A scale-up of processing non-woven flax tape and triaxial glass fibre composites

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Abstract
In the drive towards a sustainable bio-economy, a growing interest in the development of composite materials using renewable raw material resources such as flax fibre reinforced polylactic acid (PLA), known as a flax-tape composite (FTC), has been observed. Flax/PLA is one of the cornerstones for the sustainable economic growth of natural fibre composites, while the use of hydrocarbon fossil resources and synthetic fibres such as glass and carbon have caused severe environmental impacts along their entire life cycles. In this study, the manufacturing process for the production of flax tape and triaxial glass fibre were evaluated through life cycle assessment (LCA) gate-to-gate, based on an input-output model, to estimate the energy demand and environmental impacts. The quality of the natural hybrid composite produced and cost-effectiveness of their LCA were dependent on their roving processing speeds; temperature applied to the flax tape and triaxial glass fabrics during processing. This was optimised to be 4 m/min at a temperature of 170°C. In contrast, normal triaxial glass fibre production took a slower speed of 1 m/min using a roving glass fibre laminating machine. The results showed that when the flax and PLA were commingled to produce a new composite material in the form of a flax tape, the energy consumption was 0.25 MJ/kg, lower than 0.8 MJ/kg of glass fibre fabric composites. Flax tape and glass fibre fabric composites have a carbon footprint equivalent to 0.036 kg CO₂ and 0.11 kg CO₂, respectively, under the same manufacturing conditions. These are within the technical requirements in the composites industry. The manufacturing process adopted to transform flax/PLA into a similar tape composite was considerably quicker than that of woven glass fibre composite tape. Importantly, this work explored a relationship between the blending process and energy consumption of the flax tape composite in comparison to glass fibre composite, using a
Keywords: Flax fibre; Polylactic acid (PLA); Renewable raw materials; Triaxial glass fibre; Energy consumption; Carbon footprint.

1. Introduction

Natural fibre reinforced composites have attracted a lot of interest from the last decade to the present time, due to the environmental concerns and low-cost requirements [2, 3]. The attractiveness of natural fibres, as reinforcing materials, comes from their high specific strength, degradable property and low cost [4, 5]. There has already been a lot of studies focused on flax fibre reinforced composites [6, 7]. Therefore, natural fibres such as flax and matrices such as polylactic acid (PLA) have witnessed a noticeable increase in sales volume, since they are rapidly penetrating European and Asian markets in building services, transportation (automotive, aerospace and marine/ naval) and furniture [8-10]. However, glass and carbon manufacturing with conventional petroleum-based polymers, such as polyethene (PE), polypropylene (PP) and polyvinyl chloride (PVC), have negative environmental impacts during their cradle-to-grave and gate-to-gate life cycles [11].

To design and fabricate a new natural composite with lower environmental footprint, compared to the synthetic composite material, some novel natural fibres are being considered to be the base of the matrix materials, for example, flax/PLA. Flax is one of the most promising natural fibres, because it is a renewable raw material, has excellent biodegradability and favourable mechanical properties. PLA has good processability and can be readily fabricated to injection-moulded parts, film or fibre [12]. Flax/PLA has favourable mechanical and processing properties, besides good compostable biodegradation [13-15]. However, the impact performance of PLA is not good enough due to the inherent brittleness. After being mixed with flax, the impact strength of the resulting flax/PLA is significantly improved. Importantly, the environmental impacts of the flax/PLA must be evaluated before they are used as engineering materials in the near future.

In this study, a flax /PLA fibre melt point hybrid non-woven fabric was directly made from flax composite tape (FCT) by hot-press laminating process technology. Hybrid FCT has not undergone
any consolidation processing before the composite is formed. The operating parameters such as flax/PLA fibre content, temperature and speed have significant influences on the production performance of composites materials flax tape. These were carefully selected during the manufacturing process, as prepared composite plates and laminates have excellent mechanical performances. The results have proven that FCT direct forming is an efficient and cost-saving method of making fibre reinforced composites, which are suitable for industrial production. An identification of the primary drivers of the relative environmental performance of natural fibre composite tape was carried out to find a conclusion on whether the specific findings of this study can be generalised and commercialised.

Life cycle assessment (LCA) is a sustainability measurement tool for environmental impact analysis that supports decision making in product development [16, 17]. It was used to investigate the inputs (resources and energy) and outputs (waste gases, wastewater and solid waste) of a product across the entire life-cycle stages (cradle-to-grave) [18-20]. The advantages of utilising LCA include, but are not limited to the absence of problem shifting from one life cycle stage to another, locates ‘hot spots’ in the life cycle and accounts for all types of pollutant emissions and resource consumptions [21].

Therefore, it covers the entire life cycle of a product, which includes five stages (acquisition of raw materials, processing/manufacturing, consumption/utilisation, transportation and waste disposal of the products)[22]. On this process, the focus was on gate-to-gate production, to determine the energy consumption and carbon dioxide emissions. The gate-to-gate inventory includes three stages: machine, energy used and manufacture of the products[23]. Accordingly, this analysis only included the inputs and outputs between the acquisition of raw material and manufacture of the products [24, 25], which are more concise, convenient and appropriate to evaluate the gate-to-gate environmental impacts of composite materials. LCA has been associated with various design and processing technologies[26], relevant materials/products [27], decision making [28], waste management [29] and regional industrial ecology [30].

Furthermore, a few studies have considered comparative life cycle assessment of the energy consumption to produce materials and specific components made from glass (synthetic) fibre reinforced (GFR) and natural fibre reinforced (NFR) composite materials [31-39]. This is subsequently summarised with methodology and finding from some studies as subsequently discussed.
Youngs, Song and Jae [31] studied LCA of fibre reinforced composites by reporting that the first stage of the product life cycle is material extraction for plastics or similar materials, which involves pulling fossil fuels from the earth. These materials are then refined and separated before producing the input materials for manufacturing. The next step is to call for extraction and production of materials, called material production. Materials used in manifold fields have different energy intensities for extraction and production. Polymer matrices such as thermosetting and thermoplastic polymers are created through energy-intensive chemical processing. The plastic material and resin sector of the chemical industry alone accounted for 414,000 million MJ of energy consumption in the USA in 1998, which amounts to 2.2% of the total energy consumed by the USA [32]. Stiller [33] compared and analysed several manufactures of glass fibres, PPG, OwensCorning, and Vetrotex. Owens Corning consumed the lowest intensity of 12.58 MJ/kg, whereas Vetrotex had the largest intensity of 32.0 MJ/kg. At one manufacturer, energy intensities changed significantly: Vetrotex plants in Germany consumed 32.0 MJ/kg, while Vetrotex International Plants used 25.3 MJ/kg. This can be explained in part by economies of scale. That is such a low energy consumption result from large-sized plants, thus allowing energy savings of about 20%.

On the other hand, energy consumption is roughly independent of the filament diameter of the glass fibres produced. The natural fibres, including China reed and flax fibres, have relatively low energy intensities because they come from natural sources. However, there are other environmental impacts related to their cultivation, especially the use of land, water, fertilisers and pesticides [31].

Similarly, Wotzel, Wirth and Flake [34] presented life cycle assessments of a side panel for an Audi A3 car made from ABS co-polymer and an alternative design made from hemp fibre epoxy resin composite of 66% volume. Their models studied inputs, energy use and emissions up to the component manufacturing stage. The use phase and end-of-life management options such as energy recovery through incineration are not displayed through the research. For the NFR component, cultivation of hemp, hemp fibre extraction and component manufacture stages are not included. In addition, Schmidt and Beyer [36] simplified LCAs of two designs of an insulation component for a Ford car. The reference component was made from ethylene propylene diene copolymer (EPDM) and polypropylene (PP) reinforced with glass fibres. They presented their final results only in the form of net benefits of switching to the hemp fibre component from GFR.
The hemp fibre component showed a net benefits of 88.9 MJ in cumulative energy demand, 8.18 kg of CO₂ emissions and 0.0564 kg of sulphur dioxide emissions, 0.002 kg of phosphate emissions and 0.018 kg of nitrate emissions in the basic scenario.

Moreover, Vidal et al. [38] confirmed that the environmental impact potential (global warming, depletion of non-renewable energy resource, acidification and eutrophication) from the fibre reinforced polymeric composites was lower than that of virgin PP and high-density polyethene (HDPE). Bolin and Smith [38] found that the environmental impacts from lumber treated with alkaline copper quaternary (ACQ) were 14 times less for fossil fuel use, almost 3 times less for greenhouse gas emissions, potential smog emissions and water use, 4 times less for acidification, and almost half for ecological toxicity compared with those from wood plastic composite (WPC) decking. For eutrophication, the environmental impacts were approximately equal. Xu et al. [38] found that considering environmental impact, woven fibre reinforced polypropylene composites were superior to neat PP, when material service density is used as the functional unit.

The manufacturing process of a simplified generic life cycle stages of a component made from glass and natural fibres reinforced composite materials is shown in Figure 1 [40].

![Figure 1](https://example.com/figure1.png)

**Figure 1:** System boundary of the life cycle of a natural fibre flax/PLA and triaxial glass fibre (TGF) reinforced composites production [40].
The system boundary and the process used to produce a triaxial glass fibre (TGF) and flax tape is shown in Figure 1. The environment aspects and potential impacts, throughout a products life from raw material production and extraction through production, were not considered on this study. LCA takes a comprehensive gate-to-gate approach, thus focusing on only specific life cycle stage in material production and evaluation on the energy consumption, based on the recent series of ISO standards 14040 to 14043 provided in detailed guidelines for conducting LCA [31]. The LCA is limited to material production and manufacturing on the input and output called gate-to-gate, to produce composite material on tape and triaxial machines. The system boundary is limited to both machines. Therefore, details of specific material and energy flow, emissions and manufacturing processes vary, depending on the specific application. However, material flow, energy use, emissions and environmental impacts over all these stages need to be modelled, inventoried and analysed for a comprehensive life cycle assessment [40]. Based on extant literature, it is evident that very few efforts have been made to evaluate the environmental impact of flax tape composite (FTC) and the production of triaxial glass fibre (TGF). The present paper considers the application of LCA methodology (gate-to-gate) in order to explore the possibility of promoting eco-efficiency of FTC and triaxial glass fibre(TGF). Energy demand and potential environmental impacts of the FTC and TGF are investigated across its gate-to-gate stages. Then, environmental benefits of the FTC is estimated across other materials after the mechanical properties and environmental impact have been calculated.

2. Methods and Materials

2.1. Gate-to-Gate method

The measurement consists of using a domestic electricity usage monitor to compile gate-to-gate (GtG) LCA data for the project. A current sensor is clipped on to the supply cables on the engine connected to the transmitter, which then wirelessly sends real-time data to the energy monitor. The monitor receives the data and displays the demand in kilowatts of energy consumed at any given time. E2link classic allows recording direct energy consumption and carbon dioxide emissions during the production of composite materials. SimaPro was used to simulate the manufacturing process and analyse the impact of the manufacturing during production, as shown in Figure 3. The treatment of electricity is a crucial point in each material intensity analysis - as in each LCA. Thus,
as electricity is used in nearly all production processes, results have barely influenced the choice of the methodology.

![Diagram of data collection process]

Figure 2: Standard method to collect data.

Any power used during the process will pass through the sensor cable. The clip-on sensor acts as a current sensor, relaying the amount of current drawn on to the machine using the transmitter. From there it is sent wirelessly to the monitor display unit, which shows how much power is consumed. The monitor shows instant power (kW), estimated electricity per hour and carbon per hour (kgCO₂/hour). The capacities of the devices, to collect data, depends on the specification and technical information. The distance range of the sensor for transmission is less than 70 metres; the sensor voltage range is around 600v. Therefore, the data was exported to the Efergy eLink 2.0 computer software, analysed and extracted on to Excel for further analysis. The electricity used in kWh or Megajoule (1kWh=3.6 MJ or 1MJ = 0.277778 kWh) is converted into kg of carbon dioxide by using the conversion factor. If a 1000 kWh unit of electricity is consumed, the amount or quantity of CO₂ emissions is calculated by using the conversion factor [36].

2.2 Materials

The materials used are natural flax and PLA fibre and synthetic glass fibre that were transformed into fabric. The methodology consists to record the energy consumption on machine tape and triaxial machine fabrics during production (Figure 3). The inputs are flax, PLA, Glass fibre tow, and electricity. The energy consumption increases with time and material produced.
The primary objective of the manufacturing processes is to transform raw materials fibre into useful final products for their potential users, using energy and material resources. During these processes, energy is consumed and the material resources used are changed, creating new material. Several studies have focused on estimating the energy consumption of various production processes. However, by a comprehensive study on the energy consumption of manufacturing process developed by Duflou et al.[41], most of the available databases are incomplete, because they are limited primarily to the theoretical calculation of energy consumption. The study of energy consumption in various industrial processes has focused on different aspects: the development of energy consumption, indicators and power estimation models for several materials and manufacturing processes. Machines performance is compared regarding energy losses, in particular for injection moulding technology [42]. Assessing the energy efficiency of several manufacturing processes, includes new tools, heating methods and projects to improve the efficiencies of the processes [43].

Calculating the life cycle energy consumption of composite products manufactured, information from Titsaltec and Formax Companies specialising in material production and their comparable products produced using other traditional materials were taken into account raw materials.
manufactured as well as those from literature. The energy $E$ (input) in kilowatt hours (kWh) per day is equal to the power $P$ in watts (W) times number of usage hours per day $T$ divided by 1000 watts per kilowatt [44]. To find the energy consumption in kWh during the manufacturing process for specific machinery, some information about the production times and the number of voltage and ampere needed to be obtained. Therefore, the voltage and ampere can be found on the motor on the same machine that was used for this specific process [44].

$$E \left( \frac{kWh}{day} \right) = P(W) \times \frac{t \left( \frac{h}{day} \right)}{1000 \left( \frac{W}{kW} \right)}$$

(1)

and

$$E \left( \frac{kWh}{day} \right) \times CF \left( \frac{kg \ CO_2}{kWh} \right) = kg \ CO_{2e}$$

(2)

Where $E$ is the energy in kWh/day, $P$ is the power in Watt, $t$ is the time in hours/day, and

Power, $P \ (W) = Voltage, \ V \ (v) \times Current, \ I \ (A)$.

The environmental impact can be characterised by the conversion of the outputs. Therefore, the electricity used in kWh or Mega Joule (1kWh = 3.6 MJ/kg) can be converted into kg of carbon dioxide by using the conversion factor $CF$ [45].

Other factors such as heat, waste of material and global warnings were not considered during the production process.

Also, based on global warming potential (GWP), the impact contribution of a product is found by multiplying the number of emissions by the impact assessment factor [46]. The GWP was developed to allow comparison of the global warming impacts of different gases [36]. Specifically, it is a measure of how much energy the emissions of 1 tonne of gas (CO$$_2$$) will absorb over a given period. Therefore, direct global warming potentials (GWP) is expressed as:

$$GWP = \sum CO_2 \times IAF$$

(3)

Inventory analysis provides emissions data in terms of kg/functional unit and greenhouse gas emissions are converted into equivalent amounts of carbon dioxide (kg eq. CO$$_2$$) by means of GWP, where 10 kg carbon dioxide = 10 $\times$ 1(GWP) = 10 kg eq. CO$$_2$,
5 kg methane = $5 \times 24 \text{ (GWP)} = 120 \text{ kg eq. CO}_2$

0.5 nitrous oxide = $0.5 \times 296 \text{ (GWP)} = 148 \text{ kg eq. CO}_2$

Total GW impact = $10 + 12 + 148 = 278 \text{ kg eq. CO}_2$

The global warming potential can be calculated to show the higher environment impact of a product during production, therefore being able to choose other alternatives materials that are less toxic. Importantly, if the global warming potential is less than one, material production does not have any impact on the environment.

3. Manufacturing process

3.1 Flax tape

The materials of polylactic acid and flax fibre (FL/PLA) transit into the blending inputs to be mixed and aligned. They move through a hot cylindrical wheel machine, laminated at elevated temperature and are transformed into a composite material called flax tape as schematically illustrated in Figure 4. Long flax and PLA fibres are used to develop weight-controlled non-woven flax tapes. The fibres are unidirectionally arranged without any twist. To maintain the cohesion of the parallel fibres mixed together, a new process based on the manufacturing process was established to commingle laminate flax and PLA fibre into another material, called flax tape. Based on the mechanical properties of both materials and melting points, the laminate temperature was selected between 170 °C for a speed of 4 m/min. For the manufacturing of composite flax tape, three ratios of flax/PLA were selected for the production process: 60/40, 50/50 and 40/60. These ratios were selected to allow a good mixture and avoid shrinkage during the production process while the manufacturing process for the production of triaxial glass fibre fabrics was glass tow. During the single process of blending and laminating, electricity is used and produces CO$_2$ emissions. The process consists of selected two ratios of flax and polylactic acid and blended to produce a unit directional composite materials tape, as shown in Figure 4. The electricity increases with time from 0.39 kWh to 1.54 kWh. The gate to gate process is limited to Blending and laminate with an energy consumption estimated at 14.48 MJ/kg respectively with carbon dioxide at 2.09 kg.
Figure 4: Process for transforming flax and poly lactic acid (FL&PLA) into a composite material flax tape.

The manufacturing of 6.7 m² of flax tape weighs approximately 1 kg. Therefore, for one hour approximately 35.8 kg of flax tape is produced. The advantage of this process is to yield a mixture of composite material tape that can be used for the fabrication of the complex component for industry purpose. Therefore, typical processes for the flax tapes include vacuum infusion or resin transfer molding using either standard resins or bio-based resins. The tapes can also be prepregged,
and processing is carried out in the same way as glass fibre. Compared to glass fibre composites, flax offers reduced weight, improved environmental impact, vibration damping, similar specific stiffness and safer handling.

Assuming that the composite material consists of two different types of fibre (flax and PLA), the weight of the composite is equal to the sum of the weights of the fibres from Equation (6) and finding the mass of each type of fibre.

\[ W_{\text{flax}} + W_{\text{PLA}} = W_c \]  

(6)

The theory approach to calculating energy consumption can be expressed, as shown in Equation (1). The resource, activity and emissions of LCA gate-to-gate are limited in a single process. Therefore, the three phases of life, are seen as a self-contained unit, with notional “gates” through which inputs pass, and outputs emerge.

Materials and manufacturing processes of flax and PLA deal with issues that result in better utilisation of raw materials and energy, integration of design and manufacturing activities, requiring the invention of suitable new manufacturing processes and techniques. Depending on the mechanical properties, three different ratios were selected to be produced. Therefore, long fibres are used through the machine to form a continue laminating flax tape. The processes are simple, but they produce some shrinkage on flax tape during production.

### 3.2 Triaxial glass fibre

The manufacturing process of triaxial glass fibre runs at a slow speed set up to produce good quality and smooth material with the same fabric grammage. The average electricity obtained at each stage of the manufacturing process represents the production of the raw materials glass sand and borate into unidirectional (UD) glass. The electricity used is purchased and the CO\textsubscript{2}e was deducted for the energy consumption. The development of triaxial glass fibre by transforming roving/yarn into fabrics uses purchased electric. The energy consumption is evaluated during manufacturing process. The average electricity use depends on the machine set up and speeds at 1 m/min. The process that transforms glass fibre roving into fabric is the same process using the same machine to produce carbon fibre fabric in formax based at Wakefield on machine 5 Formax.
The glass roving is passed along the rolling table inserted, stitched and woven at \(-45^0, 90^0, 45^0\) before batching operation, as depicted in Figure 5.

The electricity consumption varies for each process, depending on the machine speed and the process. To transform glass into triaxial fabrics, most of the electric appliance have to be covered to avoid any spark that may cause fire during production process. The total electricity consumption is estimated at 57.93 MJ/kg, for a production rate of 600 g per 1.27 m wide. The input and output are known as gate-to-gate to seek the maximum energy use. This action by one phase may have the result of raising resource consumption, such as electricity and emissions, for the manufacturing process, due to the production of the composite material part on a special machine for a single production.
The energy consumption was evaluated for the production of fabrics (weaving/stitching) based on the gate-to-gate process as shown on the figure 5. Therefore, the glass fibre yarn are manually fixed on the trolley and the line fibres are connected to the machine. When the machine is on, the manufacturing start insertion at -45°, 90°, 45°, stitching and batching.
3.3. Results and Discussion

A company specialising in manufacturing natural fibre was used, by applying life cycle assessment, to access the production process of the machine tape. The process consists of mixing different ratios of flax and PLA fibre, to create hybrid flax tape for product development. For that, a range of natural fibres was used to produce a composite material laminate for industrial application. The development of a semi-consolidated sheet of prepreg flax, from fully aligned natural fibres, was produced with a poly lactic acid in the form of flax tape. The focus was on a cost-effective “dry” process that can be fully integrated with the spreading and orientation of technologies and improve fibre-matrix adhesion. With the production of a range of laminate mixed composite material, some theoretical expressions have been adopted to define the percentage of each composite material. The volume fraction of the composite material, $V_c$ and the sum of the amount of each material are determined based on Equation 7.

$$\% W_{\text{flax}} x \ell_{\text{flax}} + \% W_{\text{PLA}} x \ell_{\text{PLA}} = W_c$$

(7)

The weight of the composite material flax and PLA was determined using Equation (6), from the weight ($W_{\text{flax or PLA}}$) of the fibre to obtain, the density ($\ell_{\text{flax or PLA}}$) of fibre and the total weight ($W_c$) of the composite material. The focus was on the development of an integrated approach which combines the fibre spreading and arrangement technology, in a single continuous process that can be readily scaled up for commercial production. Depending on the mechanical properties for improvement, the fibre volume fraction can be increased or reduced. For example, to improve the strength of the flax tape, the flax fibre volume fraction was increased. The advantage of this process is that, it allows change in the amount of materials used such as flax and PLA, depending on the mechanical properties (stiffness and strength), that require improvement. The flax tape is commingled with 60% flax and 40% PLA, to produce 10 kg of composite flax tape for 6 kg of flax and 4 kg PLA. A theoretical analysis can be applied to obtain the volume of composite flax tape.
4. Energy consumption profile

4.1 Energy consumption during production of flax tape

For this study, the machine tape was used to measure the energy consumption during the production of flax/PLA process, all associated tasks were timed to make a comparison production with glass fibre and compare the environmental impact. The process was performed with lower energy consumption and increased with time. The electricity use for the process to produce flax/PLA was estimated. The energy use is calculated per hour and represented by each colour; the heat loss was not taken into account. The software device was connected to the input (electricity and material) on the machine before the production started, this recorded the energy consumption during the production of one batch (Figure 6).

![Figure 6: Daily electricity use by tape machine during a single manufacturing process (source: Tilsatec, T).](image)

Comparatively, the higher column represents the energy consumption, and the lower column represents the CO₂ emissions. It was evident that the electricity used at the end of production was valued at 4.46 MJ/h and carbon dioxide emissions of 0.65 kg. The production rate is estimated at 18 kg/h equivalent to 0.25 MJ/kg for composite flax tape fabric. The primary data on the test compared to the secondary data simulation SimaPro LCA software, on Figure 7, was similar.
because of lower environmental impact on the production of flax tape. Therefore, the energy consumption for a day production is estimated at $E = 35.68 \text{ MJ/day}$ for approximately 286.4 kg of flax tape.

In this method, only the energy inputs and the embodied energy in the materials are evaluated. The simulation shows that the process produced lower CO$_2$ emissions, less than 1%. The green column on disposal and reuse tape shows a lower environmental impact of the flax tape that was less than 0.1 % pollution.

4.2 Energy consumption during the production of triaxial glass fabrics

The energy consumption of triaxial glass fibre fabrics was estimated using conventional devices ecoinvent software (elink). During the manufacturing of triaxial glass process, the devices were set up on the input of glass fabrics machine and the roving glass was uploaded on a rail, as indicated
in Figure 2. The production of glass fabrics is slower, because of the lower speed at 1 m/min for a good consolidation of the glass fabrics and processing for the final quality of the product.

Figure 8 shows the daily electricity used for one single process during the manufacture of glass fibre fabrics. The electricity consumption was estimated at 23.76 MJ/h, and CO₂ emission is at 3.45 kg. Daily energy consumption is estimated at 168.38 MJ/day with a carbon dioxide emission of 24.5 kg CO₂e. The production rate is approximately 0.5 kg per minute, 30 kg/h equivalent to 0.8 MJ/kg of triaxial glass fibre fabric. Since the energy intensities of materials vary, depending on technology, methods and infrastructure, there is a wide range of values, as shown in Table 1. For example, glass fibre which is one of the most common basic materials to reinforce plastics has broadly varying production energy intensities.

Table 1 indicates that process-level energy of 64.49 MJ is needed to prepare a 1 kg prepreg flax tape/unsaturated polyester composite. It is interesting to see that consideration of composite materials leads to a high increase in the energy intensity from 12.25 MJ (for the prepreg process in itself) to 64.49 MJ. Therefore, the energy consumption to produce a component is the total energy consumption for each process. Furthermore, the sum of the total energy consumption shows that the natural fibre component uses less energy, and results in lower air emissions with a
difference of 0.8% between prepreg flax tape and china reed fibre. The energy consumption to manufacture a flat sheet of 250 mm x 250 mm for flax tape and Glass/PP with 2.1 mm to 2.3 mm thickness using the moulding process is shown in Figure 9. The total mass of each of the composite materials is estimated at 2.05 kg and 2.90 kg for flax tape and glass/PP respectively, assuming that the volume fraction of fibre is 40% flax tape and glass/PP 45% glass, and 40% PP.

Table 1: Energy consumption for various materials and processes.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Energy intensity (MJ/kg)</th>
<th>CO₂ emissions (kg CO₂)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass fibres</td>
<td>13-32</td>
<td>6.8-16.7</td>
<td>[30]</td>
</tr>
<tr>
<td>China reed fibres</td>
<td>3.6</td>
<td>1.9</td>
<td>[30]</td>
</tr>
<tr>
<td>Flax fibres</td>
<td>6.5</td>
<td>3.4</td>
<td>[29]</td>
</tr>
</tbody>
</table>

**Process analysis**

- Fibre production: 12.24, CO₂: 6.4, References: [30]
- Fabric production: 0.772, CO₂: 0.4, References: [29]
- Prepreg production: 40.0, CO₂: 20.9, References: [29]
- Resin production: 34.2, CO₂: 17.8, References: [29]
- Flax Tape fabric: 12.25, CO₂: 6.5, References: [30], source: Tilsatec
- Triaxial glass fabric: 29.04, CO₂: 15.32, References: [29], source: Formax
- Glass fabrics: 30.84, CO₂: 16.3, References: [29], source: Formax

**Prepreg material production**

- Prepreg flax tape-component: 64.49, CO₂: 34.08, References: [29], source: Tilsatec
- China reed fibre-Epoxy: 56.61, CO₂: 30, References: [29]
- Glass fibre-Epoxy: 83.84, CO₂: 44.31, References: [29]
- Triaxial glass fabric-Epoxy: 82.04, CO₂: 43.36, References: [29], source: Formax
The total energy based on the moulding process for manufacturing a sheet of composite flax tape is estimated at 14.48 MJ/kg and carbon dioxide at 2.12 kg/CO₂. This is compared with higher energy estimated at 116.43 MJ/kg and carbon dioxide at 16.66 kgCO₂ for production of a Glass/PP sheet [47]. Therefore, the energy and emissions are considerably less to produce the composites flax tape.

4.3 Environment impact of the production of composite fabrics

The environmental impact potential is the weighted sum of the product of individual pollutant emission and their characteristic factors. However, certain environmental impact potential cannot be directly compared with others, due to the different unit. Therefore, different environmental impact potentials should be normalised and weighted to evaluate the environmental impact load (EIL) for the product/service [47].

For the production of composites flax tape, the operations involve, heating, blending and laminating on the tape machine to reach the final product. The total energy consumption of fibre blending and tape manufacturing, life cycle gate-to-gate is estimated at 12.25 MJ/kg and carbon dioxide emission at 6.5 kg/CO₂. As long as the production of flax tape fulfils aesthetic expectations and dimensions are met, the process to produce composite flax tape has succeeded with lower
energy consumption. Moreover, the energy consumed to produce triaxial glass fibre can be used to produce 40% times more composites flax tape materials. The energy for both cultivation and transportation was not considered for the cultivation and harvest of flax and PLA. However, the production of flax/PLA has a less environmental impact on water and earth.

Selected comparative results from the study are summarised in Table 2. Overall, the NFR pallet results showed significantly lower environmental impacts compared to GFR pallet, except for nitrate emissions to water associated with china reed cultivation. The study also reports results from sensitivity analysis with respect to recycling at various percentages, pallet life, plastic content and changes in transport distances. It is evident that NFR pallet is environmentally superior under almost all scenarios. However, the environmental impacts of NFR are worse, if the expected life of NFR falls below three years compared to five years for the GFR.

Table 2: Environment impact to produce flax tape compare to glass fibre[29].

<table>
<thead>
<tr>
<th>Environmental</th>
<th>Glass fibre pallet/PP</th>
<th>Triaxial glass fabric-Epoxy</th>
<th>Natural fibre reed/PP</th>
<th>Flax tape (Flax/PLA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy use (MJ/kg)</td>
<td>70</td>
<td>82.04</td>
<td>35.7</td>
<td>12.25</td>
</tr>
<tr>
<td>Carbon dioxide emissions (kg)</td>
<td>3.65</td>
<td>4.27</td>
<td>2.1</td>
<td>6.5</td>
</tr>
<tr>
<td>Carbon monoxide (g) NOx(oxides of nitrogen) air emissions (g)</td>
<td>3.71</td>
<td>4.34</td>
<td>2.73</td>
<td>NE</td>
</tr>
<tr>
<td>Sulfur oxides (SOx) air emissions (g)</td>
<td>25.65</td>
<td>30</td>
<td>17.45</td>
<td>NE</td>
</tr>
<tr>
<td>Water emission—BOD (mg)</td>
<td>14.45</td>
<td>17</td>
<td>8.15</td>
<td>NE</td>
</tr>
<tr>
<td>Water emissions—nitrates (g)</td>
<td>0.086</td>
<td>0.1011</td>
<td>7.65</td>
<td>NE</td>
</tr>
<tr>
<td>Water emissions—phosphates (g)</td>
<td>0.029</td>
<td>0.0341</td>
<td>0.08</td>
<td>NE</td>
</tr>
<tr>
<td>CML—Greenhouse effect (kg CO₂ eq)</td>
<td>3.76</td>
<td>4.42</td>
<td>2.02</td>
<td>NE</td>
</tr>
</tbody>
</table>

*NE denotes not estimated.
The water emissions of nitrates, phosphates and nitrogen oxide (NOx) to air are higher as a result of fertiliser applications in natural fibre. The environmental impacts for the natural fibre composite are dominated by the energy and emissions from epoxy production. Even though natural fibre accounts for 66% of the volume of the component, it contributes only 5.3% of the cumulative energy demand [34]. As far as the energy demand, environmental impact load, water requirement consumption and solid waste are concerned, the flax/PLA composites have environmental advantages over their counterparts. This investigation provides useful information to the manufacturing, processors, consumers and policy makers of sustainable composites materials using flax tape. However, the LCA gate-to-gate can only be one of the references for the manufacturers and decision makers, since the weighting factors for different environmental impact categories depends on subjective expert opinion. On the other side, the gate-to-gate assessment of the flax tape does not include the product use and end-of-life phases, which limits the ability to identify the burden shifting.

It was clear that boundary selection had a large influence on the gate-to-gate observed results. In this study, the manufacturing requirements to use flax, PLA and glass fibre input to produce composite materials with flax tape and triaxial glass fibre use purchased electric. The consumption of electricity would lead to energy consumption and carbon dioxide production based on the recent series of ISO standards 14040 to 14043.

5. Conclusions

Life cycle assessment was carried out to estimate the energy for producing composite materials: flax tape and triaxial glass fibre for the industry. A standard and efficient method has been used to record the energy consumption during the manufacturing process of these materials during batch production. The energy consumption of each process has been recorded following the same process. The environmental impact of these materials has been investigated and calculated. The natural fibre composite material (Flax/PLA) has fewer processing steps to transform into the tape, therefore, consuming less energy and producing lower carbon dioxide emissions when compared to the synthetic glass fibre.

The results obtained show that PLA commingled well with flax, as matrix material for natural fibre composite. The energy consumption is estimated at 0.25 MJ/kg for the production of flax tape and 0.8 MJ/kg for triaxial glass fibre fabrics. Therefore, the production of composite flax tape uses
less energy than some materials already being used in industry. They are cheaper to produce and the processing technique is not complicating as much as the conventional products. The process of commercial production of flax tape composites is promising based on the manufacturing process and environment impact. The energy consumption to produce a composite material using prepreg process is estimated at 14.48 MJ/kg for flax tape, 44.48 MJ/kg for glass fibre fabrics and 72 MJ/kg for polypropylene. From this study and specific applications, NFR composites are environmentally superior to GFR composites on most performance metrics. However, there are significant differences, regarding the specific component/application being studied, in addition to the material composition of the referenced component, as well as the NFR component and specific natural fibre chosen. This is also affected by production processes, boundaries and scope of the life cycle assessment as well as environmental impacts considered and the data sources used. Importantly, care is needed in interpreting the results of LCA. Also, product comparisons across alternatives or substitute products are meaningful only when the same methods and system boundaries are used to derive the results. The repercussions of comparing natural fibre to synthetic fibre could lead to significantly flawed conclusions. Future research should hence focus on achieving equivalent or superior technical performance and component life.

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