacts are considered under the eight categories outlined in the ISO standards 2006:

- Non-Renewable Resource Depletion
- Global Warming Potential
- Ozone Depletion Potential
- Acidification Potential
- Eutrophication Potential
- Photochemical Oxidants Creation Potential
- Human Toxicity Potential
- Aquatic Toxicity Potential

These environmental effects may either be direct (such as air emissions produced from automobile usage) or indirect (such as pollution and impact on surface and ground water sources from the use of fertiliser). The use of energy in vehicles, machinery and other processes is also included. Quantitative life cycle analysis of natural fibres could help to justify their position in a more sustainable society. The life cycle assessment will be judged against glass fibre production (cradle-to-gate).

NATURAL FIBRE PRODUCTION

The typical production cycle for flax fibres [7] is:

- **Tillage** (ploughing or equivalent)
- **Drilling** (planting) the seed: this usually occurs between the end of February and early April in Belgium, France and the Netherlands or in early April in Northern Ireland (NI).

- **Fertiliser:** For flax in NI, the suggested levels of fertiliser are 20 kg N/ha, 20 kg P2O5/ha and 80 kg K2O/ha.
- **Weed control:** it is essential to minimise weeds to avoid contamination of the scutched flax fibres.
- **Dessication:** glyphosate is typically applied 10-14 days after full flower, at about mid-July in NI.
- **Harvest:** by either combining or pulling, in August/September.
- **Rippling:** the removal of flax seed capsules by drawing pulled stems through a coarse steel comb.
- **Retting** is defined for flax as the "subjection of crop or deseeded straw to chemical or biological treatment to make the fibre bundles more easily separable from the woody part of the stem. Flax is described as water-retted, dew-retted or chemically–retted, etc., according to the process employed" [8].
- **Decortication** is the mechanical removal of non-fibrous material from retted stalks or from ribbons or strips of stem or leaf fibres to extract the bast fibres. For flax, the process is usually referred to as "scutching". This is usually achieved by a manual operation, hammer mill, inclined plane/fluted rollers or willower.
- **Hackling** is the combing of line flax in order to remove short fibres, parallelise the remaining long (line) fibres and also remove any extraneous matter (shive).
- **Carding** is defined as "the disentanglement of fibres by working them between two closely spaced, relatively moving surfaces clothed with pointed wire, pins, spikes or saw teeth" [8].
- **Spinning** is the drafting [decreasing the mass per unit length] and twisting of natural (or man-made) fibres for the production of yarns or filaments. In the bast-fibre and leaf-fibre industries, the terms 'wet spinning' and 'dry spinning' refer to the spinning of fibres in the wet state, and in the dry state respectively.

The flow diagram below represents the typical production cycle of flax fibre.

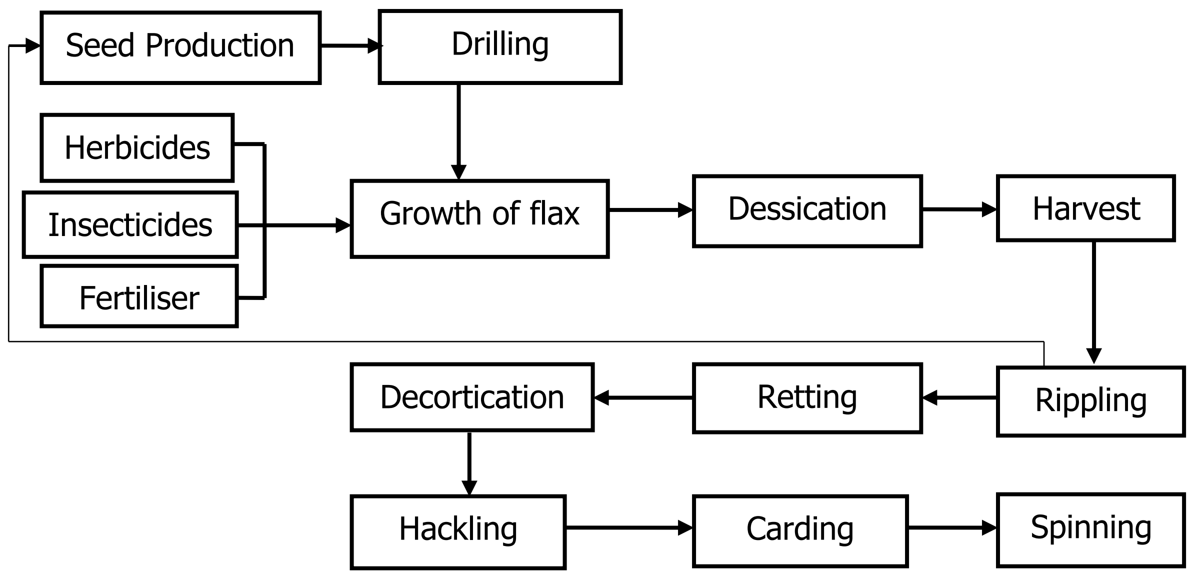

Figure 1. Flow Diagram of Life Cycle of flax fibre as reinforcement for composites.

GLASS FIBRE PRODUCTION

Glass fibres come in a variety of forms although >95% of all reinforcements are E-glass. The formulation of these fibres includes several minerals, notably [9]:

- sand – particles of minerals including quartz (silica: SiO_2), mica (complex silicates usually with K, Na, Li, H and Mg) and feldspar (aluminium silicates with varying amounts of K, Na, Ba and Ba). "Pure sand is white in colour and consists of silica" [10]
- kaolin – hydrated aluminium silicate ($Al_2O_3.2SiO_2.2H_2O$) also known as china clay [10],
- limestone – mostly calcium carbonate ($CaCO_3$) with other oxides (Si, Al, Fe), carbonates (Fe, Mg) and calcium phosphate [10], and
- colemanite – hydrated calcium borate ($2CaO.3B_2O_3.5H_2O$) [10].

These materials are melted at ~1600ºC and spun through micro-fine bushings to produce filaments of 5-24 μm in diameter. The cooled filaments are drawn together into a strand (closely associated) or roving (loosely associated), and coated with a "size" to provide filament cohesion and protect the glass from abrasion [9].

The flow diagram (Figure 2) below represents the glass fibre production process.

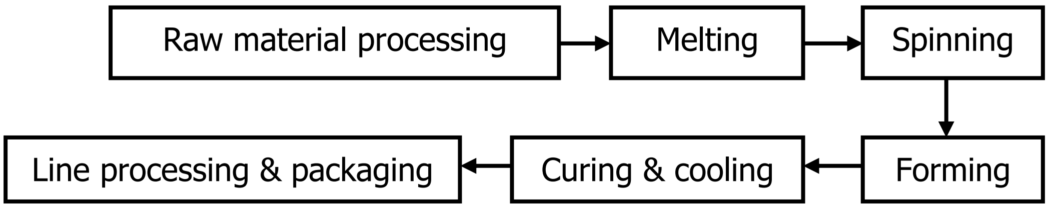

Figure 2. Flow diagram of glass fibre production process.

LIFE CYCLE ASSESSMENT

The new focus on planning for a sustainable world has revived interest in natural fibre reinforced materials. However, it is timely to consider whether the claimed benefits of these materials can be justified quantitatively. Life Cycle Assessment (LCA) is an environmental assessment method, which "considers the entire life cycle of a product from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal" [ISO 14040:2006(E)] [11]. An LCA study has four phases:

- The **goal and scope definition**
- **Life Cycle Inventory analysis (LCI)** – compilation and quantification of inputs and outputs for a product through its life cycle.
- **Life Cycle Impact Assessment (LCIA)** - understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product, and

- **Life Cycle Interpretation** – the findings of the LCI or LCIA or both are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

ISO/TR 14047:2003 [12] identifies eight environmental impacts which closely mirror the environmental impact classification factors (EICF) used by Azapagic [13, 14] (Table 1).

Table 1: Environmental Impact classification factors

ISO/TR 14047:2003(E) [12]	Azapagic et al [13,14]
Acidification	Acidification Potential (AP)
Ecotoxicity	Aquatic Toxicity Potential (ATP)
Eutrophication/Nitrification	Eutrophication Potential (EP)
Climate change	Global Warming Potential (GWP)
Human toxicity	Human Toxicity Potential (HTP)
Depletion of abiotic/biotic resources	Non-Renewable/Abiotic Resource Depletion (NRADP)
Stratospheric ozone depletion	Ozone Depletion Potential (ODP)
Photo-oxidant formation	Photochemical Oxidants Creation Potential (POCP)

Additional factors might be considered including land use (where industrial materials from non-food crops displace food plants or where waste materials are dumped into landfill sites), loss of biodiversity (if not adequately reflected by ecotoxicity), and/or noise, vibration and odour.

ISO 14040:2006(E) [11] suggests that the **goal of an LCA** should state:

- The intended application
- The reasons for carrying out the study
- The intended audience
- Whether the results are intended to be disclosed to the public

The scope should be sufficiently well defined that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal. LCA is an iterative technique, and as data and information are collected, various aspects of the scope may require modification in order to meet the original goal of the study. The **scope of an LCA** should include the following items:

- The product system to be studied
- The functions of the product system (or systems for comparative studies)
- The functional unit
- The system boundary
- Allocation procedures
- Impact categories selected and methodology of impact assessment, and subsequent interpretation to be used
- Data requirements
- Assumptions
- Limitations
- Initial data quality requirements
- Type of critical review, if any

- Type and format of report required for the study.

Acidification

Acidification is a consequence of acids (and other compounds which can be transformed into acids) being emitted to the atmosphere and subsequently deposited in surface soils and water. Increased acidity of these environments can result in negative consequences for coniferous trees (forest dieback) and the death of fish in addition to increased corrosion of manmade structures (buildings, vehicles etc.). Acidification Potential (AP) is based on the contributions of SO_2, NO_x, HCl, NH_3 and HF to the potential acid deposition in the form of H^+ (protons) and thus needs to be considered in the context of nitrogen fertilisers as run-off to water.

Ecotoxicity

Eco-Toxicity and Human-Toxicity result from persistent chemicals reaching undesirable concentrations in each of the three elements of the environment (air, soil and water) leading to damage to animals, eco-systems and humans. The modeling of toxicity in LCA is complicated by the complex chemicals involved and their potential interactions. The assessment of potential toxic effects, on non-target organisms such as aquatic biota and soil micro-organisms, from pesticides in the aquatic environment is becoming increasingly important [15] Herbicides constitute >50% of pesticide production in Denmark, France and the UK [16].

In an environmental comparison of China Reed fibre as a substitute for glass fibre in plastic transport pallets, Corbière-Nicollier et al [17] found that cultivation of the reed had a dominant role in the factors for human toxicity (when crop rotation has edible foods following the China Reed), terrestrial ecotoxicity and eutrophication due to (a) heavy metal emissions to soil and (b) phosphate emissions (from manure and fertiliser) to water.

Eutrophication

Eutrophication is defined as the potential for nutrients to cause over-fertilisation of water and soil which in turn can result in increased growth of biomass. The Eutrophication Potential (EP) value is calculated in kg based on a weighted sum of the emission of species such as N, NO_x (nitrogen oxides), NH_4^+ (ammonia), PO_4^{3-} (phosphates), P and chemical oxygen demand (COD) measured relative to PO_4^{3-}.

Reddy et al [18] and Stoate [19] report that phosphorous is the nutrient which limits plant growth in most fresh (river/pond/lake) waters. Nitrogen contamination of fresh water does not necessarily result in a significant eutrophication hazard [20] although it may be the limiting nutrient in coastal waters [18, 19]. Phosphorous binds tightly to soil particles and hence is a particular problem when sediment enters watercourses as it leads to excessive algal growth. In turn, the algal blooms reduce light penetration into the water and hence inhibit the growth of macrophytes and their invertebrate predators. Further, as the excessive plant biomass decomposes it consumes dissolved oxygen in the water initially affecting top predators and hence disrupting the ecosystem.

The use of fertilisers in agriculture is perceived as a major cause of eutrophication. However, Stoate [19] has suggested that phosphorous and other nutrients from village sewage works and from septic tanks at isolated dwellings also contribute to depletion of downstream invertebrate communities.

In an environmental comparison of China Reed fibre as a substitute for glass fibre in plastic transport pallets, Corbière-Nicollier et al [17] found that China Reed fibre was the better option for all factors except eutrophication. The CML and Eco-indicator measures confirm the CST95 results (China Reed is considered better on all factors relative to glass fibre) except for eutrophication. The China Reed has a better score from the former two methods as they consider NO_x emissions to contribute to eutrophication whereas CST95 considers that only phosphates contribute to eutrophication in Europe where lakes are normally phosphorous limited.

Bradshaw et al [21] reported that a major eutrophication of Dallund Sø (a lake in Denmark) occurred as a result of the changing agricultural system and of the retting of flax and hemp during the Mediæval period (AD 1050-1536).

Climate Change/Global Warming Potential

Global Warming is caused by the atmosphere's ability to reflect some of the heat radiated from the earth's surface. This reflectivity is increased by the greenhouse gases (GHG) in the atmosphere. Increased emission of GHGs (CO_2, N_2O, CH_4 and volatile organic compounds (VOCs)) will change the heat balance of the earth and result in a warmer climate over future decades.

Primary sources of GHG in the context of this study include the energy for

(c) melt spinning of glass fibres, or

(d) for natural fibres,

i. energy used to power agricultural equipment,

ii. energy used to produce and apply fertilisers and pesticides, and

iii. releases of CO_2 from decomposition and oxidation of soil organic carbon (SOC) following soil disturbance, and CO_2 and CH_4 (methane) from retting,

in addition to transport costs incurred by both types of fibre.

The Stern Review [22] lists fertiliser manufacture as the fourth most intensive industry with energy consuming 13.31% of total costs (after electricity production and distribution: 26.70%, gas distribution: 42.90% and refined petroleum: 72.83%). When measured in terms of carbon intensity it falls to fifth place at 4.61 ppt change at £70/tonne of carbon behind cement, lime (also used in agriculture) and plaster at 9.00. Globally around 1.3% of all energy produced is used for fertilisers.

Abrahams [23] states that there "is an appreciable flux of CO_2 from the oxidation of soil organic matter, whilst soils are also important sources of the greenhouse gases CH_4 and N_2O". The management of the land and any future climatic warming may increase these emissions.

Lal [24] reviewed the available information on energy use in farm operations and converted the data into kilograms of carbon equivalent (kg CE) shown in Table 2. The kg CE value is directly related to the rate of enrichment of atmospheric CO_2.

Table 2: Energy use in various farm operations [24] – data from abstract.

Operation	kg CE/ha	Notes
Tillage	2-20 [sic]	Not included in totals below
Conventional till	35.3	Included in highest total below
Chisel till	7.9	Not included in totals below
No-till seed bed preparation	5.8	Included in lowest total below
Spraying chemicals	1.0-1.4	
Drilling or seeding	2-4	
Combine harvesting	6-12	
Fertiliser (N)	0.9-1.8	
Fertiliser (P_2O_5)	0.1-0.3	
Fertiliser (K_2O)	0.1-0.2	
Fertiliser (lime)	0.03-0.23	
Herbicides (active ingredients)	6.3	
Insecticides (active ingredients)	5.1	
Fungicides (active ingredients)	3.9	
Irrigation (apply 25 cm water)	129±98	From deep wells and/or sprinklers
Irrigation (apply 50 cm water)	258±195	From deep wells and/or sprinklers
Lowest possible total	**62.23**	**Each appropriate item …**
Highest possible total	**513.73**	**… included only once**

Depletion of Resources

ISO/TR14047:2003(E) [12] includes both abiotic (non-biological) and biotic resources within this category. L van Oers et al [25] consider abiotic resources to include both non-renewable and renewable resources and define an abiotic depletion potential (depletion of availability) for non-renewable resources as "not replenished or broken down by geologic forces within a period of 500 years". They divide abiotic resources into three categories:

4. **Deposits** (resources that are not regenerated within human lifetimes, e.g. minerals, sediments, clays and fossil fuels). They further divide deposits into Groups:
   - IV. Primary materials for industrial processing, including both (a) the atomic elements, and (b) compounds (called "configurations" in their paper, e.g. silicon oxide),
   - V. Primary materials for building applications (e.g. stone and construction sand),
   - VI. Energy carriers (e.g. oil and natural gas).

2. Funds (resources that can be regenerated within human lifetimes, e.g. groundwater and some soils),

3. Flows (resources that are constantly regenerated, e.g. solar energy, wind and river water)

Both quartz and feldspar are used in the manufacture of glass, and feldspar is used in the manufacture of fertilisers. The ultimate reserves of these minerals within the top 1 km of the earth's crust are $5x10^{20}$ and $1x10^{20}$ kg respectively [25] and the relative contribution (based on the normalisation data for the global extraction of elements and compounds) to the depletion of abiotic resources is effectively zero.

Photo-Chemical Oxidants

Photochemical Ozone Formation results from the degradation of volatile organic compounds (VOCs) in the presence of light and the oxides of nitrogen (NO_x). Excess ozone can lead to damaged plant leaf surfaces, discolouration, reduced photosynthetic function and ultimately death of the leaf and finally the whole plant. In animals, it can lead to severe respiratory problems and eye irritation. Photochemical Oxidants Creation Potential (POCP) is related to the potential for VOCs and oxides of nitrogen to generate photochemical or summer smog. It is usually expressed relative to the POCP classification factor for ethylene. Methane, which is a significant proportion of the gas produced by decomposing organic materials, has a POCP of 0.007 relative to ethylene.

Ozone Depletion

Ozone is formed and depleted naturally in the earth's stratosphere (between 15-40 km above the earth's surface). Halocarbon compounds are persistent synthetic halogen containing organic molecules that can reach the stratosphere leading to more rapid depletion of the ozone. As the ozone in the stratosphere is reduced more of the ultraviolet rays in sunlight can reach the earth's surface where they can cause skin cancer and reduce crop yields. Normally, the Ozone Depletion Potential (ODP) indicates the potential for emissions of chlorofluorocarbon (CFC) compounds and other halogenated hydrocarbons to deplete the ozone layer. At this stage of our analysis we do not believe there is any significant contribution to ODP from the growth and processing of natural fibres.

RESULTS

Environmental impacts associated with flax fibre production and glass fibre production were evaluated using Life Cycle Method by a thorough literature search [26].

So far this LCA only involves a qualitative assessment. The following matrices were created for Environmental impact classification factors associated with the flax fibre production (Table 3) and glass fibre production (Table 4).

DISCUSSION

On the basis of the literature survey [26] we believe that in flax fibre production, eutrophication, global warming and abiotic resource depletion are the greatest contributors affecting the environment. All of these issues arise at herbicide, insecticide and fertiliser application and at the dessication stages. Non renewable / abiotic resource depletion potential and global warming potential are significant environmental impacts in crop production due to the fuel consumption in agricultural machinery. Fertiliser usage and desiccation in crop production contribute to acidification, aquatic toxicity, eutrophication, global warming, human toxicity, as well as abiotic resource depletion. Nitrate leaching from herbicides, insecticides and fertiliser are the main reasons for eutrophication. Other effects such as loss of biodiversity may result from herbicide and insecticide use and the retting process. Odour may arise from the water retting process. There is a low effect on photochemical oxidants creation potential from herbicides, insecticides, fertiliser and dessication. There was no ozone depletion potential in crop production or any data to prove it otherwise.

In glass fibre production, global warming appears to be the greatest effect on the environment. Production processes such as raw material handling, crushing, mixing, melting, refining, forming, oven drying, oven curing and fabrication are energy intensive and thus contribute to global warming. Human toxicity level is also high in some steps of glass fibre production e.g. material handling, crushing, weighing, mixing, refining etc. Fugitive dust is produced throughout the glass fibre manufacturing process which affects the environment. There are very low acidification, euthrophication and ozone depletion potentials in glass fibre manufacturing process. There are no effect on aquatic toxicity and photochemical oxidants creation potential in this production process. Other effects such as noise and vibration from the production process can be high in terms of large machinery and power is used in the system. The main impact to the environment through the glass fibre manufacturing process is the global warming due to the high power usage throughout the process.

CONCLUSION

The main environmental impact issues have been identified for both flax fibre and glass fibre production processes. In order to continue the life cycle assessment, it is important to determine the extent of variation between different sources of each fibre type. We are seeking to acquire a more comprehensive data set to inform this assessment and would welcome information which would improve our analysis.

Table 3. Environmental impact classification factors for flax fibre.

Environmental Impact Classification Factor	Land clearance	Tillage	Sowing	Herbicides	Insecticides	Fertiliser	Dessication	Harvest	Rippling	Retting	Decortication	Hackling	Carding	Spinning
Acidification Potential (AP)														
Aquatic Toxicity Potential (ATP)														
Eutrophication Potential (EP)														
Global Warming Potential (GWP)														
Human Toxicity Potential (HTP)														
Non-Renewable/Abiotic Resource Depletion (NRADP)														
Ozone Depletion Potential (ODP)														
Photochemical Oxidants Creation Potential (POCP)														
Noise and Vibration														
Odour														
Loss of biodiversity														

Table 4. Environmental impact classification factors for glass fibre.

Environmental Impact Classification Factor	Raw material handling	Raw material storage	Crushing	Weighing	Mixing	Melting	Refining	Forming	Sizing	Binding	Spinning	Oven Drying	Oven Curing	Fabrication	Packaging
Acidification Potential (AP)															
Aquatic Toxicity Potential (ATP)															
Eutrophication Potential (EP)															
Global Warming Potential (GWP)															
Human Toxicity Potential (HTP)															
Non-Renewable/Abiotic Resource Depletion (NRADP)															
Ozone Depletion Potential (ODP)															
Photochemical Oxidants Creation Potential (POCP)															
Noise and Vibration															
Odour															
Loss of biodiversity															
Fugitive Dust															

Table 5. Key for the Tables above.

KEY	
Very High Effect	
Low Effect	
No Effect	
Not Known	

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Appendix – B

Determination of arithmetic mean values of diesel consumption in agricultural operations in LCI

Diesel consumption for various agricultural operations were derived from the literature sources [[a][150] [b][149] [c][151] [d][152] [e][153] [f][154]] and presented in the table below. The average values are used to calculate energy used in crop production in LCI (Appendices D1, D2 and D3).

Operation	Diesel consumption (l/ha)						Average
Mouldboard plough	16.81[a]	17.3[b]	15.74[c]	12.09[d]	12.59[e]	15.93[f]	15.1
Chisel plough	8.89[a]	11.71[b]	10.31[c]	5.62[d]	5.93[e]	10.31[f]	8.8
Pass with no soil tillage	0.94[a]			0.94[d]			0.9
Disk harrow	6.55[a]		6.09[c]	5.99[d]	4.32[e]	6.09[f]	5.8
Harrow, spring tooth		3.75[b]	3.75[c]				3.8
Harrow, spike tooth		3.28[b]	2.81[c]				3.0
Cultivating, disc hiller		3.75[b]			3.75[e]		3.8
Cultivating, sweeps		3.28[b]	3.75[c]				3.5
Cultivtaing, rolling tines		3.28[b]	3.28[c]				3.3
Spraying		1.41[b]	0.94[c]	1.03[d]	0.99[e]	0.94[f]	1.0
Anhydrous applicator			6.09[c]	5.91[d]		5.15[f]	5.7
Mower, rotary			7.49[c]	5.72[d]	4.69[e]		6.0
Mower, cutterbar			3.28[c]			2.81[f]	3.0
Swather			5.15[c]	3.94[d]			4.5
Baler			4.22[c]	3.28[d]	3.95[e]	3.75[f]	3.8

Calculation of the energy use for crop production in Appendices D1, D2 and D3:

= Diesel consumption (l/ha) X Land use (ha) X Energy density of diesel (GJ/l)

Appendix - C

Determination of arithmetic mean values for embodied energy of agro-chemicals in LCI (MJ/kg)

The table below contains the values for embodied energy of agro-chemicals. The average values are used to calculate the energy values for agro-chemicals in LCI (Appendices D1, D2 and D3).

	Fertiliser			Pesticides		
Year of reference	N	P	K	Insecticides	Fungicides	Herbicides
2007	74.2	13.7	9.7	363	99	
2006(1)	32.2	15.8[a]	9.3[a]	237[b]	196[b]	288[b]
2006(2)	48.9	17.43	10.38	184.71	97.13	
2005	74	12.56	6.7	184.71	97.13	254.57
2004	60.6[c]	11.1[c]	6.7[c]	199[d]	92[d]	238[d]
2001	49.1	17.7	10.5	199[d]	92[d]	238[d]
2000	65	9	6	200	92	240
Average	57.2	14.4	8.7	233.1	96.3	247.3
SD	16.7	3.3	2.1	86.9	3	10.3

Data for 2007 is from [155], which is sourced from [156, 207, 208]

Data for 2006(1) is from [209], values for P and K are originally from Kaltschmitt & Reinhardt, 1997 [210], also cited by Hülsbergen 2001 [211][a]. Energy values for insecticides, fungicides and herbicides are per unit active ingredient including the mean input of primary energy and energy for transport and storage, sourced from Green 1987 [212][b].

Data for 2006(2) is from [213] sourced from [214, 215]

Data for 2005 is from [216] sourced from [217, 218]

Data for 2004 is from [219] sourced from [220][c] and [221][d]

Data for 2001 is from [222] and 2000 is from [223]

The values for embodied energy of NPK fertiliser, do not classify the percentage of nitrogen, phosphorus or potassium in each case, therefore it is assumed that the fertilisers used in the analysis are Ammonium Nitrate (33/0/0), Triple superphosphate (0/46/0/0) and Potassium chloride (0/0/60/0) due to wide commercial availability.

The available references do not distinguish between the mass for each component pesticides therefore the average value of 192MJ/kg is used in calculation as the embedded energy of pesticides and none of these references specify the type of insecticide/fungicide/herbicide.

Calculation of the energy use for fertilisers and pesticides in Appendices D1, D2 and D3:

Amount of fertiliser/pesticides use (kg) × Embodied energy of fertiliser/pesticides (MJ/kg)

Appendix – D1

Life Cycle Inventory (LCI) for Scenario -1

Inputs and the energy usage in the production of flax fibres using no-till and warm water retting method are given in the table below.

	For the production of one tonne of flax sliver	For the production of one tonne of flax yarn
Land used	3.53 ha	3.67 ha
Seed	407 kg	423 kg
Lime	2350 kg	2445 kg
Ammonium nitrate	427.1 kg	444 kg
Triple superphosphate	384.8kg	400 kg
Potassium chloride	293 kg	304.6 kg
Pesticides	9.1 kg	9.4 kg
Crop Production	**Energy (GJ/tonne of sliver)**	**Energy (GJ/tonne of yarn)**
Pass with no soil tillage	0.1	0.1
Harrow – spike tooth	0.4	0.4
Cultivating - rolling tines	0.4	0.4
Fertiliser application	2.1	2.2
Spray pesticides	0.5	0.5
Harvest – cutterbar mower	0.4	0.4
Swather	0.6	0.6
Baler	0.5	0.5
Fertiliser & Pesticides		
Lime	3.4	3.5
Ammonium nitrate	24.4	25.4
Triple superphosphate	5.5	5.8
Potassium chloride	2.5	2.7
Pesticides	1.7	1.8
Fibre Processing		
Warm water retting	0.6	0.6
Scutching	9	9.4
Hackling	2.1	2.2
Wet spinning		23.9
Total	**54.4**	**80.4**

Data in Appendices B,C and the study carried out by Turunen and van der Werf [86, 87] are used to create the LCI.

Emissions of Scenario-1

The outputs (emissions) from the production of flax fibres using no-till and warm water retting method are given in the table below.

Emissions	Amount (kg/tonne of sliver)	Amount (kg/tonne of yarn)
CO	3.5×10^{-3}	3.6×10^{-3}
CO_2	5198.2	9518.1
NOx	5.6	5.8
SO_2	4.4	4.6
NMVOC	1.6×10^{-3}	1.7×10^{-3}
N_2O	14.3	14.9
NH_3	65.5	68.1
NO	0.1	0.1
NO_3	2.1	2.2
N-leaching	85.6	89.0
Fluorides (air)	0.1	0.1
Fluorides (water)	38.2	39.7
P_2O_5 (air)	0.1	0.1
P_2O_5 (water)	42.2	56.3
As	2.3×10^{-3}	2.4×10^{-3}
Cu	1.1×10^{-2}	1.2×10^{-2}
Cr	1.1×10^{-2}	1.2×10^{-2}
Hg	2.2×10^{-3}	2.3×10^{-3}
Ni	9.2×10^{-3}	9.5×10^{-3}
Zn	1.4×10^{-2}	1.4×10^{-2}
Chlorides	7.9×10^{-5}	8.2×10^{-5}
Dichlorides	1.6×10^{-2}	1.7×10^{-2}
Hydrogen chloride	9.5×10^{-9}	9.8×10^{-9}
Pesticides (land)	8.2×10^{-9}	8.4×10^{-9}
Pesticides (air)	9.0×10^{-6}	9.3×10^{-6}
Chlorpyrifos	1.5×10^{-8}	1.6×10^{-8}
Hexachlorocyclohexane	4.3×10^{-9}	4.4×10^{-9}
Pentachlorophenol compounds (water)	9.5×10^{-9}	9.8×10^{-9}
Pentachlorophenol compounds (land)	6.5×10^{-5}	6.7×10^{-5}

Values given in Appendix E are used to calculate the emissions.

Appendix – D2

Life Cycle Inventory (LCI) for Scenario -2

Inputs and the energy usage in the production of flax fibres using conservation tillage and stand/dew retting method are given in the table below.

	For the production of one tonne of flax sliver	For the production of one tonne of flax yarn
Land used	6.84 ha	7.11 ha
Seed	787 kg	818 kg
Lime	4554 kg	4736 kg
Ammonium nitrate	827.6 kg	860 kg
Triple superphosphate	745.6 kg	775 kg
Potassium chloride	567.7 kg	590.1 kg
Pesticides	17.6 kg	18.3 kg
Dessicant (herbicides)	34.2 kg	35.6 kg
Crop Production	**Energy (GJ/tonne of sliver)**	**Energy (GJ/tonne of yarn)**
Chisel ploughing	2.1	2.2
Harrow – spring tooth	0.9	0.9
Cultivating - sweeps	0.8	0.9
Fertiliser application	4.2	4.3
Spray pesticides	0.9	1.0
Spray dessicant	0.3	0.3
Harvest – rotary mower	1.4	1.5
Swather	1.1	1.2
Baler	0.9	1.0
Fertiliser & Pesticides		
Lime	6.6	6.8
Ammonium nitrate	47.3	49.2
Triple superphosphate	10.7	11.2
Potassium chloride	4.9	5.1
Pesticides	3.4	3.5
Dessicant (Herbicides)	8.5	8.8
Fibre Processing		
Stand/dew retting	4.6	4.7
Scutching	11.7	12.2
Hackling	2.8	2.9
Wet spinning		23.9
Total	**113.1**	**141.6**

Data in Appendices B, C and the study carried out by Turunen and van der Werf [86, 87] are used to create the LCI.

Emissions of Scenario-2

The outputs (emissions) from the production of flax fibres using conservation tillage and stand/dew retting method are given in the table below.

Emission	Amount (kg/tonne of sliver)	Amount (kg/tonne of yarn)
CO	9.0×10^{-3}	9.4×10^{-3}
CO_2	8850.4	13312.6
NOx	10.8	11.2
SO_2	5.1	5.3
NMVOC	3.6×10^{-3}	3.7×10^{-3}
N_2O	15.7	16.3
NH_3	126.8	131.9
NO	0.2	0.2
NO_3	4.1	4.3
N-leaching	165.8	172.4
Fluorides (air)	0.2	0.2
Fluorides (water)	74.0	77.0
P_2O_5 (air)	0.2	0.2
P_2O_5 (water)	79.8	83.0
As	4.4×10^{-3}	4.6×10^{-3}
Cu	2.2×10^{-2}	2.3×10^{-2}
Cr	2.2×10^{-2}	2.3×10^{-2}
Hg	4.2×10^{-3}	4.4×10^{-3}
Ni	1.8×10^{-2}	1.8×10^{-2}
Zn	2.7×10^{-2}	2.8×10^{-2}
Chlorides	1.5×10^{-4}	1.6×10^{-4}
Dichlorides	3.1×10^{-2}	3.2×10^{-2}
Hydrogen chloride	1.8×10^{-8}	1.9×10^{-8}
Pesticides (land)	1.6×10^{-8}	1.6×10^{-8}
Pesticides (air)	1.7×10^{-5}	1.8×10^{-5}
Chlorpyrifos	2.9×10^{-8}	3.1×10^{-8}
Hexachlorocyclohexane	8.3×10^{-9}	8.6×10^{-9}
Pentachlorophenol compounds (water)	1.8×10^{-8}	1.9×10^{-8}
Pentachlorophenol compounds (land)	1.3×10^{-4}	1.3×10^{-4}

Values given in Appendix E are used to calculate the emissions

Appendix – D3

Life Cycle Inventory for scenario – 3

Inputs and the energy usage in the production of flax fibres using conventional tiallage and bio-retting method are given in the table below.

	For the production of one tonne of flax sliver	**For the production of one tonne of flax yarn**
Land used	3.12 ha	3.24 ha
Seed	359 kg	373 kg
Lime	2076 kg	2160 kg
Ammonium nitrate	377.5 kg	392 kg
Triple superphosphate	340 kg	353.2 kg
Potassium chloride	259 kg	268.9 kg
Pesticides	8.04 kg	8.4 kg
Crop Production	**Energy (GJ/tonne of sliver)**	**Energy (GJ/tonne of yarn)**
Mouldboard ploughing	1.6	1.7
Harrow – disk	0.6	0.7
Cultivating – disc hiller	0.4	0.4
Fertiliser application	1.9	2
Spray pesticides	0.4	0.4
Harvest – rotary mower	0.7	0.7
Swather	0.5	0.5
Baler	0.4	0.4
Fertiliser & Pesticides		
Lime	3	3.1
Ammonium nitrate	21.6	22.4
Triple superphosphate	4.9	5.1
Potassium chloride	2.3	2.3
Pesticides	1.5	1.6
Fibre Processing		
Post harvest field operations and green scutching	8.97	9.33
Bio-retting, rinsing, drying and mechanical softening	68.36	71.1
Hackling	2.14	2.23
Wet spinning		23.9
Total	**119.3**	**147.9**

Data in Appendices B, C and the study carried out by Turunen and van der Werf [86, 87] are used to create the LCI.

Emissions of Scenario – 3

The outputs (emissions) from the production of flax fibres using conventional tillage and bio-retting method is given in the table below.

Emission	Amount (kg/tonne of sliver)	Amount (kg/tonne of yarn)
CO	4.7×10^{-3}	4.9×10^{-3}
CO_2	16441.5	21356.6
NOx	4.9	5.1
SO_2	2.3	2.4
NMVOC	1.8×10^{-3}	1.9×10^{-3}
N_2O	11.9	12.3
NH_3	57.8	60.1
NO	0.1	0.1
NO_3	1.9	2.0
N-leaching	75.6	78.6
Fluorides (air)	0.1	0.1
Fluorides (water)	33.7	35.1
P_2O_5 (air)	0.1	0.1
P_2O_5 (water)	36.4	37.8
As	2.0×10^{-3}	2.1×10^{-3}
Cu	1.0×10^{-2}	1.1×10^{-2}
Cr	1.0×10^{-2}	1.1×10^{-2}
Hg	1.9×10^{-3}	2.0×10^{-3}
Ni	8.1×10^{-3}	8.4×10^{-3}
Zn	1.2×10^{-2}	1.3×10^{-2}
Chlorides	7.0×10^{-5}	7.3×10^{-5}
Dichlorides	1.4×10^{-2}	1.5×10^{-2}
Hydrogen chloride	8.4×10^{-9}	8.7×10^{-9}
Pesticides (land)	7.2×10^{-9}	7.5×10^{-9}
Pesticides (air)	8.0×10^{-6}	8.3×10^{-6}
Chlorpyrifos	1.3×10^{-8}	1.4×10^{-8}
Hexachlorocyclohexane	3.7×10^{-9}	3.9×10^{-9}
Pentachlorophenol compounds (water)	8.4×10^{-9}	8.7×10^{-9}
Pentachlorophenol compounds (land)	5.7×10^{-5}	6.0×10^{-5}

Values given in Appendix E are used to calculate the emissions

Appendix – E

The appendix contains the values which are used to calculate the emissions from diesel and agro-chemicals in LCI (Appendix D1, D2, D3)

Calculation: *Amount of diesel/agro-chemicals used (kg) × Environmental emission (g/kg)*

Emissions associated with diesel combustion in agricultural tractors

Environmental emission	g/ kg of Diesel
CO	0.0291
CO_2	3.04
NO_x	0.0571
SO_2	0.00415
NMVOC	0.00916

Source : Ref [166]

Emissions associated with Nitrogen fertiliser production and application

Environmental emission	g/kg of N - production	g/kg of N - application
CO_2	1570	12.5
N_2O	16	0.50%
NH_3	13	14%
NO_3	0.22	
NO_x	13	
N - leaching		20%

Source : Ref [166, 224]

Emissions and other pollutants associated with Phosphate fertiliser production and application

Environmental emission	g/kg of P - production
Fluorides	0.46
P_2O_5 (air)	0.45
NO_x as NO_2	5.43
Particulate	2.32
SO_x as SO_2	11.45
As	0.01
Cd	0.01
Cu	0.05
Cr	0.05
Hg	0.0095
Ni	0.04
Zn	0.06
Fluorides	167
P_2O_5 (water)	103
Pb2&4	0.043
Gypsum	7500

Source : Ref [166]

P_2O_5 leaching is estimated at a rate of 5kg/ha according to the study by Shuman 2001 [225]

Emissions and other pollutants from pesticides production in UK

Environmental emission	Total emissions per tonne active ingredient, 1994 (g)
Atrazine	0.0000017
Benzene	4.19
Biocides	0.002604
Chlorides	8.68
Dichloride	1771.26
Hydrogen chloride	0.001041
Particulates	9.81
(air)	0.0008977
Simazine	0.0086843
Sulphur dioxide	2.6
VOCs	41.87
Amitrole	0.4
Chlorpyrifos	0.001667
Diquat	1.56
Hexachlorocyclohexane	0.0004688
Mercury	0.0081616
Paraquat	1.74
Pentachlorophenol compounds	0.001041
Simazine	0.3
Aqueous residues	10690.08
Oil and oil/solid mixture	38.2
Pentacholorophenol compounds	7.12
Pesticides (water)	0.99

Source : Ref [166]

Emissions associated with production and application of lime

Emission	kg/tonne of lime
CO_2 from process	750
CO_2 from fuel used	200-450
CO_2 from applied lime	59

Source : Ref [113]

Emissions from electricity generation in Europe

Source	% use to generate electricity	Carbon Footprint (gCO_2eq/kWh)	Energy Density /kWh
Oil	40	650	86g
Natural Gas	24	500	$0.09m^3$
Coal	18	1000	150g
Nuclear Energy	13	5	
Renewable	5		

References : [167, 168, 197]

1kWh of electricity consumption emits 59.1g of CO_2, 10mg of short-lived radioactive waste and 0.9mg of long-lived radioactive waste to the environment [226]

Calculation:

Total electricity consumption (kWh) × percentage used in electricity generation (column 2) × allocated carbon footprint (g CO_2eq/kWh) (column 3)

Appendix – F1

Life Cycle Impact Assessment (LCIA) for scenario-1

For sliver:

Emission	GWP (kg)	ODP (kg)	AP (kg)	EP (kg)	POCP (kg)	HTP (kg)	ATP(m^3x10^{12})
CO						4.7×10^{-5}	
CO_2	5198.2						
NOx	1645.9		3.9	0.7		4.3	
SO_2			4.4			5.3	
NMVOC	1.8×10^{-2}	8.1×10^{-6}			1.1×10^{-5}		
N_2O	4221.7		10.0	1.9		11.1	
NH_3			122.9	21.6		0.1	
NO_3	27.9		0.1	1.2×10^{-2}		0.1	
NO	633.4		1.5	0.3		1.7	
N -leaching				35.9		0.1	
Fluorides (air)						7.3×10^{-3}	
Fluorides (water)						2.6	
P_2O_5 (air)						6.9×10^{-6}	
P_2O_5 (water)				42.2		1.9×10^{-3}	
As						5.4×10^{-3}	0.7
Cu						3.8×10^{-4}	34.8
Cr						1.1×10^{-2}	17.4
Hg						1.7×10^{-2}	1659.5
Ni						8.8×10^{-4}	4.6
Zn						6.7×10^{-5}	8.0
Chlorides						2.3×10^{-5}	
Dichloride						4.7×10^{-3}	
Hydrogen chloride			8.3×10^{-9}			2.7×10^{-9}	
Pesticides (land)						1.1×10^{-9}	9.6×10^{-6}
Pesticides (air)						1.3×10^{-6}	1.1×10^{-2}
Chlorpyrifos						4.4×10^{-9}	
Hexachlorocyclohexane						1.2×10^{-9}	
Pentachlorophenol compounds						2.7×10^{-9}	
Oil and oil/solid mixture							1.9×10^{-2}
Pentacholorophenol compounds						1.9×10^{-5}	
Total	**11727.1**	**8.1×10^{-6}**	**142.7**	**108.1**	**1.1×10^{-5}**	**25.4**	**1725.1**

For yarn:

Emission	GWP (kg)	ODP (kg)	AP (kg)	EP (kg)	POCP (kg)	HTP (kg)	ATP(m3x10^{12})
CO						4.9×10^{-5}	
CO_2	9518.1						
NOx	1711.1		4.0	0.8		4.5	
SO_2			4.6			5.5	
NMVOC	1.8×10^{-2}	8.3×10^{-6}			1.2×10^{-5}		
N_2O	4389.1		10.4	1.9		11.6	
NH_3			127.7	22.4		0.1	
NO_3	28.9		0.1	3.8		0.1	
NO	657.2		1.6	0.3		1.7	
N -leaching				37.3		0.1	
Fluorides (air)						7.5×10^{-3}	
Fluorides (water)						2.7	
P_2O_5 (air)						7.2×10^{-6}	
P_2O_5 (water)				56.3		2.0×10^{-3}	
As						5.6×10^{-3}	0.7
Cu						4.0×10^{-4}	36.2
Cr						1.1×10^{-2}	18.1
Hg						1.8×10^{-2}	1725.4
Ni						9.1×10^{-4}	4.8
Zn						7.0×10^{-5}	8.3
Chlorides						2.4×10^{-5}	
Dichloride						4.8×10^{-3}	
Hydrogen chloride			8.6×10^{-9}			2.8×10^{-9}	
Pesticides (land)						1.2×10^{-9}	1.0×10^{-5}
Pesticides (air)						1.3×10^{-6}	1.1×10^{-2}
Chlorpyrifos						4.5×10^{-9}	
Hexachlorocyclohexane						1.3×10^{-9}	
Pentachlorophenol compounds						2.8×10^{-9}	
Oil and oil/solid mixture							2.0×10^{-2}
Pentacholorophenol compounds						1.9×10^{-5}	
Total	**16304.5**	**8.4×10^{-6}**	**148.4**	**112.4**	**1.2×10^{-5}**	**26.4**	**1793.5**

Appendix – F2

Life Cycle Impact Assessment (LCIA) for scenario-2

For sliver:

Emission	GWP (kg)	ODP (kg)	AP (kg)	EP (kg)	POCP (kg)	HTP (kg)	ATP(m^3x10^{12})
CO						1.5×10^{-4}	
CO_2	8850.4						
NOx	3197.1		7.6	1.4		8.4	
SO_2			5.1			6.1	
NMVOC	0.1	2.3×10^{-5}			3.2×10^{-5}		
N_2O	4638.2		11.0	2.0		12.2	
NH_3			238.5	41.9		0.2	
NO_3	54.0		0.1	2.4×10^{-2}		0.1	
NO	1226.9		2.9	0.5		3.2	
N -leaching				69.6		0.1	
Fluorides (air)						8.4×10^{-3}	
Fluorides (water)						3.0	
P_2O_5 (air)						8.0×10^{-6}	
P_2O_5 (water)				79.8		3.2×10^{-3}	
As						6.2×10^{-3}	0.8
Cu						4.4×10^{-4}	40.1
Cr						1.3×10^{-2}	20.1
Hg						2.0×10^{-2}	1910.7
Ni						1.0×10^{-3}	5.3
Zn						7.7×10^{-5}	9.2
Chlorides						4.4×10^{-5}	
Dichloride						9.0×10^{-3}	
Hydrogen chloride			1.6×10^{-8}			5.3×10^{-9}	
Pesticides (land)						2.2×10^{-9}	1.9×10^{-5}
Pesticides (air)						2.4×10^{-6}	2.1×10^{-2}
Chlorpyrifos						8.5×10^{-9}	
Hexachlorocyclohexane						2.4×10^{-9}	
Pentachlorophenol compounds						5.3×10^{-9}	
Oil and oil/solid mixture							3.7×10^{-2}
Pentacholorophenol compounds						3.6×10^{-5}	
Total	**17966.7**	**2.3×10^{-5}**	**265.1**	**195.3**	**3.2×10^{-5}**	**33.6**	**1986.2**

For yarn:

Emission	GWP (kg)	ODP (kg)	AP (kg)	EP (kg)	POCP (kg)	HTP (kg)	ATP(m^3x10^{12})
CO						1.5×10^{-4}	
CO_2	13312.6						
NOx	3324.4		7.9	1.5		8.8	
SO_2			5.3			6.3	
NMVOC	0.1	2.4×10^{-5}			3.3×10^{-5}		
N_2O	4823.4		11.4	2.1		12.7	
NH_3			247.9	43.5		0.2	
NO_3	56.1		0.1	2.5×10^{-2}		0.1	
NO	1275.8		3.0	0.6		3.4	
N -leaching				72.4		0.1	
Fluorides (air)						8.7×10^{-3}	
Fluorides (water)						3.2	
P_2O_5 (air)						8.3×10^{-6}	
P_2O_5 (water)				83.0		3.3×10^{-3}	
As						6.5×10^{-3}	0.8
Cu						4.6×10^{-4}	41.7
Cr						1.3×10^{-2}	20.9
Hg						2.1×10^{-2}	1988.4
Ni						1.1×10^{-3}	5.5
Zn						8.0×10^{-5}	9.5
Chlorides						4.6×10^{-5}	
Dichloride						9.4×10^{-3}	
Hydrogen chloride			1.7×10^{-8}			5.5×10^{-9}	
Pesticides (land)						2.3×10^{-9}	1.9×10^{-5}
Pesticides (air)						2.5×10^{-6}	2.1×10^{-2}
Chlorpyrifos						8.8×10^{-9}	
Hexachlorocyclohexane						2.5×10^{-9}	
Pentachlorophenol compounds						5.5×10^{-9}	
Oil and oil/solid mixture							3.8×10^{-2}
Pentacholorophenol compounds						3.8×10^{-5}	
Total	**22792.3**	**2.4×10^{-5}**	**275.6**	**203.1**	**3.3×10^{-5}**	**34.9**	**2066.9**

Appendix – F3

Life Cycle Impact Assessment (LCIA) for scenario-3

For sliver:

Emission	GWP (kg)	ODP (kg)	AP (kg)	EP (kg)	POCP (kg)	HTP (kg)	ATP(m^3x10^{12})
CO						5.6×10^{-5}	
CO_2	16441.5						
NOx	1457.3		3.4	0.6		3.8	
SO_2			2.3			2.8	
NMVOC	2.0×10^{-2}	9.0×10^{-6}			1.3×10^{-5}		
N_2O	3513.5		8.3	1.5		9.3	
NH_3			108.7	19.1		0.1	
NO_3	24.6		0.1	1.1×10^{-2}		0.1	
NO	559.4		1.3	0.2		1.5	
N -leaching				31.8		0.1	
Fluorides (air)						3.8×10^{-3}	
Fluorides (water)						1.4	
P_2O_5 (air)						3.6×10^{-6}	
P_2O_5 (water)				36.4		1.5×10^{-3}	
As						2.8×10^{-3}	0.4
Cu						2.0×10^{-4}	18.3
Cr						5.8×10^{-3}	9.2
Hg						9.0×10^{-3}	871.3
Ni						4.6×10^{-4}	2.4
Zn						3.5×10^{-5}	4.2
Chlorides						2.0×10^{-5}	
Dichloride						4.1×10^{-3}	
Hydrogen chloride			7.4×10^{-9}			2.4×10^{-9}	
Pesticides (land)						1.0×10^{-9}	8.5×10^{-6}
Pesticides (air)						1.1×10^{-6}	3.8×10^{-3}
Chlorpyrifos						3.9×10^{-9}	
Hexachlorocyclohexane						1.1×10^{-9}	
Pentachlorophenol compounds						2.4×10^{-9}	
Oil and oil/solid mixture							1.7×10^{-2}
Pentacholorophenol compounds						1.7×10^{-5}	
Total	**21996.3**	**9.0×10^{-6}**	**124.2**	**89.7**	**1.3×10^{-5}**	**19.0**	**905.7**

For yarn:

Emission	GWP (kg)	ODP (kg)	AP (kg)	EP (kg)	POCP (kg)	HTP (kg)	ATP(m^3x10^{12})
CO						5.8×10^{-5}	
CO_2	21356.6						
NOx	1515.1		3.6	0.7		4.0	
SO_2			2.4			2.9	
NMVOC	2.1×10^{-2}	9.4×10^{-6}			1.3×10^{-5}		
N_2O	3652.9		8.6	1.6		9.6	
NH_3			113.0	19.8		0.1	
NO_3	25.6		0.1	1.1×10^{-2}		0.1	
NO	581.6		1.4	0.3		1.5	
N -leaching				33.0		0.1	
Fluorides (air)						4.0×10^{-3}	
Fluorides (water)						1.4	
P_2O_5 (air)						3.8×10^{-6}	
P_2O_5 (water)				37.8		4.0×10^{-3}	
As						2.9×10^{-3}	0.4
Cu						2.1×10^{-4}	19.0
Cr						6.0×10^{-3}	9.5
Hg						9.4×10^{-3}	905.8
Ni						4.8×10^{-4}	2.5
Zn						3.7×10^{-5}	4.3
Chlorides						2.1×10^{-5}	
Dichloride						4.3×10^{-3}	
Hydrogen chloride			7.7×10^{-9}			2.5×10^{-9}	
Pesticides (land)						1.1×10^{-9}	8.9×10^{-6}
Pesticides (air)						1.2×10^{-6}	9.8×10^{-3}
Chlorpyrifos						4.1×10^{-9}	
Hexachlorocyclohexane						1.1×10^{-9}	
Pentachlorophenol compounds						2.5×10^{-9}	
Oil and oil/solid mixture							1.7×10^{-2}
Pentacholorophenol compounds						1.7×10^{-5}	
Total	**27131.8**	**9.4×10^{-6}**	**129.1**	**93.2**	**1.3×10^{-5}**	**19.7**	**941.6**

Appendix – G

Classification Factors for Global Warming Potential (GWP)

Burden	GWP (*vs* Co2 over 100 years)
CO_2	1
CH_4	11
NO_x (Oxides of nitrogen)	296
Chlorinated hydrocarbons (HFCs)	400
Trichloroethane	100
Chlorofluorocarbons (PFCs)	5000
SF6 (sulfur hexafluoride)	3200
Other volatile organic compounds	11

Source : Ref [13, 14, 117, 227]

Calculation of GWP in LCIA:
Amount of emission (kg) from LCI × Allocated GWP classification factor

Classification Factors for Ozone Depletion Potential (ODP)

Burden	ODP (*vs* CFC11)
Trichlorofluoromethane (CFC11)	1
Chlorinated hydrocarbons	0.5
Chlorofluorocarbons	0.4
Other volatile organic compounds	0.005

Source : Ref [13, 14]

Calculation of ODP in LCIA:
Amount of emission (kg) from LCI × Allocated ODP classification factor

Classification Factors for Acidification Potential (AP)

Burden	AP (*vs* SO_2)
SO_2 (sulphur dioxide)	1
NO_x (oxides of nitrogen)	0.7
HCl (hydrogen chloride)	0.88
HF (hydrogen fluoride)	1.6
NH_3 (ammonia)	1.88

Source : Ref [13, 14]

Calculation of AP in LCIA:
Amount of emission (kg) from LCI × Allocated AP classification factor

Classification Factors for Eutrophication Potential (EP)

Burden	EP(*vs* PO_4^{3-})
Phosphates	1
Nitrates	0.42
Ammonia	0.33
Oxides of nitrogen	0.13
Chemical Oxygen Demand (COD)	0.022

Source : Ref [13, 14]

Calculation of EP in LCIA:
Amount of emission (kg) from LCI × Allocated EP classification factor

Classification Factors for Photochemical Oxidation Creation Potential (POCP)

Burden	POCP (*vs* ethylene)
Ethylene	1
Methane	0.007
Other hydrocarbons (except methane)	0.416
Aldehydes	0.443
Styrene	0.142
Other volatile organic compounds	0.007

Source : Ref [13, 14]

Calculation of POCP in LCIA:
Amount of emission (kg) from LCI × Allocated POCP classification factor

Classification Factors for Human Toxicity Potential (HTP)

Burden	HTP
CO (carbon monoxide)	0.012
NOx (oxides of nitrogen)	0.78
SO2	1.2
Hydrocarbons (excluding methane)	1.7
Chlorinated hydrocarbons	0.98
Chlorofluorocarbons	0.022
As (arsenic vapour)	4700
Hg (mercury vapour)	120
F2 (fluorine)	0.48
HF (hydrogen fluoride)	0.48
NH3 (ammonia)	0.0017-0.020
As (arsenic as soilds)	1.4
Cr (chromium)	0.57
Cu (copper)	0.02
Fe (iron)	0.0036
Hg (mercury as liquid)	4.7
Ni (nickel)	0.057
Pb (lead)	0.79
Zn (zinc)	0.0029
Fluorides	0.041
Nitrates	0.00078
Phosphates	0.00004
Chlorinated solvents and compounds	0.29
Cyanides	0.057
Pesticides	0.14

Source : Ref [13, 14]

Calculation of HTP in LCIA:
Amount of emission (kg) from LCI × Allocated HTP classification factor

Classification Factors for Aquatic Toxicity Potential (ATP)

Burden	Aquatic toxicology ($m^3 x 10^{12}/g$)
As	0.181
Cr	0.907
Cu	1.810
Hg	454
Ni	0.299
Pb	1.810
Zn	0.345
Oils and greases	0.045
Chlorinated solvents and compounds	0.054
Pesticides	1.180
Phenols	5.350

Source: Ref [13, 14]

Calculation of ATP in LCIA:
Amount of emission (kg) from LCI × Allocated ATP classification factor ($m^3 \times 10^{12}/g$)

Classification Factors for Non-Renewable/Abiotic Resource Depletion

Burden	Resource Depletion (vs world reserves)
Coal Reserves	87200×10^9 tonnes
Oil Reserves	124×10^9 tonnes
Gas Reserves	109×10^{12} m^3

Source: Ref [13, 14]

Calculation of NRADP in LCIA:

$$\frac{\textit{Amount of electricity used (kWh)} \times \textit{\% used in electricity generation} \times \textit{Energy Density}}{\textit{NRADP classification factor}}$$

Appendix – H

Comparison of mass loss at each processing stage of flax fibre sliver/yarn production

(1) Using warm water retting (Scenario-1)

Dry, green flax stems, 22022 kg

↓

Dry, retted flax, 17760 kg

↓

Scutched long fibre, 1600 kg
Short fibre, 4096 kg
Shive, 7104 kg
Dust, 2672 kg
Coarse plant residues, 2288 kg

↓

Sliver, 1040 kg
Short Fibre 400 kg

↓

Yarn 1000kg

Summary: Yarn 1000kg, Short fibre 4496kg, Shive 7104kg, Dust 2672kg, Coarse plant residues 2288kg

(2) Using stand/dew retting (scenario-2)

Dry, green flax stems, 42667 kg

↓

Dry, retted flax, 23088 kg

↓

Scutched long fibre, 2080 kg
Short fibre, 5325 kg
Shive, 9235 kg
Dust, 3474 kg
Coarse plant residues, 2974 kg

↓

Sliver, 1040 kg
Short Fibre 832 kg

↓

Yarn 1000kg

Summary: Yarn 1000kg, Short fibre 6157kg, Shive 9235kg, Dust 3474kg, Coarse plant residues 2974kg

(3) Using bio-retting (scenario-3)

Dry, green flax stems, 19546 kg

↓

Green, scutched long fibre, 2432 kg
Short fibre, 2432 kg
Shive, 8840 kg
Dust, 2335 kg
Coarse plant residues, 3502 kg

↓

Long fibre, 1600 kg
Short fibre, 18 kg
Shive, 85 kg

↓

Sliver, 1040 kg
Short Fibre 400 kg

↓

Yarn 1000kg

Summary: Yarn 1000kg, Short fibre 2850kg, Shive 8840kg, Dust 2335kg, Coarse plant residues 3502kg

Source: Ref [86, 87]

Appendix – I

LCI for glass fibres

According to the Summary Progress Report of Sustainability at Owens Corning [158], the energy use and the associated emissions are given in the table below.

Environmental Performance at Owens Corning

Year	Energy[1]	GHG[2]	NO_x[3]	VOC[3]	PM[3]	Waste-to-landfill[3]	Water[4]
2002	10.7	6.1	7.3	2.5	3.9	364	15
2008	9.4	6.9	5	2.5	2.5	309	14

[1]millions of Megawatt hours
[2]millions of Metric tonnes per year
[3]thousands of Metric tonnes per year
[4]millions of m^3

Assuming the global glass fibre production is 2.3 million tonnes per year [228, 229] and Owens Corning has a market share of 16% [230], the annual glass fibre production at Owens Corning is 0.4 million tonnes. By calculating from the above values, the energy required to produce one tonne of glass fibre is 84.6GJ which could involve energies for ancillary processes such as heating and lighting, storage long distance transport etc.

LCIA for the production of one tonne of glass fibres (derived from the table for year 2008)

GWP (kg)	ODP (kg)	AP (kg)	EP (kg)	POCP (kg)	HTP (kg)
20950	0.03	8.75	1.63	0.04	9.75

The values for NRADP or ATP could not be derived from the available data.

Appendix – J

N, P and K analysis of flax fibres

The aim of the experiment was to analyse the N, P and K uptake by the flax fibres and to determine the effect of the different levels of N,P and K on the plant growth.

Experimental Method: Flax seeds were purchased from Suffolk Herbs, Essex, UK and planted in 250mm diameter pots (surface area of 0.05m^2) in the University of Plymouth in May 2009. The Taguchi method (L16 array) was used to carry out the experiment with 4 levels of 3 fertilisers (N, P and K). The four levels were no fertilisers, half of the UK recommended level, UK recommended level and twice the UK recommended level. The experiment was replicated using a total of 32 pots. Fertilisers used were Sulphate of Ammonia with 21% of Ammonical Nitrogen, Super Phosphate with 17% of Phosphorous Pentoxide and Sulphate of Potash with 49% of Potassium Oxide. The standard fertiliser levels of N, P, K are taken as N 40kg/ha and 50kg/ha each of P_2O_5 and K_2O according to the recommendations of Hanfaes Institute, Bangor, UK [61].

Figure J.1 Seeds were planted with a seed rate of 50 per pot and at a depth of 1.5-2 cm

Figure J.2 Emerging plants with some weed

Figure J.3 Flowering plants in early August

Figure J.4 Before the harvest in early September

The soil pH value was between 6.5 and 7.0 at the beginning of the experiment and assumed to contain other nutrients as Turner suggested in Linseed Law [50], the soil pH should be between 6.0-7.0 (slightly acid to very slightly acid soils).

Lodging was not observed, but the site at which the plants were grown was protected by a high wall to the South. The pots were positioned towards the Northern edge of the walled garden.

The pots were only watered before the plants emergence. The plants were monitored every week and the heights of the each plant were carefully measured and recorded. The weed emergence was also noticed and controlled by hand pulling the invasive species. The plants were harvested in early September by pulling and total height, root length, diameter of stem, and weight was recorded for each plant. Chemical analysis was carried out to determine the N, P and K levels in the stems.

Chemical Analysis: The method used for the soil samples in the School of Geography, Earth and Environmental Sciences in the University of Plymouth was adopted for the plant (stem) samples. Nitrogen and Phosphorus was analysed by acid digests and by using an auto analyser. Potassium was analysed by acid digests followed by analysis using a flame photometer.

Method used for Nitrogen and Phosphorus determination: The grinded flax stem was digested under reflux with concentrated sulphuric acid in the presence of sodium sulphate (to raise the temperature of digestion) and copper catalyst (to promote oxidation of organic matter) to convert nitrogen compounds present to ammonium sulphate. The ammonia of the digest solution is then determined by continuous air-segmented flow colorimetry using Bran and Luebbe Autoanalyser.
An autosampler is filled with samples, standards and quality controls and the order of analysis is programmed into the computer. A peristaltic pump continuously pumps all the reagents and the samples from the autosampler into the chemical manifolds. Small discrete air bubbles are introduced into the flow at regular intervals to reduce the effects of cross-contamination and present discrete samples for analysis. In the manifolds the smaples and reagents are mixed and treated according to the method protocols. On leaving the chemical manifolds the samples are passed through a colorimeter and their absorbance is measured at specific wavelength. The computer then compares this to the calibration curve and calculates the concentration of the analyte in the sample.

Method used for Potassium determination: Potassium analysis was done by suing the flame photometer. The principle used in the flame photometer is that the alkali metals, when heated to a sufficient high temperature, will absorb heat energy and be raised to an excited state in their atomic form. As these atoms cool they will fall back to their original unexcited state and re-emit their absorbed energy as radiation at specific wavelengths. Therefore, if an alkali metal in solution is aspirated into a low temperature flame it will, after excitation by the flame, emit a discrete frequency which can be isolated by an optical filter. A photocell detects the emitted light and converts it to a voltage, which can be recorded. Since $Na+$ and $K+$ emits lights of different wavelengths, by using appropriate coloured filters the emissions due to $Na+$ and $K+$ (and hence their concentrations) can be measured in the same sample. One drawback of flame photometers, however, is that they respond lineally to ion concentrations over a rather narrow concentration range so suitable dilution usually have to be prepared.

Results: There were no significant differences noticed in the growth of the flax plants and no correlation was found in the N, P and K uptake by the stem of the plant with the applied levels of fertilisers. The following Figure J.5 shows the average growth of the plant with time in pots with no fertilisers, half of the recommended level, recommended level and twice the recommended level.

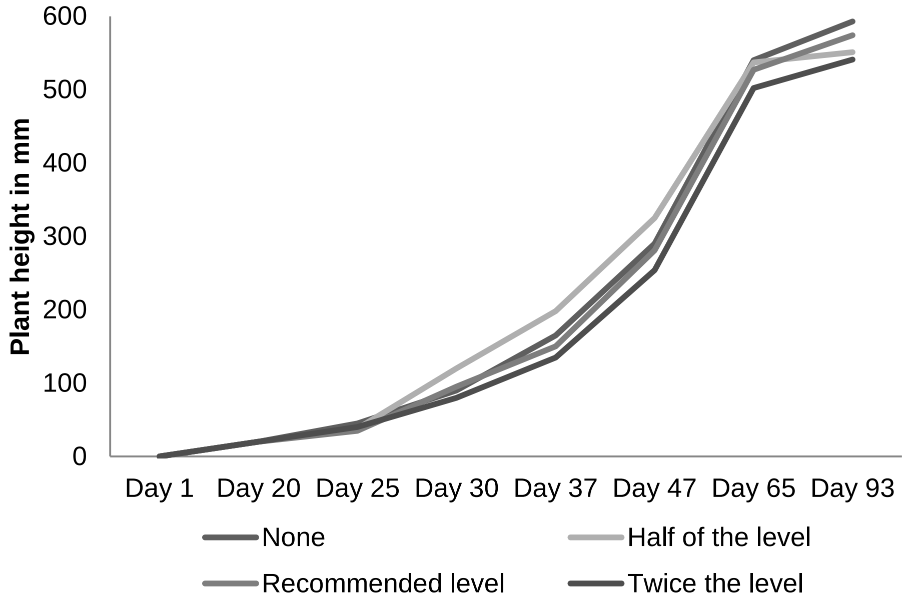

Figure J.5 Plant growth vs time with different levels of fertilisers N, P and K

As well as the height, root length, diameter of the stems and weight were also very similar in all the pots even with different levels of fertilisers applied.

The nitrogen, phosphorous and potassium uptake by the stems in which no fertilisers were applied are similar to the other stems with different fertiliser levels. The average amounts of N, P and K intake by the flax stems when four different levels of fertilisers were applied are shown in the Figure J.6.

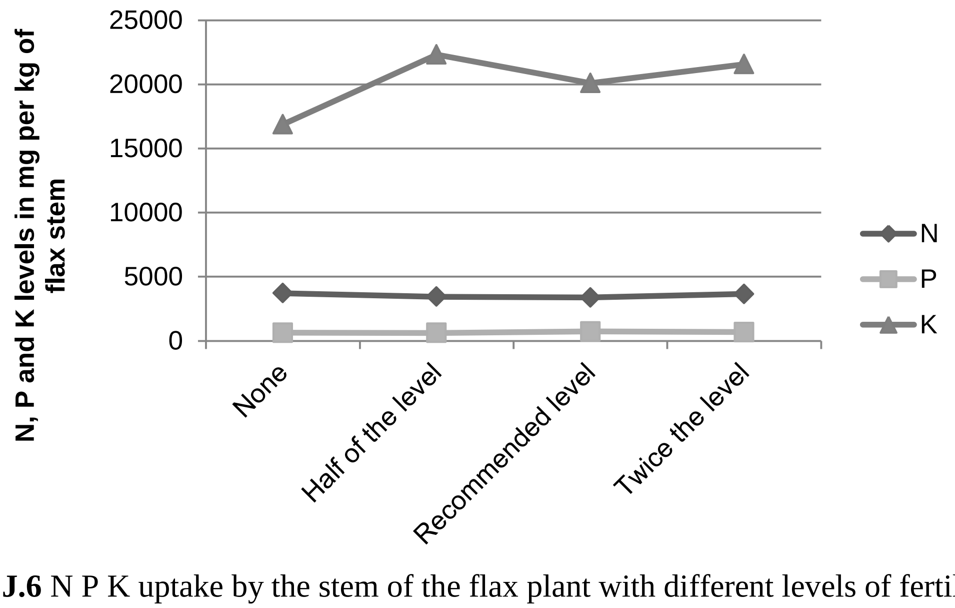

Figure J.6 N P K uptake by the stem of the flax plant with different levels of fertiliser

Conclusion: The fertiliser input has not made an impact on the N, P and K uptake by the plant stem or has not contributed towards the growth of the flax plant. It is assumed that the soil used already had adequate nutrients.

Appendix – K

Measurements of the twist angles in flax yarn

The angle of twist on flax yarn was measured at 120 points using a high resolution microscopic image. The following Table K.1 shows the mean values of the angle of twist and the fibre orientation distribution factors (FODF) derived using Krenchel Equation [46].

Table K.1 The mean values for angle and FODF of flax yarn and

	Angle of twist (X)	FODF
Arithmetic Mean	20.32	0.77
Geometric Mean	19.80	0.76

Table K.2 shows the measured angles and FODF derived using Krenchel Equation [46].

Table K.2. Angle of twist of fibre yarn and fibre orientation distribution factors

Angle of twist (X)	FODF
14.40	0.88
10.06	0.94
12.68	0.91
16.94	0.84
21.52	0.75
18.31	0.81
18.05	0.82
16.40	0.85
16.87	0.84
21.25	0.75
19.98	0.78
20.89	0.76
21.94	0.74
27.06	0.63
25.44	0.66
28.20	0.60
25.82	0.66
24.95	0.68
27.53	0.62
23.27	0.71
17.68	0.82
16.53	0.84
21.10	0.76
20.22	0.78
18.43	0.81
15.84	0.86

Angle of twist (X)	FODF
14.81	0.87
15.59	0.86
17.65	0.82
15.40	0.86
17.13	0.83
17.39	0.83
20.56	0.77
21.80	0.74
27.05	0.63
22.57	0.73
23.96	0.70
25.43	0.67
25.26	0.67
23.66	0.70
19.29	0.79
18.06	0.82
16.70	0.84
19.23	0.79
17.55	0.83
17.47	0.83
24.78	0.68
17.65	0.82
24.59	0.68
29.25	0.58
22.50	0.73
22.91	0.72

21.39	0.75

Angle of twist (X)	FODF
22.29	0.73
23.20	0.71
26.02	0.65
28.18	0.60
21.08	0.76
25.56	0.66
18.23	0.81
21.67	0.75
19.37	0.79
16.76	0.84
22.91	0.72
16.45	0.85
20.01	0.78
15.35	0.86
15.58	0.86
16.26	0.85
19.93	0.78
18.65	0.81
18.52	0.81
15.75	0.86
17.41	0.83
16.50	0.85
16.29	0.85
21.80	0.74
17.99	0.82
19.01	0.80
14.53	0.88
21.09	0.76
22.20	0.73
18.43	0.81
26.31	0.65
24.39	0.69
22.17	0.74
18.87	0.80

17.99	0.82

Angle of twist (X)	FODF
22.01	0.74
22.53	0.73
16.71	0.84
18.24	0.81
19.15	0.80
16.19	0.85
24.59	0.68
21.47	0.75
13.39	0.90
16.77	0.84
15.84	0.86
19.38	0.79
16.90	0.84
14.33	0.88
17.09	0.83
14.16	0.88
13.57	0.89
10.58	0.93
13.94	0.89
22.06	0.74
26.29	0.65
26.57	0.64
22.20	0.73
12.55	0.91
18.71	0.80
22.33	0.73
25.46	0.66
23.35	0.71
23.63	0.70
23.86	0.70
31.73	0.52
35.54	0.44
34.76	0.46
25.11	0.67

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