Composite Material Design for Aircrafts from Sustainable Lignocellulosic Fibers—A Review

Çiğdem Gül and Emine Dilara Kocak

Abstract Transportation vehicles include aircraft, automobiles, motorcycles, trucks, buses, trains, boats, ships, trams, etc. Composite materials are used extensively in this industry. Required properties for composite materials are good mechanical properties, biodegradability, renewability, abundance and low cost. Composites, which are the most important component of the aerospace industry, began to be used in aircraft in the 1950s. A lot of aircraft parts are made of synthetic fiber reinforced composites. The most commonly used fibers in synthetic fiber reinforced composites for aircrafts are glass, carbon and Kevlar. However, leading aircraft manufacturers have goals such as reducing aircraft weight, increasing fuel efficiency and minimizing the impact of manufactured products on climate change. Therefore, the composites produced for the cabinet are desired to be recyclable, flame retardant, strong, flexible, biodegradable and lightweight. Natural fibers are preferred as reinforced material instead of synthetic fibers because of low density, biodegradable, recyclable, non-abrasive, low cost and easy availability. For example, Airbus, the world's largest aircraft manufacturer, is working on the use of hemp, linen, kenaf and sisal fibers for manufacturing of the sidewall and ceiling panels, the insulation covers and the other aircraft interior components. It is considered to use natural fibers as a reinforcement element in composite materials to increase fire resistance, reduce smoke level and toxicity. In this study, information will be given about the latest developments in composite design from lignocellulosic fibers in aircrafts will be given.

Keywords Sustainability · Composites · Lignocellulosic fibers · Carbon footprint · Aircraft

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1 Introduction

The environmental issues are very serious for the future of human beings and the solution to those problems is one of the global goals. Synthetic production activities increase environmental problems. Greenhouse gases generated as a result of synthetic production activities absorb heat trapping it between the atmosphere and the earth and cause the temperature of the planet to rise. One of the most important reasons for the rapid increase of greenhouse gases for 150 years is human activities. The most important reason for greenhouse gas emissions in the United States; is the use of fossil fuels in electricity, heating and transportation. According to 2018 data, the largest part of greenhouse gases is generated by transportation sector. This sector involves 28.2% of all greenhouse gas emissions. In the transportation sector, greenhouse gases actually result from the use of fossil fuels in land (car, bus, truck, etc.), air (plane, helicopter, etc.) and sea (ship, etc.) vehicles [1]. According to the International Air Transport Association (IATA) and Air Transport Action Group data, all of the flights constituted 915 million tons of CO_2 gas in 2019, which is equivalent to 2% of CO_2 gas from human activities worldwide. All over the world, people have produced more than 43 billion tons of CO_2 gas [2]. The rapid rise of carbon dioxide gas in the atmosphere causes major disasters such as global climate change. In addition, excessively use of petroleum-based materials and the inability to dispose of non-degradable solid waste are other important problems. This has raised awareness of producing new biodegradable materials. Materials science has begun to follow a sustainable path since the end of the twentieth century due to growing environmental concerns. Sustainable, renewable, environmentally friendly materials are called "green materials, green chemistry." Green chemistry is the design of chemical products and processes that reduce or eliminate the use or production of hazardous substances [3]. Green composites have attracted great attention from both academia and industrial sectors due to the need for new environmentally friendly products [4]. There is a growing research interest in bio-based products due to the rapid consumption of natural sources and synthetic production activities that are responsible for environmental pollution. The Food and Agriculture Organization (FAO) of United Nations, or the Common Fund for Commodities (CFC), has foreseen the use of plant-based materials for leaving a clean environment to future generations and disposing of harmful chemicals; thus, the legislation on the use of natural materials and wastes has been adopted by governments in this context [5].

The decision of which material to choose must be taken during product design and this material must comply with the demands of the market, the legislation, cost and a sustainable environment [6]. Composites are the most promising material of this age. Composite materials are among those that play an important role in current and future aviation components. The composite is a new material that is formed by the combination of at least two or more different materials and is stronger than its components when combined. A great deal of aircraft parts is made of polymer composites that are reinforced with man-made fibers such as glass, carbon and

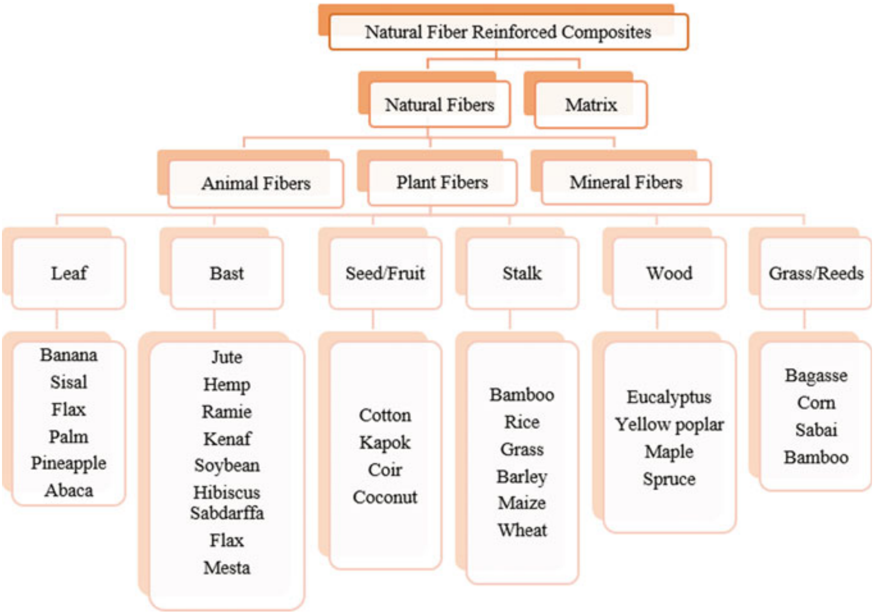

Fig. 1 Plant fibers types [7, 8]

kevlar. Composites consist of two parts as matrix and reinforcement element. Natural fibers are divided into three parts: animal fibers, vegetable fibers and mineral fibers. The diagram below shows the subcategories of plant fibers. In recent years, researches on plant fiber reinforced composites have been at the forefront of aviation (Fig. 1).

Synthetic fibers, which are reinforcement elements, are generally more resistant and harder than matrix materials [9]. The basic purpose of designing aircraft parts from composites is to minimize the aircraft weight as much as possible. Composites allow the design of more strength aircraft parts. Aircraft parts are subjected to too much compression and tensile rough out the distance from take-off to landing. Therefore, it is an advantage to have both strength and light parts and that stress enhances the safety rate [10]. Carbon fiber reinforced composites are an ideal material for manufacturing many parts of an aircraft, thanks to their lightness, strength and smooth surfaces. Using carbon fiber reinforced composite in the airframe allows it to be produced with less fuel saving, more aerodynamic and lighter parts [11]. Carbon fiber reinforced composites provide a better strength/weight ratio than metals and are more resistant to fatigue and corrosion [12]. Although synthetic fiber reinforced composites show good mechanical properties, thermal stability, corrosion and fatigue resistance, are not completely biodegradable in nature [13]. Figure 2 shows the proportion of composites used in the Airbus A350 XWB type aircraft.

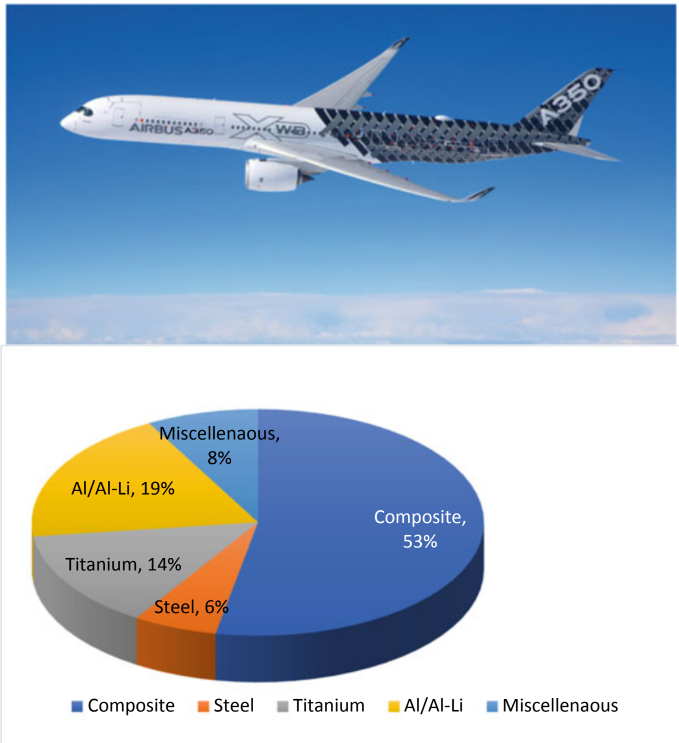

Fig. 2 Airbus A350 XWB (https://www.airbus.com/aircraft.html)

The use of composite materials in aircraft design is gradually increasing. The A350 XWB is the latest example of this upward slope. While aluminum material was used in aircraft in the early 70s, composites developed by the designers to reduce fuel costs facilitated the transition. Because composites weigh 20% less than aluminum and the reduction in weight also reduces fuel consumption. Composites consist of reinforcing elements and matrix parts. Using fibers or fabrics as reinforcement elements will provide strength and stiffness to composites [14].

Composites are widely used in some parts of modern aircraft such as rudder spoilers, air brakes, elevators, LG doors, engine covers, keel beam, rear bulkhead, wing beams, main wings, turbine engine fan blades, propeller and aircraft interior components [15]. These parts consist of glass fiber or carbon fiber reinforced composites. Aircraft parts are manufactured from carbon or glass fiber reinforced composites due to their superior strength-to-weight ratio and aerodynamic efficiency [14]. Although composites obtained with synthetic fibers show superior mechanical properties, they are disadvantageous due to some properties. Some toxic residues are formed during the production process of synthetic fibers. The fact that these wastes are not completely degraded in nature causes great environmental problems. To solve this problem, economical and environmentally friendly natural material with good mechanical properties is needed [16]. Natural fibers consist of cellulose, hemicellulose, lignin, pectin, wax. Although natural fibers have excellent properties compared to synthetic fibers such as biodegradability in nature, cheap, readily available and low density, the main limits of using natural fibers are low flame resistance and moisture absorption [6].

In this chapter, information will be given about the research on natural fibers in the design of aircraft components, the manufacturing processes of their components and their efficiency compared to synthetic fiber reinforced composites. Firstly, information will be given about the advantages and limitations of natural fiber reinforced composites, then the selection of the materials used in aircraft will be mentioned. In the next part, the applications of sustainable lignocellulosic fiber reinforced aircraft components will be explained, and in the last part, suggestions for contributing to future studies will be presented.

2 Advantages and Limits of Natural Fibers

2.1 Advantages

Specific properties: Cellulose-based natural fibers have a relatively low density, stiffness and strength.

Cost: Because many natural fibers are cheaper than synthetic fibers, natural fiber reinforced composites are also cheaper than synthetic fiber reinforced composites. In addition, due to the low density of natural fibers, the transportation cost of these fibers is lower than synthetic fibers [17].

Health: People who produce natural fiber reinforced composites have fewer health problems. Natural fibers do not cause skin irritation or lung cancer.

Biodegradability and environment: While natural fiber reinforced composites can be converted into environmentally harmless (biodegradable) and recyclable products, synthetic fiber reinforced composites cannot. Materials that cannot degrade in nature cause great environmental pollution. Non-degradable and accumulated wastes threaten the future of our planet and humanity. From an environmental point of view, natural biodegradable materials are more advantageous than synthetic materials.

2.2 Limits [18, 19]

Natural fibers are highly affected by the environmental conditions and these conditions determine the fiber properties. The environmental conditions that determine the fiber properties are the region and time of harvest, the nutrient and mineral properties of the soil, the amount of sunlight and rain.

Natural fibers have a strong affinity for water. So they have hydrophilic structures. However, synthetic fibers have a reverse situation, they have hydrophobic structures. The disadvantage of using plant fibers is that the fibers are not distributed homogeneously in the matrix, resulting in poor interfacial bonding.

When natural fibers are exposed to high humidity, their mechanical properties decrease.

Another disadvantage is that the processing temperature is below 200 °C. Above 200 °C, the fibers begin to degrade.

Lower strength, especially impact strength compared to synthetic fiber composites,

Less durability than synthetic fiber reinforced composites.

3 Sustainable Aircraft Interior: Material Selection

The aviation industry has focused on the development of sustainable, environmentally friendly aircraft interiors based on natural fibers. The use of natural fiber polymer composites in aircraft interiors increases fuel efficiency while reducing carbon footprint and weight. C.V. dos Santos et al. [20] prepared a guide for selecting and designing materials for use in executive aircraft interiors. According to Santosa material selection decision is usually taken stage product design. The chosen material should meet demands, cost reduction, legal regulations and sustainability of the environment. They emphasized that sustainable materials for the existing honeycomb panels are biopolymer composites reinforced with natural fibers and solid cores [20]. The aviation industry has taken a step forward in revolutionizing natural fiber aircraft panels. Linen, ramie, and hemp are used to create interior parts, especially for cabin services [21].

4 Sustainable Lignocellulosic Fiber Reinforced Aircraft Components

4.1 Radome Applications for Aircraft

Aircraft radomes are dome-formed structures that defend the radar antennas from aerodynamic loading (definition of how much weight the wing must lift per unit area), rigors of the weather and effects of bird strikes [13]. It is made of composite materials, usually from glass fiber (Fig. 3).

Glass fiber is widely used in composite material making for the aerospace industry due to its high strength, just like carbon fiber and Kevlar. However, these fibers are not biodegradable, so scientists started working on natural fibers. They have some superior properties compared to synthetic fibers, such as low density,

Fig. 3 Aircraft radome structure (https://www.aeronewstv.com/en/lifestyle/in-your-opinion/2985-what-is-a-radome.html)

Table 1 Mechanical properties of some fibers that are used in radomes [22]

Fiber	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Ref.
Kenaf	930	53	9.8	[25, 26]
Banana	392–677	20–24	5.9	[13, 27]
Bamboo	615–862	35.45	1.4	[13, 28]
Oil palm	50–400	1–9	8–18	[29]
Pineapple	170	34.5–82.5	1–3	[30]
E-glass	2,000–3,500	70	2.5–3	[13]
S-glass	4,570	86	2.8	[13]

low cost, renewable, abundant in nature and biodegradable. Because of these properties, the material has attracted the attention of scientists. Haris et al. [22] studied the properties of banana, bamboo, palm oil, kenaf and pineapple leaf fiber used in aircraft radome composites. At the end of the review, they mentioned that epoxy-hybrid kenaf (NaOH treated)-glass fibers can be used as potential materials for aircraft radome. Dielectric is crucial for aircraft radome selection. The dielectric constants of natural fibers range is between 2.8 and 3.2 [23]. Composites used for light aircraft radome have materials with low dielectric constant and high strength [24].

It is clear from Table 1 that the kenaf fiber has the best mechanical properties among other fibers. Kenaf fiber has similar hardness as glass fiber and low dielectric constant. As a result, kenaf fiber is suitable for radome in aircraft.

4.2 *Natural Fiber Reinforced Composites for Aircraft Wings and Wing Boxes*

The wing box is a major part of aircraft engineering to provide support and hardness to the wings. It can contain some supportive spars and chambers designed to isolate impacts. Spars are the main bearing element of the wings. There are one or two spars on the wing and join the body perpendicularly or with an angle. While in flight, intense shear stresses occur on the wings of the aircraft. Without sufficient support, the wings would fold up toward the side of the plane. The wing box absorbs some of this stress and distributes to the framework, preventing the wing of the aircraft from swinging or bending. It also helps to absorb the blows experienced during events such as turbulence.

The use of high-performance carbon fibers in aircraft reduces structural weight, but causes environmental problems as carbon fiber reinforced composites are non-renewable. Boegler et al. (2015) have designed a model of civil transport aircraft from natural fiber composites (Airbus A320-200). In this study, the potential of NFC in aircraft wings is emphasized. They compared the weight of the wing box made of ramie fiber reinforced composites with a reference wing box made of aluminum alloy. When using ramie fiber reinforced composites, the weight reduction was found to be around 12–14% [31].

The use of natural fibers in the production of the wing can reduce greenhouse gas production considering the CO_2 footprint. The carbon footprint of the natural fiber reinforced composite wing made of ramie fiber is 12,600–22,600 kg. Table 2 shows the airplane wing masses produced from various natural fiber reinforced composites. Hemp and flax fiber reinforced composites significantly increase the weight of aircraft wing box, while Ramie fiber reinforced composites reduce the wing box weight [31].

Kumar et al. (2018) analyzed the bending, buckling and vibration behavior of an airplane wing made of natural fiber reinforced composites. Compared to synthetic fibers, natural fiber reinforced composites are low cost, low density and weight, easily biodegradable and environmentally friendly. In this study, two different combinations have been investigated, the first is two layers of graphite epoxy at the top and bottom and between 16 layers are sisal, flax, or aloe Vera epoxy; and the other is the top and bottom 2 of the glass epoxy and 16 layers are sisal, flax, or aloe Vera epoxy. The composites used in aircraft wings are required to have less displacement value, high natural frequency and high buckling factor. When the results

Table 2 The effect of composites made of different materials on wingmass in comparison to aluminum reference [31]

Material	Mass m (kg)
Epoxy/Flax	11,355
Epoxy/Hemp	10,503
Epoxy/Sisal	–
Epoxy/Ramie	*7,576*
PLA/Flax	11,784
PLA/Hemp	10,815
PLA/Sisal	–
PLA/Ramie	7,758
Aluminum 7,000 (reference)	*8,829*

are examined, it can be seen that the flax-epoxy composite fulfils all the above conditions in both cases. Therefore, flax can be used as a reinforcement material in the structural design of small robotic aircraft [32].

4.3 Natural Fiber Reinforced Composites for Aircraft Cabin Interior

Nowadays, sustainability and “green” interiors are of increasing importance in the aviation industry, just as in the automotive and construction sector. A European project called “Cayley” brought together Boeing Research and Technology Europe, Invent GmbH, Aimplas and Lineo. The main goal of this project was to industrialize environmentally friendly interior panels made with renewable polymers or recyclable thermoplastic sheets and natural fibers, namely flax. Boeing Research and Technology Europe announced that it aims to develop a bio composite sandwich panel that can be used for sidewalls inside its aircraft. Throughout the project, Boeing manufactured a sidewall panel for a Boeing 737 aircraft made with the flax-thermoset composite. Lineo reports that the linen uni tape called FlaxTape and FlaxPreg linen/epoxy prepregs designed for transport interiors (cars, trains and aircraft interiors) are 35% lighter than carbon fiber/epoxy prepreg tapes [33, 34]. FlaxPreg T-UD consists of a series of prepreg materials based on thermosetting resin and a unidirectional flax fiber reinforcements (FlaxTape™) system. This material is suitable for many applications in aviation. FlaxPreg T-UD prepregs can be used in combination with glass or carbon prepreg to optimize the strength, comfort and mechanical and anti-vibration performance of composite parts [35] (Fig. 4).

It is thought that natural fiber reinforced composites, which are widely used in construction and automotive industry applications, can play an important role in the secondary structures of new-generation aircraft. The biggest advantages of using

Fig. 4 Long flax fibers in thermoset reinforced sandwich panel (https://www.castrocompositesshop.com/en/156-flax-epoxy)

natural fiber composites are environmental benefits, low energy consumption, lightness, insulation and sound absorption properties. The South African Council for Scientific and Industrial Research (CSIR) and international commercial aircraft manufacturer Airbus have been working on developing composites from natural fibers and phenolic matrices for use as commercial panels for cabin interiors. The main purpose of this research is the use of natural fibers such as linen, hemp and hemp in the production of aircraft interior components such as ceiling and side wall panels and insulation covers. The Airbus team is looking for a strong, flame retardant, flexible, lightweight and biodegradable natural fiber for the cabin interior. Natural fibers such as kenaf and sisal caught the attention of the Airbus team due to their low cost, biodegradability, low density and recyclability [13, 36].

ECO-COMPASS, an important project, aims to evaluate the potential applications of ecologically optimized composite materials in the aviation industry in an international collaboration with Chinese and European partners. In this project, bio-sourced and recycled materials for aircraft that can be converted into environmentally friendly composites were identified. The hollow structure of the specified plant fibers can provide benefits such as structural damping, noise reduction and thermal insulation desired for the interior structure of the aircraft. In the future, the composite materials identified and developed in this project could be aircraft interior panels, gear doors, winglets and other secondary structures. Preliminary results have shown that bio-based composites made from flax and ramie plant fibers have the potential to be used in natural fiber reinforced plastics for aviation. However, in order to compete with the currently used glass fiber reinforced plastics, their tensile strength and fire-retardant properties need to be improved in particular [37, 38].

4.4 Latest Developments in Aircraft Industry

Natural fiber reinforced composites are also used in the outer structure of the aircraft. Scarponi (2015) designed a Naca cowling made of woven hemp-reinforced epoxy composite. Environmentally friendly Hemp/epoxy composites are used in the production of Naca cowling for ultra-light aircraft. Engine cover produced using hemp/epoxy composites shows that it would be effective to produce aviation components from natural fibers [39].

The manufacturing and use of aircraft cause places with big environmental cost. For this reason, studies are carried out to minimize the carbon footprint formed. Producing sustainable aircraft is just one of these studies. The hemp airplane prototype by the Canadian company Hempearth is the first in the world and will soon make its first test flight. So, for which features is it preferred? Hemp fibers are ideal for building durable structures. Hemp material is used as a reinforcement element in the production of composite materials. Hemp fiber is increasingly being used as an alternative to glass fiber polymers, especially in the automotive industry. It was inevitable to work on the use of this fiber in the aviation industry. The plane

Fig. 5 Perfect conversion from hemp fiber to airplane (https://www.theeducationmagazine.com/education-now/hemp-plane-develop-stronger-steel/)

that is made of hemp is capable of carrying one pilot and four passengers. The wingspan of the plane is 36 feet. Hemp/Cannabis is one of the healthiest and most versatile herbs in the world. It is ten times stronger than steel. This property means that it can withstand much more weight and can break and bend much more than metal. So it has a great feature for the aviation industry [40, 41] (Fig. 5).

Composites made from natural fibers can be 25–30% stronger than those made from glass fibers. The addition of hemp fibers to glass fiber reinforced composites increases the tensile and flexural strength of the material (up to 30–35%). For example, composites made from hemp fibers used in car parts reduce weight. In addition, hemp fiber composites provide greater comfort to users as they absorb sound very well [42]. If hemp works in the automotive industry, why not aviation researchers decided to use this fiber for aircraft construction. Today's aircrafts are usually made of metal alloys and composites reinforced with glass fibers. Aircraft made of hemp that is as strong as glass fiber but does not cause environmental problems has provided a great advantage. Unlike many materials commonly used in aviation, hemp is non-toxic.

Expleo, Arkema, Cobratex, Specific Polymers, Cirimat, Compositadour, Lisa Aeronautics and Mécano ID formed a consortium to develop bio-sourced composites using long bamboo fibers. It was announced that this new material, called BAMCO (Bamboo long fiber reinforced bio-based Matrix Composites), could help reduce the environmental footprint of aircraft. As the glass/phenolic polymer composites currently used in aircraft will soon be affected by the European REACH regulation, there is an urgent need to develop alternative solutions. Expleo and CIRIMAT are working together on a bio-composite concept created using bamboo fiber to reinforce a bio-sourced thermoplastic matrix. It is a material that will replace glass/phenolic composites due to their very low weight, thermal resistance and mechanical properties (Fig. 6).

In the aviation industry, Bamco biocomposites can be used in cabin furnishings and cover panels and fuselage cladding panels and aircraft kitchen panels. Cirimat is responsible for the design and lab-scale production of thermoplastic or thermoset composites reinforced with bamboo fibers. Expleo will design the prototype

Fig. 6 Bamboo fibers are being used for bio-sourced composites for aerospace

components in this project. Arkema and Specific Polymers are responsible for the formulation of bio-sourced polymers used in composite matrices. Cobratex will research and recommend bamboo species. Mécano ID is responsible for conducting vibration-damping tests and modeling the behavior of bi-composites. Aircraft manufacturer Lisa Aeronautics will participate in the development of the prototype part. The first prototype parts are planned to be produced in 2021 [43].

5 Conclusion

Increasing environmental problems and efforts to overcome this make it inevitable to use natural fibers in future aircraft designs. Results regarding the use of ligno-cellulosic fibers in aircraft are as follows:

1. In aircraft, material selection should be determined during product design. The selected material should be environmentally friendly and biodegradable.
2. Kenaf fiber has superior mechanical properties among natural fibers. Kenaf fiber has similar hardness like glass fiber and low dielectric constant. As a result, kenaf fiber is suitable for radome applications.
3. Rami fiber reinforced composites significantly reduce wing box weight.
4. Flax fiber reinforced composites can be used in aircraft cabin interiors.
5. The hemp airplane prototype by the Canadian company Hempearth is the firs in the world and will soon make its first test flight.
6. Major commercial aircraft manufacturers such as Airbus and Boeing have begun research about producing various components of the aircraft using natural fibers.

The use of natural fiber reinforced composites in various aircraft components is expected to increase in the near future.

7. Expleo, Arkema, Cobratex, Specific Polymers, Cirimat, Compositadour, Lisa Aeronautics and Mécano ID formed a consortium to develop bio-sourced composites using long bamboo fibers. Bamco bio composites can be used in cabin furnishings and cover panels and fuselage cladding panels and aircraft kitchen panels.
8. The natural fibers such as kenaf, bamboo, coir, sisal have proved to be some materials with the high strength in aerospace application.

6 Proposal for the Future

In this review study, it is seen that natural fiber reinforced composites have a promising future in the production of light and environment-friendly aircrafts. The performance of plant fiber reinforced composites depends on the chemical composition and structure of the fiber, the angle of the microfibrils, its physical and mechanical properties, and the interaction of the fiber with the polymer. While natural fibers are hydrophilic, problems arise in composite production with hydrophobic polyethylene and polypropylene. The hydrophilicity of natural fibers affects the mechanical properties. Because, due to the high moisture retention of natural fibers in hydrophilic structure, poor adhesion occurs between the fiber and matrix. Modifications made on the surface of the fiber with alkali and other chemical treatments provide the improvement of adhesion and mechanical properties. When evaluated in terms of sustainability, the use of lignocellulosic plant wastes in the production of composite materials will contribute to the production of environmentally friendly materials. Cellulosic fibers can easily burn due to their nature. Another one of the studies carried out today is aimed at providing natural fibers with a non-flammable feature to be used in aircraft. They are nitrogenous and phosphorus compounds that increase the flame retardancy of cellulosic fibers. The addition of these compounds to the structure of cellulose will give the material flame retardant properties. However, instead of using flame retardant chemicals, it would be appropriate to use naturally occurring phosphorus compounds in order to provide non-flammability to composites obtained from natural materials.

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