Life cycle assessment of bio-composite laminates. A comparative study

N Gkoloni¹ and V Kostopoulos¹,²

¹ School of Science and Technology, Hellenic Open University, 26335, Patras, Greece
² Department of Mechanical Engineering & Aeronautics, University of Patras, University Campus, 26504, Pion Patras, Greece

ngkoloni@upatras.gr, kostopoulos@upatras.gr

Abstract. The use of glass fiber reinforced plastics is steadily increasing in the aerospace industry for aircraft interiors. However, the glass fiber reinforced plastics, although provide a robust solution they have many issues concerning their environmental friendliness. An alternative environmentally friendly solution for aircraft interiors is the use of bio-composites. Bio-composites used in this kind of applications are made of natural fibers as reinforcement and the use of bio-resins as matrix material. In the present study a life-cycle assessment approach is applied to selected bio-composites scenario and the comparison were made against the currently used glass fiber reinforced plastics. Results show the use of flax fiber reinforced materials seems to have lower environmental impact.

1. Introduction

The aviation industry has experienced rapid growth and according to the EUROCONTROL forecast, the number of flights in Europe will have an average growth of 1.8% per year in the most-likely scenario. For example, both Airbus and Boeing forecast a doubling of the aircraft fleet until the year 2035 compared to 2016 [1,2]. These figures although have changed due to the pandemic of COV-SARS 2 are still valid for the post pandemic era, where the aviation development will return to a normality. This continued growth has raised concerns about the future effects of aviation emissions on the global environment. International Civil Aviation Organization (ICAO) forecasted that by 2050 global aviation emissions could grows by a 300%-700% [3].

In recent years there has been an increasing trend in the application of composite material, which are defined as fiber reinforces polymers (FRP), due to their high specific modulus and strength and their fatigue resistance and durability. However, the high environmental impact of the production of composite materials, such as carbon or glass fiber reinforced epoxy, and their poor recyclability create many environmental concerns [4]. To overcome these deficiencies, bio-composites reinforced with natural fibers such as flax, herb and jute, have been investigated in literature as alternative environmentally friendly solution [5-7].
Besides this, most of the composite components used in primary aircraft structures are currently produced by using epoxy based prepreg laminates cured in an autoclave at high temperature and pressure. However, autoclave curing has a numerous of disadvantages such us high acquisition costs, energy intensive operation and long process times. This is the reason why the industry has focused in alternative methods such as out of autoclave infusion technique (OOA) for the manufacturing of composites. With OOA process manufactures can avoid the high cost equipment, but the disadvantage of long curing cycle time remains together with the lower mechanical properties of the processed component, due to the lower fiber volume fraction achieved by these manufacturing methodologies. One possible way to reduce process cycle time of OOA processes is by replacing the conventional oven curing with microwave one. The application of this technology could reduce process times, increase energy efficiency, and lower investment cost [8].

2. Goal and scope of the study

The aim of this study is to assess and quantify the environmental impact and the resulted environmental differences between three different composite plates manufactured for serving needs of aircraft interiors. The reference composite material is a glass fiber reinforced epoxy composite, manufactured by using infusion technique, cured by using a conventional oven and finally post cured for concluding its final properties. The first alternative is to replace the glass fibers by flax fiber and keeping the same type of matrix material, manufacturing, curing and post-curing processes. The final alternative is the use of flax fibers as reinforcing material for the epoxy matrix and then after applying infusion process for the manufacturing of the plate, to use microwave oven for the curing and the same conventional oven for the final step of post curing. In all three cases the mechanical properties of the final composite plate are the same both for the modulus of elasticity and the tensile strength.

The functional unit used for this LCA analysis and comparison is defined as the manufacturing of a 250x200x2 mm³ composite laminate. In conclusion the following combination of materials and manufacturing scenarios are considered:
Scenario 1: Glass fiber reinforcement with epoxy matrix and conventional over curing
Scenario 2: Flax fiber reinforcement with epoxy matrix and conventional over curing
Scenario 3: Flax fiber reinforcement with epoxy matrix and microwave over curing

3. Methodology

3.1. Life-cycle assessment (LCA)

Life cycle assessment is analysis tool which is used to evaluate how a product or material affects environment, human health, and resource consumption. LCA takes into consideration all the steps that lead from raw material through manufacture, distribution, and usage to final disposal. LCA as is defined by ISO 14040-14044 [9,10] is ‘the collection and evaluation of the inputs, outputs and the potential environmental impacts of a product system through-out its life cycle’.

LCA is also an internationally and scientifically recognized methodology. The European Commission’s Integrated Product Policy Communication identified LCA as the ‘best framework for assessing the potential environmental impacts of products’ [11]. According to ISO 14040 there are four steps in LCA as they are shown in Figure 1.
In the present study OpenCLA is used for performing the Environmental Assessment [12] and Ecoinvent database is used for the processes in the Inventory stage [13].

3.2. System boundaries and scenario descriptions
For the scope of the study, a ‘cradle to gate’ LCA is carried out, as the steps after laminate production (use and end of life) are identical and only small weight variations between scenarios are assumed. The geographical boundary for this study was set to be within Europe and the European average power mix is applied for all operations. All raw materials production for flax and glass fiber as well as for epoxy resin are considered with their transportation and their intermediate production steps. The manufacture of consumable materials required for each manufacturing processes is also considered as well as their disposal after use, assumed to be through incineration with energy recovery.

3.3. Raw materials
The system diagram of the manufacturing process for the Glass fiber/Epoxy composites and the Flax fiber/Epoxy composites are given in Figure 2 (a) and (b) respectively.

![Figure 2: System boundaries for (a) Glass fiber Epoxy composites (b) Flax fiber Epoxy composites.](image)
As it is already stated, after cutting of the woven fabrics to the predefined dimensions 8 cut woven fabrics are laid up as a dry stack of materials in a symmetric way into the appropriate open mold. The fiber stack is then covered with peel ply and a knitted flow distribution mesh. The whole dry stack is then vacuum bagged, and once bag leaks have been eliminated, resin is allowed to flow into the laminate under vacuum conditions. Rather than starting with excess and drawing resin out, Vacuum Infusion Process starts with none and pushes resin in. Ideally, any excess resin that is introduced will eventually be sucked out into the vacuum line. As a result, only the minimum amount of resin is introduced to the mold. After filling the mold with the necessary quantity of epoxy resin the system is placed into the oven for curing, followed by a post curing stage. This manufacturing process is followed for all the manufacturing plates. However, in the case where the reinforcement is flax, the flax fabrics must be conditioned in a conventional oven for drying before use. Furthermore, for the needs of the present study in the case of flax fiber/epoxy laminates the curing process is executed either into a conventional oven or in a microwave oven, after optimizing the curing conditions to conclude to a high quality flax composite laminate.

3.4. Inventory data
The summary of materials quantities and energy use for each production scenario is shown in table 1, where «waste» refers to off-cuts from consumables. Inventory data for the flax fiber production, glass fiber production and consumable materials were obtained for Ecoinvent Centre. Table 2 lists the consumable and fiber type with the associated materials and processes chosen.

| Table 1. Summary of materials quantities and energy use for each production. |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Flow                        | Scenario 1 | Scenario 2 | Scenario 3 | Unit |
| electricity, low voltage    | 4,15       | 4,1         | 2,9         | kWh  |
| epoxy resin, liquid         | 0,27       | 0,27        | 0,27        | kg   |
| fibre, flax                 | 0,05       | 0,05        | 0,05        | kg   |
| fibre, glass                | 0,1        |             |             | kg   |
| flow media                  | 0,003      | 0,003       | 0,003       | kg   |
| peel ply                    | 0,003      | 0,003       | 0,003       | kg   |
| sealant_tape                | 0,504      | 0,504       | 0,504       | kg   |
| tube insulation, elastomere | 0,00374    | 0,00374     | 0,00374     | kg   |
| vacuum                      | 0,005      | 0,005       | 0,005       | kg   |
| waste                       | 0,63374    | 0,63374     | 0,63374     | kg   |

| Table 2. Materials and process selected from Ecoinvent to represent Inventory data. |
|----------------------------------|-------------------------------------------------|
| Product                      | Materials                                         |
| flax fibre                   | fiber production, flax, retting | fibre, flax | Cutoff, ROW |
| glass fibre                  | glass fiber production | glass fibre | Cutoff, RER U |
| Peel ply                     | nylon66, at plant/RER U | weaving, cotton/GLO U |
| Flow media                   | polypropylene, granulate, at plant/RER U | Melt spinning, cotton/GLO U |
| Tube                         | Silicone product, at plant/RER U |

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Extrusion, plastic pipes/RER U
Sealant tape
tetrafluoroethylene, at plant/RER U
Melt spinning, cotton/GLO U
vacuum bag
synthetic rubber, at plant/RER U
Melt spinning, cotton/GLO U
electricity
market low voltage electricity /GR

4. Results and discussion
A comparative life cycle impact assessment (LCIA) was carried out with the use of IMPACT 2002 + Endpoint and RECIPE 2016 End point methods. These methods include a variety of impact categories that can help policy decision makers [14] and they are the most widely used and known methods. For the aim of this study we use the three-end point damage categories, resources, ecosystem quality and human health. The Impact 2002+ assessment and Recipe 2016 Endpoint results for all production scenarios are presented and compared in the bar chart of Figure 4 and Figure 5 respectively. For each indicator the maximum result is scaled to 100% and the results of the variants are displayed in relation to this result. In both assessments, Flax fiber reinforcement with epoxy matrix and microwave over curing has a lower value for all the environmental impact indicators and methods studied.

![Figure 3. Impact2002+ results.](image)

![Figure 4. Recipe 2016 results.](image)

In conclusion, results showed that materials, in particular glass fibers, contributed most significantly to components of environmental impacts. Furthermore, flax fiber reinforcement fabrics shows to have a beneficial effect to the environmental impact of the final composite. In the case of using flax fiber reinforcement in combination with Microwave oven curing, the final composite product has a considerably lower environmental impact. The only parameter that one has to take into consideration is the requested investment cost for the microwave curing oven.

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