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Environmental analysis of innovative sustainable composites with potential use in aviation sector—A life cycle assessment review

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The forecast of growing air transport in the upcoming decades faces the challenge of an increasing environmental impact. Aviation industry is working on promising technologies to mitigate this environmental impact. Lightweight design is a strong lever to lower the fuel consumption and, consequently, with it the emissions of aviation. High performance composites are a key technology to help achieve these aims thanks to their favourable combination of mechanical properties and low weight in primary structures. However, mainly synthetic materials such as petrol based carbon fibres and epoxy resins are used nowadays to produce composite in aviation. Renewable materials like bio-based fibres and resin systems offer potential environmental advantages. However, they have not found their way into aviation, yet. The reasons are reduced mechanical properties and, especially for the use of natural fibres, their flammability. Improvements of these shortcomings are under investigation. Therefore the application of bio-based and recycled materials in certain areas of the aircraft could be possible in the future. Good examples for applications are furnishings and secondary structures. The motivation for this paper is to give an overview of potential environmental properties by using such eco-materials in aviation. Life cycle assessment (LCA) is a tool to calculate environmental impacts during all life stages of a product. The main focus is laid on the bio-fibres flax and ramie, recycled carbon fibres and bio-based thermoset resin systems. Furthermore an overview of environmental aspects of existing composite materials used in aviation is given. Generally, a lack of LCA results for the substitution of synthetic materials by bio-based/recycled composite materials in aviation applications has been identified. Therefore, available information from other transport areas, such as automotive, has been summarized. More detailed LCA data for eco-composite materials and technologies to improve their properties is important to understand potential environmental effects in aviation.

aviation, composite, natural fibre, recycled carbon fibre, bio-resin, cabin interior, secondary structure, life cycle assessment (LCA)

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1 Introduction

The aviation industry faces a significant growth in air transport for the next decades and the ambitious aim to reduce environmental impacts. For example, both Airbus and Boeing calculated a doubling of the aircraft fleet until the year 2035 compared to 2016 [1,2]. By 2020, global international aviation emissions are forecasted to be around 70% higher than in 2005 even if fuel efficiency improves by 2% per year. International Civil Aviation Organization (ICAO) forecasted that

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*Corresponding author (email: jens.bachmann@dlr.de) by 2050 the emissions could grow by a 300%–700% [3]. Simultaneously, the climate change and the achievement of the aims set by the Intergovernmental Panel on Climate Change (IPCC) are a huge challenge [4].

Since the start of 2012 flight emissions from all flights to and within the European Economic Area (EEA)—The 28 EU Member States, plus Iceland, Liechtenstein and Norway—are included in the EU Emissions Trading System (EU ETS). The EU ETS works on the “cap and trade” principle, which set a cap on the total amount of certain greenhouse gases that can be emitted: according to EC goals, in 2020, emissions from all sectors covered by the EU ETS should be 21% lower than that in 2005. By 2030, as the Commission proposes, they would be 43% lower [5].

In recent years there has been an increasing trend in the application of composite materials in the aerospace and transportation industries due to their excellent mechanical properties combined with low weight and good fatigue behaviour. In the course of this paper, composites are defined as fibre reinforced polymers (FRP). FRP are made of a polymeric matrix material reinforced with fibres that have a high aspect ratio (length/width) leading to a anisotropic behaviour. Composites enable the construction of lighter and more efficient aircrafts resulting in the reduction of fuel consumption. High performance composites like carbon fibre reinforced polymers (CFRP) are used in primary structures of modern aircrafts like Airbus A350 (Figure 1) [6] and Boeing 787 Dreamliner. They replace more and more the classic materials, such as aluminium or steel. Furthermore sandwich made of glass fibre reinforced polymers (GFRP) and phenolic resins as matrix system find their application in the interior due to their low weight to stiffness ratio and fire resistance.

The environmental advantage of composite material architectures over their lifetime compared to conventional aluminium structures in planes have been proved and studied in various life cycle assessment (LCA) studies. The global transition of aircraft with composite architecture is estimated to contribute 15%–20% of industry CO_2 reduction targets by 2050. The analysis demonstrated that CFRP structures result in a reduced environmental impact, despite the higher environmental impact in the manufacturing phase because composites are more energy intensive to manufacture and more difficult to dispose or recycle. Environmental benefits are due to the reduced fuel consumption that allows a reduction of atmospheric emissions over the lifetime. This is especially relevant since in air transport emissions can be more environmentally damaging compared to those at ground level due to increased interaction with gases at high altitudes [7].

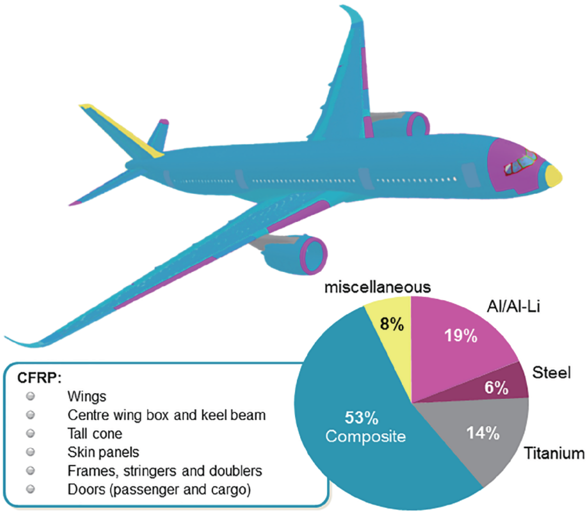

Figure 1 (Color online) Materials used in a modern aircraft, the Airbus A350 XWB [6].

All composite materials currently used in aviation have one thing in common: they are synthetic. In the early days of aviation, renewable materials like bamboo and wood have been used for biplane construction [8]. Flax fibres were even utilized by mankind since more than 30000 years and therefore most likely the oldest used fibre [9]. Nowadays, bio-fibres and bio-resins are under investigation for their use in composites but they have not been introduced into a modern aircraft, yet. The fulfilment of the demanding requirements is a main challenge for the application of renewable materials. As safety is of primary importance in aviation, the lack of experience and confidence in the long-term performance and mechanical properties of composites made of renewable materials is still an obstacle for their usage.

To gain advantage during the important use-phase of the aircraft, the materials need to be light and strong. Bio-fibres like flax and ramie offer very good specific fibre properties but these are not completely transferred in the final composite [10]. Not all natural fibres are available in form of semi-finished products for composites and the reproducibility of fibre properties has to be considered because of different growing conditions during their cultivation. Limited fibre-matrix-adhesion, natural damage of fibres and moisture sensitivity are important reasons for this behaviour. Furthermore, the cellulosic bio-fibres are highly flammable compared to glass and carbon fibres, therefore they need to be treated with flame retardants to pass safety requirements for interior use.

It is therefore at the moment out of scope to substitute high performance and safety-relevant composites in primary structural parts of the aircraft with bio-based materials. On the other hand, secondary structures and interior composites which are not stressed at such levels offer possible areas of application. Examples for secondary structural parts are fairings and the landing gear doors. In the interior, cabin ceiling panels, sidewalls and floor panels are possible targets for the substitution with ecological improved developments. Furthermore the multifunctional aspects of composites could be important to gain advantages to classic material solutions. The integration of functions may utilize the intrinsic damping properties of natural fibres to improve passive acoustic behaviour of interior panels and with it the passenger comfort.

This paper has the aim to give an overview of currently used composite materials for aviation and possible bio-based and recycled substitution materials with the focus on their ecological properties. Data has been obtained by literature and LCA database research. A short introduction to LCA methodology with a typical life-cycle of composite materials from raw-materials to the End-of-Life is given. In the context of this paper the following base materials are considered to reduce ecological impacts compared to the state-of-the-art: bio-based thermoset resins (epoxy, furan), bio-based fibres (flax, ramie) and recycled carbon fibres. Bio-based thermoplastics and alternative bio-fibres such as hemp or jute offer promising properties. They are out of scope in this LCA overview as they are not included in the ECO-COMPASS project. The aims of the cooperation of Chinese and European partners are also described.

2 The ECO-COMPASS project

ECO-COMPASS stands for “ecological and multifunctional composites for application in aircraft interior and secondary structures”. It is a Horizon2020 research and innovation action (RIA) project with overall 19 partners from Europe and China. The main objective of the project is to develop and assess ecological improved composites for application in the aviation sector. It is the aim to bundle the knowledge from participants in China and Europe to improve renewable and recycled materials for their application in aviation structures with a better ecological balance than materials currently used. In the context of this paper the following base materials are considered to reduce ecological impacts compared to the state-of-the-art: bio-based thermoset resins, bio-based fibres (flax, ramie) and recycled carbon fibres. Bio-based thermoplastics and alternative bio-fibres such as hemp or jute offer promising properties. But they are out of scope in this LCA overview as they are not included in the ECO-COMPASS project.

Pure bio-composites made of bio-fibres and bio-resin (e.g. bio-epoxy) will be evaluated in parallel with a new approach that aims at combining valuable recycled carbon fibres and bio-fibres in a hybrid non-woven. In parallel the development of bio-based epoxy resins to substitute the currently used bisphenol-A based epoxies and phenolic resins will be carried out. As the use of biological materials brings new challenges like moisture sensitivity and fungal attack, special attention will be paid to suitable protection technologies. It will be of high importance in the project that these protection technologies should only be applied if they are necessary to fulfil their desired function, as every further material and treatment of these eco-composites may increase their ecological footprint, cost and weight. Therefore the environmental impacts compared to selected state of the art parts with an accompanying LCA will be calculated.

3 Introduction to LCA methodology

Life cycle assessment (LCA) is an analysis tool which is used to evaluate how a product or material, from the start of production to its end-of life, potentially affects ecosystems. The ISO framework of LCA (ISO 14040-14044) defines LCA as “The collection and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle”.

LCA is internationally accepted tool to analyse a product from an environmental perspective, since it is a standardised, objective, holistic and scientifically recognised methodology. LCA allows the systematic quantitative assessment of products, goods and services, in terms of environmental impact, human health, and resource consumption considerations. The European Commission’s Integrated Product Policy Communication (COM (2003)302) identified LCA as the “best framework for assessing the potential environmental impacts of products”. The four phases of LCA according to ISO 14040 are shown in Figure 2.

An important step in the LCA is the life cycle inventory analysis (LCI). Figure 3 shows a simplified life cycle of a composite, starting with the production of pre-products, the manufacturing of the composite, assembly, use-phase and waste treatments at the end-of-life (EoL). During the LCI, all inputs and outputs of the system boundaries need to be quantified and assigned to the different stages and processes of the product. Raw-materials and energy are typical inputs, emissions (air, soil, water) and waste typical outputs.

4 Composites currently used in aviation

This section provides an overview of the state-of-the-art

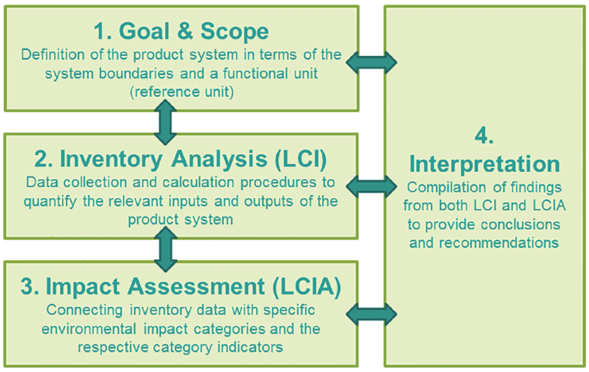

Figure 2 (Color online) Methodology and steps for LCA studies according to ISO:14044:2006.

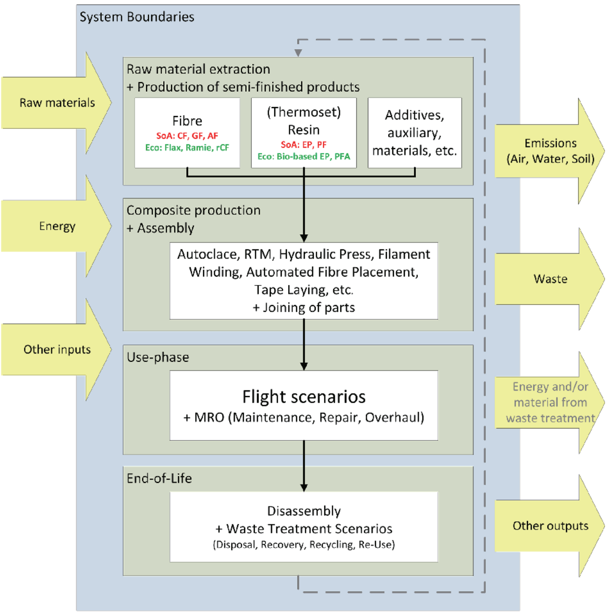

Figure 3 (Color online) Life cycle inventory analysis (LCI) of a simplified composite life cycle with inputs and outputs.

composites currently used in aircraft applications. It must be distinguished between the identified applications, primary/secondary structures and interior parts, because the requirements differ considerably. Composites for interior (e.g. cabin sidewalls and furnishings) need good fire properties combined with a very low weight as it is realized by currently used glass fibre (GF) reinforced phenolic resin sandwich panels. On the other side, the secondary and primary structures have more demanding requirements regarding the mechanical properties of the composite. Exampled for secondary structures are fairings, winglets and gear doors. Secondary or primary structures are basically made of the same materials with different reinforcement architectures like unidirectional and woven fabric.

4.1 Composite materials in aviation

This chapter gives an overview of constituent materials used to produce composites in aviation today. Fibres and resins are from various grades that influence the environmental assessment thanks to the energy intensity associated. As a general rule, aeronautics uses the top grade for its specific and high requirement applications. An overview of physical and mechanical properties of selected synthetic state-of-the-art (SoA) fibres and bio-based fibres is given in Table 1 [11–17].

Carbon fibres are the main type of CF used for aviation is polyacrylonitrile (PAN) based. Alternatives like coal pitch or lignin based CF are not used in aeronautics. According to the properties required, aeronautics can select high modulus (HM, graphitizing at 1500–2800°C), high strength (HS, carbonization at 1000–1700°C) or an intermediate state (IM, intermediate modulus). The properties of these CF are different through variation of crystallinity due to the thermal treatment applied [18].

GFs are also of various types. They are resistant to high temperatures and corrosive environment and radar transparent. E-glass is the most common used GF (E because of initial electrical application) but is prone to fractures in case of acoustic emissions. The other widely used type is R and S (R for reinforcement, and S for strength) with high tensile strength. Other types are A, E-CR, C and D-glass.

Aramid fibres (aromatic polyamide, AF) are a class good thermal, chemical and radiation resistance polymer. Nomex® and Kevlar® are the most widespread registered

Table 1 Properties of synthetic fibres used in aeronautics and selected bio-based fibres for comparison [11–17]

Fibre type		Density (g/cm^3)	Price (USD/kg)	Young's modulus (GPa)	Tensile strength (MPa)	Elongation (%)	Length (mm)	Diameter (μm)	Moisture content (wt%)	Cellulose content (wt%)
Synthetic	Carbon HS	1.7–1.8	66–110	200–250	3500–4900	1.4–2.1	–	5–10	–	–
	Carbon HM	1.9	200	350–550	2700–4400	0.7–1.2	–	5–10	–	–
	Carbon IM	1.8	100	250–350	5400–6300	1.9–2.2	–	5–10	–	–
	Aramid meta	1.38	15–33	12–20	700–850	15–30	–	10–20	<8	–
	Aramid para	1.44	n/a	58–124	2500–4100	2.4–3.3	–	~12	<8	–
	S/R-glass	2.46–2.53	20–37	85–87	3000–4400	4.0–5.0	–	9–11	–	–
	E-glass	2.55–2.6	1.63–3.26	72–85	1900–2400	1.8–4.5	–	5–24	–	–
Fruit	Coir	1.15–1.22	0.25–0.5	4–6	135–240	15–35	20–150	10–460	8	32–43.8
	Cotton	1.52–1.56	2.1–4.2	7–12	350–800	5–12	10–60	10–45	7.85–8.5	82.7–90
Bast	Flax	1.42–1.52	2.1–4.2	75–90	750–940	1.2–1.8	5–900	12–600	8–12	62–72
	Hemp	1.47–1.52	1.0–2.1	55–70	550–920	1.4–1.7	5–55	25–500	6.2–12	68–74.4
	Jute	1.44–1.52	0.35–1.5	35–60	400–860	1.7–2.0	1.5–120	20–200	12.5–13.7	59–71.5
	Ramie	1.45–1.55	1.5–2.5	38–44	500–680	2.0–2.2	900–1200	20–80	7.5–17	68.6–85
Leaf	Sisal	1.4–1.45	0.6–0.7	10–25	550–790	4.0–6.0	900	8–200	10–22	60–78
Grass	Bamboo	0.6–1.1	0.5	11–32	140–800	2.5–3.7	1.5–4	25–40	–	26–65

trademarks of aramid. Honeycomb cores are made of chopped aramid fibres with a length between 2 to 12 mm, impregnated with phenolic resin. There are several types of AF used in aeronautics split among the two main groups *meta*- and *para*-aramid with Nomex® and Kevlar® as their respective example. Nomex® is the AF used mainly for interior components.

Epoxy resins are used as matrix for composites in primary and secondary structures. Epoxy can be used with resin infusion and for pre-impregnated fibres (prepreg). Epoxy resins can have two or more epoxide functions ()–: di, tri or tetra. Examples for di-functionality bisphenol A diglycidyl ether (DGEBA) or 9,9-bis(4-hydroxyphenyl)fluorene (DGEBF). Another example for tri-functionality is *N*,*N*-triglycidyl *meta*-aminophenol (TGMAP). Aeronautics uses a blend of these. The hardener mostly used to react with the resin is diaminodiphenylsulfone (DDS).

Phenolic resins are used in fibre-reinforced polymer with glass mostly and also to impregnate aramid paper. Their polycondensation reaction which emits water during curing makes phenolic resins only usable as pre-impregnated and pre-cured fabric (prepreg). Phenolic resins (or phenol formaldehyde) are obtained by the reaction of phenol or substituted phenol with formaldehyde. Many variations in both production and input materials lead to a wide variety of resins for special purposes, mainly novolacs (formaldehyde/phenol molar ratio <1 under acidic conditions) or resoles (formaldehyde/phenol molar ratio >1 under basic conditions). They have a disadvantage due to their brittleness and inability to be coloured.

The following list gives an overview of possible combinations of fibres and resin systems used in aviation nowadays:

(1) CF and epoxy resin for primary and secondary structures.

(2) CF and high performance thermoplastic like polyethersulfone (PES), polyphenylene sulfide (PPS), polyetherimide (PEI) and polyetheretherketone (PEEK). They are only used for special applications for primary and secondary structure parts.

(3) GF/CF with phenolic resin whenever a health hazard associated to fire risk is identified. They are mostly found for interior components because of good temperature resistance, low smoke and toxic emissions of phenolic resins.

(4) Sandwich panel made from GF or CF with phenolic resin prepreg for skin layers of honeycomb core made of aramid paper (*meta*-Nomex®) impregnated with phenol-formaldehyde resin.

(5) Glass reinforced aluminium (GLARE), a hybrid (fibre metal laminate, FML) stacking combination of GFRP and aluminium. GLARE is currently used in sections of the Airbus A380 fuselage.

4.2 Manufacturing processes

The main composite manufacturing processes used in aeronautics are listed below:

(1) Prepreg cutting/laying/moulding under vacuum and autoclave/followed by a curing cycle.

(2) Resin transfer moulding (RTM) injection of the liquid polymer through a dry preform laid in a closed mould under pressure/followed by curing cycle.

(3) Liquid resin infusion or vacuum assisted resin transfer moulding VARTM (LRI) derived from RTM, a single sided moulded process where the dry preform is placed into the mould, followed by a cover placed over the top to form a vacuum tight seal, then the resin through the mould and impregnates the fibres due to vacuum applied.

(4) Automated tape laying (ATL) and automated fibre placement (AFP) use computer-guided robotics to lay reinforcement fibre tape or tows (typically carbon fibre) onto a mould. Aerospace applications include wing skins and fuselage.

4.3 Buy-to-fly ratio

Buy-to-fly (BtF) ratio in an LCA analysis is key factor for environmental and economic assessment. It is the amount of material used (bought) compared to what is really put into the manufactured parts. A large share of cuts during the manufacturing of a composite can end as waste. This amount matters a lot for the environmental assessment. BtF ratio is hard to evaluate, it depends on the part, the process and technology used, as well as optimization practices. For example, prepreg is more material intensive than LRI or RTM. BtF can be slightly above 1 up to several units. CFRP in aeronautics is said to surpass aluminium/titanium with a BtF of 1.5:1 [17], but metallic scraps are easily recycled. For some aeronautics insider the overall BtF is closer to 10:1 [19].

4.4 Mechanical properties of composites

The mechanical properties of fibre reinforced polymers differ considerably and depend mainly on type of fibre, reinforcement architecture, fibre volume content, lay-up, resin system and manufacturing method. An overview of tensile strength and Young's modulus for selected composites made of synthetic, bio-based and recycled fibres is given in Table 2. The difference of mechanical properties is obvious.

Because of the varying mechanical properties of composites, comparisons based on constant volume and mass units are not an accurate approach for comparison in LCA studies. Furthermore, limited knowledge of in-service behaviour and service life of bio-based composites adds to the complexity. Therefore, even LCAs that incorporate initial material properties into analyses often do not take into account material degradation during service or region-specific influences. Hence, current knowledge gaps result in environmental comparisons with large levels of uncertainty or comparisons that do not consider durability of the studied materials.

Table 2 Exemplary comparison of tensile properties (strength and Young's modulus) of composites reinforced with synthetic, biological and recycled fibres. Data has been obtained from scientific literature and technical data sheets

Composite a)		Fibre content (wt%)	Tensile strength (MPa)	Young's modulus (GPa)	Comments b)	Source c)
Fibre	Matrix					
CF IM (UD)	EP	67 d)	2860	160	Prepreg	TDS Hexcel M21 [20]
CF HM (UD)	EP	67 d)	1000–1600	135–175		ACP composites [21]
CF HM (fabric)	EP	58 d)	350–600	70–85		ACP composites [21]
E-GF (UD)	EP	74 d)	1000	40		ACP composites [21]
E-GF (fabric)	EP	66 d)	440	25		ACP composites [21]
AF (fabric)	EP	53 d)	480	30		ACP composites [21]
rCF (Random non-woven)	EP	37 d)	207	25	Compression moulding	Shah2016 [22]
rCF (Random non-woven)	EP	37 d)	245/263	27/32	MD/CD	TDS ELG Carbiso M [23]
rCF (Aligned non-woven)	EP	52 d)	422	80	Prepreg	Shah2016 [22]
rCF (Aligned non-woven)	EP	29 d)	282	44	SMC	Shah2016 [22]
Flax (UD)	EP	65	330	35	Prepreg	TDS Lineo Flaxpreg [24]
Flax yarn (aligned)	PP	72	321	29	Filament winding	Pickering2016 [25]
Flax yarn (aligned)	EP	~31	160	15	Hand lay-up	Pickering2016 [25]
Flax yarn (aligned)	EP	45	133	28	Autoclave	Pickering2016 [25]
Flax (fabric)	EP	~50	104	10	Prepreg	Pickering2016 [25]
Flax (random)	PLLA	30	99	9	Film stacking	Pickering2016 [25]
Jute (fabric)	UP	35	50	8	RTM	Pickering2016 [25]
Ramie (fabric)	EP	~48	~120	~12	Hot compaction	Gu2014 [26]

a) CF=carbon fibre, GF=glass fibre, AF=aramid fibre, rCF=recycled carbon fibre, UD=unidirectional, EP=epoxy, PLLA=poly(lactic acid), UP=unsaturated polyester; b) MD=machine direction (non-woven), CD=cross direction (non-woven), SMC=sheet moulding compound, RTM=resin transfer moulding; c) TDS=technical data sheet; d) calculated from given fibre volume content.

4.5 Environmental considerations of composites currently used in aviation

In nearly all data given related to LCA study, the grade of the assessed materials is not specified; therefore we are prone to assume that assessments are made for the most widespread material (i.e. automotive, leisure and sports goods). Another assumption is that aeronautics is taking the top grade for its specific and high requirements applications. Therefore LCA results, including those in database, could be underestimated.

The main outputs found in published LCA type study are greenhouse gas (GHG) or energy intensity. Energy intensity is equivalent to cumulative energy demand (CED) corresponding to primary energy. GHG and CED are close together as a major part of GHG comes from the energy needed to achieve the desired product, process or services through the grid mix specific to each country or area.

For carbon fibre most papers are referring to Japanese data from the Japan Carbon Fibre Manufacturer Association (JCMA) and the results have been updated twice since 1999 (Table 3), but we have been unable to track what hypotheses were used to perform this assessment.

Table 3 Standard grade PAN based carbon fibre [27]

	Energy (MJ/kg)	GHG (kg CO_{2eq}/kg)
First data 1999	478.5	29.7
Recalculated 2004	285.9	20.5
Recalculated 2009	286	22.4

Song et al. [28] displayed the energy intensity of various resins and fibres, or material as well as energy intensities of manufacturing processes. Suzuki and Takahashi [29] took CF data again from JCMA, but for CFRP in aeronautics they referred to a range with autoclave moulding at more than 600 MJ/kg, a lower range is not mentioned. This document gave also the energy intensity of resins, prepreg manufacturing and moulding methods. Michaud [30] mentioned also the same figures as Suzuki and Takahashi [29] with an additional input regarding GHG for both carbon and glass fibres. It referred also to the HIVOVOMP project mentioning noticeably higher indicators than JMCA for CF [30,31]. Caution should be paid to this data, as they lack of background explanations.

GREET study [32] gave some assessment regarding E-glass production based on US DOE (US Department of Energy) data in 2002. Densley Tingley et al. [33] provided some data regarding phenolic foam as well as Moliner et al. [34] and Suzuki et al. [29] in an indirect manner. Plastics Europe database includes data for epoxy resin. No datum has been found for aramid or aramid paper. Dataset exists in Ecoinvent, ELCD for PAN based CF fibres only and GaBi database. The following tables give an overview on the data for materials found in databases (Table 4), data found in literature is listed for materials (Table 5), composites (Table 6) and manufacturing processes (Table 7).

4.6 Aviation use-phase in LCA

Use-phase in aviation consists of all flights and maintenance, repair and overhaul (MRO) of the aircraft (Figure 3). The requirement of a strict equality of weight, or even better a weight reduction, can be illustrated by LCAs performed on a whole aircraft. They show that the use-phase is of major

Table 4 Available data in database in LCA tools [34,35]

Material	Data set	Provider
GF	Glass fibre	Ecoinvent
	Continuous filament glass fibre	GaBi
CF	Polyacrylonitrile fibres (PAN)	ELCD
	Carbon fibre from PAN	GaBi
Epoxy	Bisphenol-A epoxy based vinyl ester resin	Ecoinvent
	Epoxy resin	GaBi
Phenolic	Phenolic resin	Ecoinvent

Table 5 Literature data for greenhouse gas emissions (GHG) and primary energy demand for materials used to produce composites

Material	Energy (MJ/kg)	GHG (kg CO_{2eq}/kg)	Source
Epoxy	76–80	–	Michaud 2016 [30]
	137	8.1	Plastics Europe
	76–137	4.7–8.1	Deng 2014 [36]
	76	–	Suzuki 2005 [29]
Phenolic	–	7.0 (foam)	Densley 2014 [33]
	33	–	Suzuki 2005 [29]
	102 (incl. composite manufacturing)	5.8	Moliner 2013 [34]
Carbon fibres	286 (186–360)	22.4	Michaud 2016 [30]
	1122	53 (std)	Verpoest 2014 [31]
	286–704	24.4–31	Deng 2014 [36]
	286 (JMCA 2004)	–	Suzuki 2005 [29]
	286 (JMCA 2009)	–	Zhang 2009 [27]
Glass fibres	45.6	2.5	Michaud 2016 [30]
	21.1	–	Dai 2015 [32]
	13-32	–	Song 2009 [28]
	45	2.6	Deng 2014 [36]
	10.3 glass fibres 30 (incl. comp manuf.)	1.6	Moliner 2013 [34]
Aramid paper	–	–	none

Table 6 Literature data for GHG and primary energy demand for final composites

Composite	Energy (MJ/kg)	GHG (kg CO_{2eq}/kg)	Source
CF/Epoxy	–	26.7	Michaud 2016 [30]
	–	34.5 (high T_G (ρ=1.52))	Verpoest 2014 [31]
	>600	–	Suzuki 2005 [29]
GF/phenolic	45.5 (manufacturing)	–	Moliner 2013 [34]

Table 7 Literature data for GHG and primary energy demand for composite processes

Manufacturing	Energy intensity (MJ/kg)	Source
Autoclave	21.9	Song 2009 [28]
Spray up	14.9	Song 2009 [28]
RTM	12.8	Song 2009 [28]
RTM (glass)	11.6	Dai 2015 [32]
LRI/VARI	10.2	Song 2009 [28]
Prepreg production	40.0	Song 2009 [28]
Prepreg (with glass fibre fabric)	3.9	Dai 2015 [32]
Glass fabric manufacturing	2.6	Song 2009 [28]

importance. The use-phase of an airplane includes fuel consumption including upstream phase and combustion. Energy consumption is directly related to greenhouse gas emissions (GHG). GHG indicator weights more than 75% for the use-phase [37–39]. Several studies are even closer to 95% to 99% for GHG [39–41]. The use-phase share depends on assumptions made and perimeter, but is still preeminent.

As on-board weight is proportionate to fuel consumption, any extra weight consecutive to alternative composite materials would inevitably reduce any benefit from bio-based resin or recycled fibres, at least regarding climate change, throughout the aircraft on its entire life-cycle.

5 Overview of LCA results for bio-based fibres, recycled carbon fibres and bio-resins

The following chapter gives an overview of results from published LCA on selected materials that are broadly considered to be ecological improved when compared to the currently used state-of-the-art materials in aviation: bio-sourced fibres (flax, ramie), recycled carbon fibres and bio-based thermoset polymers. These materials are the base-line for the developments in the ECO-COMPASS EU-China project.

5.1 Bio-based fibres

Natural fibres such as jute, hemp, ramie or flax are materials that are produced from renewable sources and with production techniques that typically have a lower energy demand than synthetic fibre production. They are perceived as sustainable materials since they are abundant, inexpensive, and biodegradable. The plant fibres have similar specific stiffness to E-glass fibre reinforcement and consequently they have recently received considerable interest for their potential use as substitution of conventional synthetic fibres in composites [42]. It is forecasted that by 2020 bio-based fibres will represent up to 28% of the total market of reinforcement materials [43]. Flax is the most widely used plant fibre for polymer reinforcement thanks to its exceptional good mechanical properties; in 2012 flax had a market share of 50% of the total volume of natural fibre composites in the European automotive sector [44]. Nonetheless, it was concluded that there still exist challenges to overcome in this field, including moisture stability, fibre-polymer interface compatibility, consistency of fibres and flammability. The fibres analysed in this paper are flax and ramie, since they are the two fibres used within ECO-COMPASS project.

Fourteen LCAs dealing with natural reinforcing fibres have been selected and reviewed [36,42–53]. Most of them compared natural fibres composites with synthetic fibres composites (such as GFRP) for the same applications to demonstrate the competence of the natural counterparts. One of the applications more studied through LCAs is the automotive industry. No published LCA on bio-fibres specifically for aviation applications have been identified.

LCA has been applied to a large range of natural fibre composites for assessing the environmental aspects and potential impacts. Most LCAs confirmed that the inclusion of natural fibres by replacing synthetic materials in composites can reduce environmental impacts of a composite [51–54]. These results in reduced dependence on non-renewable energy and material sources, lower pollutant emissions, lower greenhouse gas (GHG) emissions, enhanced energy recovery, and end of life biodegradability of components [55,56]. This trend is also maintained when analysing fully bio-based composites with varying natural fibre reinforcement in a biosynthesized polymer matrix [51]. However, results of Dissanayake suggested that flax fibres may require similar or higher energy due to the intense use of agrochemicals [46].

5.1.1 *Flax fibres*

Flax fibre was widely studied in LCAs [36,43,44,46–48,50]. LCAs comparing flax with glass fibres have shown that flax fibres have relevant environmental benefits. A cradle to gate LCA by Barth and Carus [44] quantified the carbon footprint of flax fibre production as 798 kg CO_{2eq}/t where the highest impacts come from the fertilizer production, followed by the field operations. Emissions from the fibre processing stage have the third highest release of GHG emissions. It represents a considerably lower impact than glass fibre production, which has an impact of 2.2 t CO_{2eq} per ton (Ecoinvent 3).

Some studies analysed the effect of flax fibre into thermoplastic composites. Le Duigou and Baley [50] found that for similar function, a 30% *w*/*w* flax fibre polypropylene (PP) composite is around 5.6% lighter than a GF/PP composite with similar fibre weight content. Flax/PP composites have an environmental impact −20% lower than glass/PP composites due to the fact that the production stage of flax fibres have lower environmental impacts compared to glass fibres. Furthermore the lighter flax/PP composites part has lower fuel consumption and emissions during the use phase. End-of-life management through incineration with energy recovery gives further advantages to flax/PP composites since flax fibres have a higher calorific value. Polypropylene composite reinforced with flax fibres decreased the environmental impacts by 10% for abiotic depletion and global warming, and up to 20% for acidification. Non-renewable energy used was also reduced by 12%; from 109.8 MJ/kg for GF/PP composite to 96.5 MJ/kg for flax/PP composite. Results showed that using an equal stiffness criterion flax/PP is environmentally more advantageous in the climate change category in comparison GF/PP composite [43]. Nevertheless, when a higher quantity of flax is used to reach the targeted samilar stiffness or strength, the environmental advantage of flax may be minor.

Other LCAs results confirm that flax mat-PP composites exhibit lower values for most environmental impact categories than its corresponding glass fibre based counterpart; up to 70% can be achieved. On the other hand, replacing the short GF-PP by short flax fibre-PP only results in modest environmental impact reductions in multiple impact categories, including the impact categories of climate change and fossil depletion where only reductions of around 10% are recorded [36].

Nevertheless, another comparative LCA from Duflou et al. [43] between flax fibre and glass fibre indicated that flax fibres had a limited replacement potential in structural components due to lower mechanical strength compared to GF. For applications targeting equal strength equivalence, flax fibres had higher environmental impacts, due to their relatively low tensile and bending strength properties. For compression moulded parts under bending load, results show environmental advantages for flax fibre reinforced composites. Nevertheless, for impact categories related to agricultural activities, such as land use and freshwater ecotoxicity, the impacts of flax fibre reinforced composites are typically higher in all cases [43].

5.1.2 *Ramie fibres*

Fewer LCA covering ramie fibres have been found. In a study by Carvalho et al. [42], ramie and jute were compared with the E-glass and carbon fibre reinforced epoxy composites (aluminium as conventional material is used as baseline) form an environmental, cost and technical performance point of view. The main contributing phase is the manufacturing phase and the differences between the alternatives in this phase are related with the cycle time. For a longer cycle time, more energy is required, which causes a higher environmental impact. The impacts are quite similar between the different composite materials with slight variations, whereas aluminium option presents a significantly higher value due to material production from primary sources, although in the end-of-life phase the aluminium has benefits from material recycling. Ramie is the best solution material from LCA perspective, with lower impact than jute, essentially due to the lower amount of material required. Results from LCA unique valuation are summarized in Table 8 [42].

5.1.3 *Raw materials, agriculture production*

Several stages are required to extract and refine fibres for textile production. This life cycle stage includes cultivation, retting, scutching, hackling, and transport between the field and extraction sites [50]. Retting is a (micro-) biological fibre separation process that can be conducted in several ways, classically including dew and water retting. Some recently developed processes were chemical, enzymatic or steam explosion [44]. Then usable fibres were extracted from dried stems during scutching, the mechanical separation of fibres from the woody core and bark. Scutching was followed by hackling, a process to remove impurities and residual sugars by combing them out [46]. Some gaps were usually reported within inventory of this raw material processing stage, which could be relevant for impact assessment results.

5.1.4 *Use stage—Lifespan considerations*

The material durability can change a material overall environmental profile, for this reason is important to integrate the expected in-service degradation of natural-fibre composites into environmental impact analyses. In some LCAs, the use of degradation models as a technique to predict the service-life of materials was incorporated in order to perform a complete LCA of natural fibre reinforced composites. Relevant differences on results for some composites with and without service-life considerations were identified. The differences in environmental impacts associated with the initially designed composite materials and the real volume of composite material needed to meet serviceability targets, stresses the importance of incorporating both life cycle impact and material

Table 8 Comparative LCA results for fibres materials [42]

Material	LCA (pt)
E-glass	0.25
CF T300	0.27
Ramie	0.21
Jute	0.26
Aluminium alloy	1.18

durability in composite design in order to avoid misleading design decisions [51]. In aviation applications, the effect of the final weight on the fuel consumption is a key aspect to be assessed in LCAs (see Chapter 4.6).

5.1.5 End-of-life

One relevant issue is to define the most sustainable end-of-life options for composites reinforced with bio-based fibres. Bensadoun et al. [45] investigated three end-of-life possibilities for flax fibre reinforced thermoplastics: chemical recycling, mechanical recycling and incineration. According to their results, although a chemical recycling technique is feasible and maintains the initial composite properties, it has negative environmental impacts due to its processing time, chemicals and equipment needed. On the other hand, the mechanically recycled composites with discontinuous short fibres involve a decrease in mechanical properties of about 75% compared to the initial composites. Nevertheless, this method has lower environmental impacts due to the speed and simplicity of the process. Finally, incineration with energy recovery could be a good alternative, since all the material can be fully combusted and they have a high calorific value (CP_{Flax}=19.46 MJ/kg) [50,53].

5.2 Recycled carbon fibres

As shown in Figure 1, a rising amount of structural parts of a modern aircraft is made of carbon fibre reinforced plastics (CFRP). On the other hand, Table 9 shows that on the global composite market just about 1.5 wt% of synthetic reinforcement fibres are carbon fibres [57]. CFRP with their huge potential for strong and lightweight structures and very good fatigue behaviour are especially interesting for the transport sector, where a weight reduction can lead to reduced energy consumption during the use-phase [58]. Therefore the demand for CF is expected to have double-digit growth rate in the next ten years [59]. As carbon fibres are very valuable, the question for sustainable waste treatments for an increasing amount of CFRP end-of-life (EOL) parts is getting more and more important. Therefore CFRP waste should be treated as a resource for new applications of carbon fibres. Potential cost savings of more than 20%–83% for cost and 82%–98% less energy consumption through CF recycling have been predicted by Carberry [60] in 2008.

Landfilling is currently the dominating practice of end-of-life treatment for fibre reinforced polymers (FRP) and European manufacturers have to pay a fee for waste disposal [61]. Therefore incineration is becoming an EOL treatment with lower cost but with high associated emissions [62]. Pressure from public and legislation to reduce environmental impact of waste is already high, for instance by the EU waste framework directive (2008/98/EC). The directive defines waste management with five stages of hierarchy (Figure 4). The most desirable situation is of course the prevention of waste while disposal (landfill and incineration without energy recovery) should be avoided as most plastics are relatively stable in landfills [63,64]. Disposal as least desirable step is followed by recovery (e.g. energy recovery by incineration). Recycling and re-use are considered as best variant for any kind of accruing waste. Recycling means a conversion of waste into a new substance or product while re-use could include the checking, repair or refurbishing of whole parts [61].

The waste treatment of FRP with their heterogeneous nature is difficult, especially in combination with cross-linked thermoset polymer systems used predominantly as matrix for composites in aviation [65]. Furthermore different types of fibre reinforcements and contamination with fillers, core materials, paints and metallic inserts are challenging for recycling. Another challenge is the identification, collection and separation of FRP waste before it can be introduced to the recycling process [66,67]. The most prominent recycling processes for FRP are pyrolysis, solvolysis and mechanical grinding, while fluidised bed and microwave heating are often mentioned as potential alternatives [61].

Although this review paper's main recycling topic is on CFRP, the recycling of GFRP is shortly summarized: GF being by far the most used reinforcement of FRP on the global market (Table 9), but there is only limited interest to reclaim glass fibres because they are comparatively inexpensive. Furthermore, the current recycling technologies for GFRP could cause serious fibre damage (e.g. 50%–90%) lost on GF strength for fluidized bed recycling [68], leading to limiting secondary applications for rGF. Besides the undesired and already restricted landfilling, today's main EOL solution for GFRP is therefore grinding with application as filler (glass fibres) and fuel (using the calorific value of the polymer) in the cement kiln route [22,66,69].

Despite having a much lower volume on the world market, the high value (Table 9) of carbon fibres makes them very interesting for recycling. It must be distinguished between production waste (dry fibres or prepreg from cutting and trimming) and EOL waste (cured composites). Several recycling routes for carbon fibres from CFRP EOL waste are under

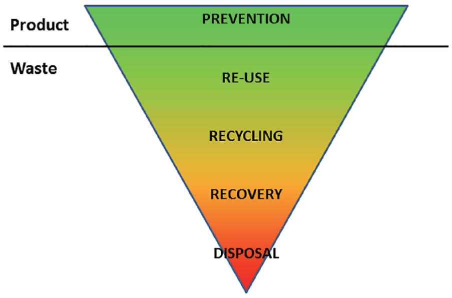

Figure 4 (Color online) Waste management hierarchy in the European Waste Framework Directive 2008/98/EC.

Table 9 Amount and value of global shipment of fibres used for composite manufacturing 2011 based on data from Guitérrez et al. [57]

	Shipment (10^3 T)	Shipment (Million €)	Average price (€/kg)
GF	2570	4720	1.80
AF	2	48	24.00
CF	39	912	24.00
Total	2611	5680	
CF%	1.49	16.06	

investigation and already industrially available on a small scale (Figure 5) [70,71]. For currently discussed recycling processes, the general quality of the recycled carbon fibres (rCF) is lower compared to virgin carbon fibres (vCF). A main reason is the discontinuous length due to a preceding shredding process [72]. Therefore the application of rCF is nowadays restricted to alternative use-cases with lower quality requirements [61,73]. Today, recycled carbon fibres are available in chopped, milled and pelletized form. Non-woven for composite production are under development and already available on the market [58,74,75].

In the present LCA review, seven papers containing LCA results dealing with recycled carbon fibres from CFRP waste have been considered. The main focus was laid on rCF from (commercial available) pyrolysis processes [62,67,76–79].

5.2.1 *LCA results for recycled carbon fibres from the pyrolysis of EOL waste*

Pyrolysis is a recycling technology with high maturity for CFRP waste and already found its way into commercial application in Europe (UK, Germany) [58]. Before the CFRP waste is fed in the pyrolysis chamber, EOL parts need to be reduced in size. During the thermal decomposition between 200 and 600°C [80], the polymer material vaporizes while leaving the fibres intact [58,72]. Of all recycling technologies for CFRP, it has the highest technology readiness level (TRL) level of 8. For comparison, most solvolysis processes are ranked to a TRL of just 3 [61].

A property comparison of rCF from pyrolysis with vCF has been carried out by Fischer and Schmid [81]. They concluded that the pyrolysis process can lead to incomplete removal of resin with residues on the fibres. Contrary, fibre damage with surface corrosion and crater formation is possible. Another important aspect of rCF from pyrolysis is the removal of fibre sizing, but recycling companies offer to reapply a suitable sizing to rCF [58]. These findings enhanced the importance of a comprehensive fibre characterization of rCF as support to identify the best remanufacturing processes and potential applications [67,81]. Tenacity tests have shown similar results compared to vCF for two of three tested rCF batches [81]. This confirms information given by the recycling industry on mechanical properties of rCF: typically a reduced tensile strength of 10% while the fibre stiffness remains unchanged [72].

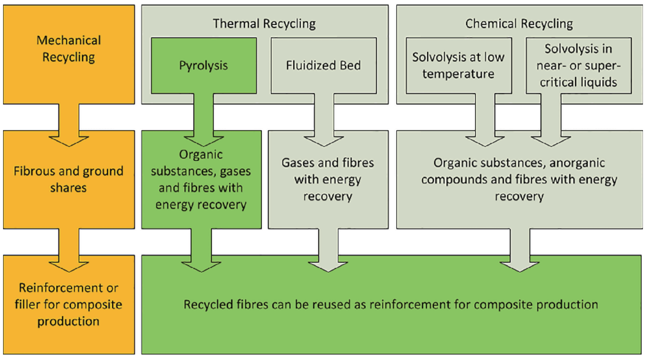

Figure 5 (Color online) Overview of recycling processes for thermoset composites [70].

Witik et al. [67] compared the environmental impacts of three EOL scenarios for CFRP: recycling (pyrolysis), energy recovery and disposal (landfilling). The use-case considered was a short fibre reinforced composite beam of equivalent stiffness reinforced with rCF to substitute GF (Case 1) respectively vCF (Case 2). An equivalent mechanical performance of rCF and vCF has been assumed. This assumption must be reconsidered for long fibre reinforced composites due to the adverse property changes of rCF compared to vCF. Data for the LCI of the rCF scenario have been obtained from a patent [80] and further assumptions as no data from industry was available. Post processing steps that could be necessary for the successful application of rCF have been omitted due to lack of data. Four environmental impact categories have been calculated: resources, climate change, human health and ecosystem [67].

Case 1: compared to landfilling as reference, the incineration scenario leads to lower impacts in three of the four categories while only climate change was increased. The replacement of GF by rCF has been calculated with higher impacts by rCF in the categories climate change, resources and human health. A detailed view on the climate change results shows that the pyrolysis process energy consumption and emissions are higher compared to virgin GF production emissions [67].

Case 2: the replacement of vCF by rCF in a short fibre reinforced composite beam shows clear environmental benefits. All four impact categories have been reduced from at least

65% (human health) up to 84% (resource) compared to landfilling as reference. The main reason for the reduced environmental impact of the rCF beam lies in the energy intensive production of vCF which emits about 54 kg CO_{2eq} in this calculation. When using rCF instead of vCF, these CO_2 equivalents could be reduced by 44.5 kg to 9.5 kg [67].

As the GF beam is heavier compared to the rCF respectively vCF reinforced beam, the use-phase in a passenger car has been considered to determine potential fuel saving with a factor of 0.35*l*/(100 kg×100 km) [82]. Calculated CO_2-equivalents over use distance showed a break-even point for the rCF beam compared to the GF variant at about 41000 km [67]. The much higher material related emissions from the vCF beam production are a malus that prevents a positive use-phase result for distances up to approximately 450000 km when compared to the variant with GF (Figure 6).

The data quality of the pyrolysis process was found to be uncertain. Therefore, a sensitivity analysis has been conducted. Initially, an energy consumption of 30 MJ/kg has been used for the calculation. Even by lowering the energy consumption to zero, the pyrolysis process has still higher environmental impacts compared to the GF variant. On the other hand, the pyrolysis energy demand could be increased up to 225 MJ/kg without exceeding the impacts of CFRP landfilling. A second sensitivity analysis by Witik et al. [67] compared different energy sources for vCF production to the European average energy mix as reference, where hydroelectric energy reduces the impact on climate change by 42%.

Another study on four CFRP recycling methods for composite carbody-shell of a tilting train has been carried out by Lee et al. [77]. Recycling processes are acid, pyrolysis in oxygen and nitrogen, organic solvents and a supercritical process. Of these recycling methods, only acid and pyrolysis passed technical performance criteria. For those, energy consumption and GHG emissions have been calculated. Energy consumption for pyrolysis was found to be approximately six times higher compared to acid while greenhouse gas emissions were five times higher [77]. Therewith the promising potential of alternative recycling methods, acid treatment in this case, has been shown.

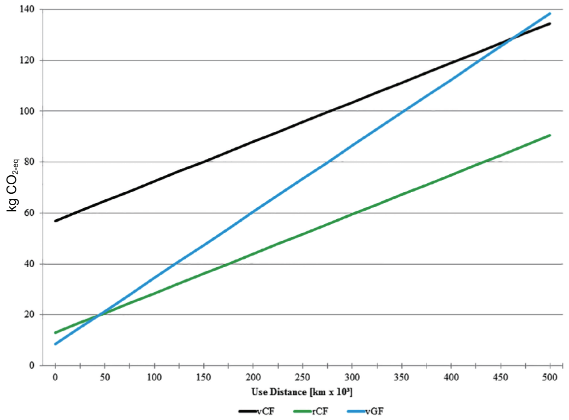

Figure 6 (Color online) Break even analysis for CO_{2eq} of a short fibre reinforced composite beam in a hypothetical automotive application. Graph based on ref. [67].

5.2.2 *Other CFRP recycling methods in LCA*

In their comprehensive review of composite recycling processes, Asmatulu et al. [71] summarized very limited available information on the energy consumption to 0.1–0.5 MJ/kg for grinding and 10–40 MJ/kg for a whole pyrolysis process. Furthermore they assessed structural recycling and concluded that such a way would be beneficial compared to the recycling of composites constituents only as it results in degraded fibres. Structural recycling is the re-use of composite products by cutting them into smaller-scale pieces for a secondary application. This recycling method is especially interesting for large EOL components from aircrafts or ships. Inevitable scrap from the cutting process could be introduced to other recycling processes.

La Rosa et al. [76] used cumulative energy demand (CED) to compare virgin to recycled carbon fibres in the production of a composite laminate. A novel epoxy resin with acetic chemical treatment to recover the CF is described in the paper. As no experimental data on the mechanical properties of recovered CF were available, La Rosa et al. hypothetically assumed that the rCF could be used in comparable products. Results to ten other environmental impact categories like eutrophication and global warming potential (GWP) have been presented according to the CML2000 method. Overall, rCF have less impact in all categories compared to vCF. Especially the impact on fresh water/marine aquatic ecotoxicity is reduced considerably according to the calculations. The fact that the recovered fibres needed further treatment to be useful was left out in the system boundary of the study. Nevertheless it could be shown that the avoided use of PAN to produce vCF leads to less environmental impacts. A study that uses LCA data gathered on plant level except on laboratory level is planned for the future.

Solvolysis with near or supercritical fluids as recycling technology for polymers is been extensively developed since the year 1995 [83]. Few studies on the recycling of CFRP have been conducted and they produce very clean rCF with properties similar to vCF. An initial LCA has been carried out by Princaud et al. [78] to compare the solvolysis based rCF with landfilling. A gain of averagely 80% for the eco-indicators by the "ReCipe Midpoint H" impact assessment method has been found. Climate change has been reduced by almost 100%, the reason is the use of the French energy mix with mainly nuclear energy for the calculations.

Howarth et al. [79] modelled the energy demand for mechanical recycling of CFRP with different panel thicknesses and processing rates. The energy intensity of a milling process has been calculated between 0.27 and 2.03 MJ/kg while the embodied energy of vCF is much higher with183–286 MJ/kg.

Li et al. [62] calculated the environmental impacts of landfilling, incineration with energy recovery and mechanical recycling of CFRP. Mechanical recycling by shredding and hammer milling results in fibrous and powdery recyclates for re-use. Greenhouse gas emissions, primary energy use and landfill waste generation have been found to be reduced by mechanical recycling. According to the authors, it is also one of the first studies calculating not only LCA but also Life Cycle Cost (LCC) data. They concluded that the high cost for the waste dismantling and recycling processes with strong degradation of fibre properties impedes industrial introduction mechanical recycling for CFRP.

5.3 Bio-based thermoset resins

Thermosets are polymeric materials which have interconnections between their chains generating covalent crosslinked three dimensional structures. Because of their thermal resistance, stability, and high strength and mechanical properties, thermosets are often chosen for demanding applications like aeronautics. However, all thermosetting composites used for aircraft applications (CFRP and GFRP) are obtained from fossil-source monomers. Moreover, they also show difficulties to be processed or recycled due to their crosslinked three dimensional structure. Epoxy and phenolic resins are the thermosets currently used in aeronautics sector. From this point of view, the aim of ECO-COMPASS project is to change some of the fossil-source monomers currently used by bio-sourced monomers which are able to polymerize generating thermosetting structures. These final thermosetting composites are expected to be more sustainable.

Despite steps having been made to reduce the environmental impact of producing composite materials by replacing glass fibre with natural fibre, it has been found that the most damaging component to the environment in GFRP composites is in the synthesis of the resin/matrix. These results suggested that alternative resins need to be used in order to reduce the environmental impact of composite production [84].

Nowadays, various renewable bio-sourced raw materials are used as feedstock for the bio-based thermoset market (natural oils, proteins, saccharides, glycerols and polyphenols such as lignin and tannin). These materials can be obtained from nature and they are abundant. The most promising bio-resins to be analysed for aviation application have been identified by ECO-COMPASS project as epoxy and furan resins. These thermosets materials are currently not covered widely by LCA, since LCA for bio-resins are usually focused on thermoplastics. LCA results about bio-based epoxy and furan resin that have been found in the literature are summarized in the following paragraphs.

5.3.1 Furan resins

Principal monomers used as building blocks for furan derivatives polymerization can be obtained from bio-sources such as sugarcane bagasse. Resins synthesised from these monomers could be applied in aeronautics sector, specifically for the fabrication of new thermosetting composite materials interior parts of aircrafts due to their good heat resistance properties. Moreover, some of them are usually used as a matrix in GFRP due to their good fibre-matrix adhesion.

Polyfurfuryl alcohol based resins (furan) is gaining attention as an alternative thermoset resin with reduced CO_2 emissions in comparison to the existing petrochemical-based systems. When combined with natural fibres like flax, furan resins offer the potential to produce a bio-derived sustainable composite with fire-resistant properties. However, the mechanical properties of furan flax and E-glass fibre laminates were found to have reduced mechanical performance in comparison to polyester and epoxy [85].

Aside from the use of renewable materials, one advantage of using furan resin as matrix is the additional CO_2 fixation by the polymer itself. For thermoset-based natural fibre reinforced polymers (NFRP), evaluation of carbon storage potential is vital in establishing their environmental impacts. The use of biosynthetic resin such as furan showed a substantial improvement to the NFRP's carbon storage potential with the increased utilization of bio-based carbon over fossil-based carbon [86].

5.3.2 Bio-based epoxy resins

Epoxy systems have been used for a long time in aircraft primary and secondary structures. Commercial epoxy resins are usually synthesized from building blocks obtained from petrochemical sources. Renewable natural sources, such as natural plant and tree oils, starches, cardanol, tannins, rosin and lignin derivatives are investigated as substituting building blocks for epoxy resins. These raw materials can easily be epoxidized to generate environmental friendly and low cost curable epoxy resins.

Few published LCA compare bio-based epoxy composites with conventional epoxy composites. A LCA comparing a sandwich made of bio-based epoxy resin and natural fibres with a conventional sandwich made of epoxy/glass-fibres has been found. The bio-epoxy studied was mainly made of bio-based materials from co-products or waste streams of other industrial processes (e.g. wood pulp and bio-fuels). Results showed that the use of a commercial plant based epoxy resin reduces the impacts in most impact categories in comparison with a petroleum based epoxy resin (Table 10). Moreover, biomass coming from coproducts or waste streams has further benefits since it significantly reduces carbon footprint and does not represent conflicts with food resources [87].

Table 10 Comparative impacts by one tonne of petroleum-based and bio-based epoxy composites [87]

Impact category	Unit	Petroleum-based epoxy	Bio-based epoxy
Abiotic depletion	kg Sb_{eq}	59.4	0.0
Global warming	kg CO_{2eq}	6693	4079
Ozone layer depletion	kg $CFC11_{eq}$	1.26×10^{-6}	0.00
Cumulative energy demand	MJ_{eq}	2.16	1.90

6 Conclusion

One way to reduce environmental impact especially for greenhouse gas emissions of transportation is lightweight design of structural and other components of an aircraft. High performance composites like CFRP for structural applications are energy intensive during their production phase but offer potential fuel savings during the life cycle of an aircraft because of their very good performance to weight ratio. GFRP are another class of composites with a wide application in aviation, for example in the interior. All these reinforcement fibres and also the resin systems (epoxy, phenolic) used today to produce composites for aviation have one thing in common: their synthetic origin. Bio-fibres like flax and ramie are a possible alternative to glass fibre reinforcements. But bio-based fibres and also resin systems have not yet found an application in aviation in considerable amounts.

The substitution of synthetic fibres and resin systems in composites with bio-based and recycled materials could be one of many approaches to reduce the environmental impact of aviation and other transport systems. The collaboration of Chinese and European partners in the project ECO-COMPASS aims to develop and assess promising composite technologies for their applicability in aviation interior and secondary structures. A comparison of the environmental impacts of these eco-materials is necessary to assess their advantages and challenges over the whole life-cycle from production to end-of-life.

This paper gives an overview on published LCA results for the selected eco-materials. The main focus was laid on bio-based fibres flax and ramie, recycled carbon fibres and bio-based thermoset resins. In addition, an overview of existing state-of-the-art composite materials used in aviation with their environmental aspects is given. For energy consumption and corresponding greenhouse gas emissions, the most important stage for the LCA of aviation is the use-phase because it is directly related to the weight. A gap of LCA dealing with bio-based and recycled materials with a use-case in aviation has been identified. Reliable data is generally limited leading to many assumptions during the life cycle inventory phase and subsequent uncertainties.

6.1 Bio-based fibres and thermoset resins

While literature on the properties of natural fibre reinforced composites is manifold, LCA results and especially data are available only in limited amounts. This review article shows that bio-based fibres have potential advantages over synthetic fibres regarding environmental impacts, especially due to the reduced energy consumption and global warming potential reduction from cradle-to-gate; from the production processes, during use in transport applications (thanks to a potentially lower weight) to the end-of-life. Most LCAs confirm that the use of natural fibres by replacing synthetic materials in composites can reduce the global environmental impacts of a composite.

Nevertheless, an important source of environmental impact of a composite comes from the matrix resin, for this reason it is important to develop more sustainable bio-based resins. Less environmental information is available for thermoset resins such as epoxy, which are the materials to be further investigated and developed in ECO-COMPASS project for aeronautics sector. Nevertheless, existing literature show potential environmental benefits from the substitution of petroleum based resins by both bio-based epoxy and furan resins in most environmental impact categories such as global warming potential.

Most available studies identified several data gaps when assessing these bio-based innovative materials, such as the agriculture and processing inventory data, the effect of the mechanical and functional properties, the durability, degradation and expected lifespan. All these parameters could influence the environmental profiles of the studied materials and the comparative analysis with the conventional counterparts.

6.2 Recycled carbon fibres

It can be anticipated that recycling of CFRP will be subjected to further regulation in the future. Therefore it is of high importance to set up a network for the use of recycled carbon fibres (rCF) in secondary applications. Significant for the success of recycling is the reintroduction of the recycled materials in a secondary product. Only in this case it is possible to gain environmental benefits by the potential avoidance of virgin material production and alternative waste treatments such as landfill. The reported properties of rCF from pyrolysis lead to the conclusion that they still offer similar mechanical properties compared to vCF. However, the designer has to respect constrains like limited length (chopped) and difficult processing properties due to their random, often called “fluffy”, appearance. In fact, they are downcycled.

The published LCA results show environmental advantages in the cradle-to-gate phase of rCF reinforced composites for specific cases. A hypothetical substitution of vCF by rCF (short fibres) shows clearly less environmental impacts but not for GF replacement. In an automotive use-case the break-even-point is reached after a relatively short time because of the reduced weight by rCF application. Again, this is emphasizing the importance of the use-phase for transportation cases. Generally, the importance of a mechanical equivalence when comparing different reinforcements must be ensured, a pure volume or mass based calculation is prone to errors.

As industrial scale recycling of FRP is just in the starting phase, future developments and the resulting quality of the recycled fibres need to be taken into account for correct LCA results. Furthermore an improvement of energy demand for the production of vCF is anticipated, for example by use of renewable precursors and energy. This could of course have negative impacts on other environmental impact categories and should be considered carefully in LCA.

7 Outlook

Life Cycle Assessments (LCA) on materials such as bio-composites have to deal with several challenges and data gaps. One of the most crucial phases of LCA is the goal and scope definition. For innovative composites, the functional unit and the scope of the study should be well defined. The net change depends on many processes throughout the life cycle of an envisaged application, including energy and mass flows as well as emissions and waste. Because composites are often potentially lighter than their traditional counterparts, it is important to compare their impacts on a functionally equivalent basis. Comparisons based on constant volume and mass do not allow an accurate analysis. Furthermore, service-life is rarely accounted due to the lack of knowledge of in-service behaviour of bio-based materials. Consequently, even studies that take into account initial material properties do not consider material degradation during service or region-specific influences. Current knowledge gaps related to deterioration properties for innovative materials result in comparisons with high level of uncertainty or even comparisons where durability is not consider at all. This evidence emphasizes the need to develop and apply material durability models in order to integrate these predictions into LCAs studies as proposed by Le Duigou [50] in 2014.

During the ECO-COMPASS project, the environmental impact of the developed eco-composites will be studied for selected use-cases for interior and secondary structures with a comparative LCA. Not only raw materials mentioned in this article need to be considered for the LCA but also the modifications of fibre, resin and the resulting composites need to be assessed for possible adverse effects on the environment. These modifications could be treatments for better mechanical properties like nano-cellulose, plasma or grafting of nano-particles to enhance fibre-matrix adhesion. Further examples are several types of flame retardants that need to be introduced to for the use of natural fibres in interior applications of an aircraft.

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