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REVIEW PAPER

Advanced biopolymers for automobile and aviation engineering applications

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Abstract

Various petroleum-based polymers are being widely used in the automobile and aviation industries. However, the scarcity of petroleum-based polymers, their lack of biodegradability, and stringent environmental regulations lead researchers to look for green biopolymers/biocomposites as an alternative to petroleum-based polymers. Biopolymers have potential applications in various exterior and interior parts of an automobile, including steering, doors, wheels, electrical components, engine parts, exhaust systems, and so on. Almost all automakers are currently focusing on developing novel biopolymers, and they have successfully used bio-based materials in their newer version of automobiles, eventually replacing petroleum-based polymers. However, biopolymer uses in the aviation industry are not yet widespread because of stricter property requirements. Some advanced biopolymers are applied in interior aircraft panels, waste and drainage systems, engine components, cockpits, portholes, windshields, aircraft tires and inner tubes, exterior lighting, and helicopter windscreens. These materials are expected to substitute traditional plastics with the help of modifying agents, cutting-edge manufacturing technology, and a reliable supply chain of biopolymers. This review discusses the current practices, recent advances, and prospects of biopolymers in automotive and aviation engineering applications.

Keywords Automobile · Aviation · Biopolymers · Composites · High-performance polymers

Introduction

The current need for sustainability, environmental and social awareness, as well as the rapid rise in oil prices, have stimulated researchers to produce biopolymers that are environmentally viable throughout their entire service life (i.e., from manufacturing to disposal) [1, 2]. Biopolymers have many advantages over petroleum-based polymers, including reducing chemicals extracted from oil. Unlike conventional polymers, biopolymers and their composites have enhanced functionality, are renewable and biodegradable, and pose no environmental threats [3]. These materials also act as a carbon storehouse, limiting the amount of carbon in the atmosphere and thus reducing greenhouse gas [4, 5]. Biopolymers have a wide range of applications, especially in automobiles and aircraft [6]. High-performance biopolymer-derived substances have been incorporated in automotive parts such as seatbacks, door panels, dashboards, trunk liners, headliners, and other interior components [1, 7].

Nowadays, polymeric materials have become essential in many aircraft applications due to their high performance and ability to meet specific requirements. It is possible to

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produce such materials with high stiffness and low weight, resistance to most chemical corrosions, and long-term durability under harsh operating conditions. Polymeric materials with a reduced weight of 20–40% can provide high specific strength, making them more attractive than traditional metallic materials [8–15].

There is a constant desire for flexible and compatible materials for light spacecraft applications, including antennas, solar sails, sun shields, radar, rovers, reflect arrays, and solar concentrators. Therefore, polymer composites are used to make up to 80% of current spacecraft components used for satellite launches, such as honeycomb frameworks, cylinder support structures, component panels, antennas, solar array substrates, and so on. Recently invented micron-thickness films may aid in advancing certain spacecraft types, such as solar sails.

A significant reduction in cost savings (in commercial flights) and military capability (in modern warfare jets) occurs without synthetic polymer-based plastic materials. Interior components, structural elements, propulsion components, and navigational components can be produced from plastic products. Applying a relatively significant amount of plastics (about 12 wt%) in automobiles has made the automobile industry a major consumer of plastic materials. A typical car, for example, uses approximately 14 kg of plastics [16]. However, considering performance and cost over synthetic polymers, biopolymers can be distinctly advantageous in some cases. Furthermore, environmental consciousness has driven attention toward biopolymers and encouraged the replacement of synthetic polymers with biopolymers. The development of biopolymer materials in the last few decades has been immense and poses great potential. Specific needs in automobiles and aircraft can be met using biopolymer materials. Therefore, an overview of biopolymers is made in this review paper, particularly emphasizing applications of biopolymers in automobiles and aircraft.

Biopolymers

Biopolymers are polymeric biomolecules that are produced by living organisms. Due to their high mechanical properties, biopolymers and their derivatives have become attractive in industrial applications [2, 7]. The naturally synthesized biopolymer can be thermoplastic and thermoset, and they are increasingly replacing petroleum-based polymers due to their superior properties. Bio-thermoplastics are categorized into three groups depending on their origin and chemical process: agro-polymers, bio-polyesters, and microorganisms or modified bacteria-generated polymers. Agro-polymers are mainly polysaccharides that are extracted directly from biomass. A typical example of agro-polymers is thermoplastic starch. Biopolyesters are synthesized from biobased monomers, such as lactic acid from sugar fermentation, which is used to polymerize polylactic acid (PLA), while microorganisms can produce biopolymers such as polyhydroxyalkanoate.

Plant-based oils, including linseed, corn, and soybean, are primary sources of biobased thermosetting plastics. Plant-based proteins such as corn, soybean, and wheat can also be used to extract thermoset and thermoplastic biopolymers [17]. PLA is the most commonly utilized biopolymer in industrial applications due to its biodegradability and recyclability. Naturally occurring macromolecules such as sugars and starch are applied to produce polyesters through large-scale fermentation processes. Various hydrosoluble biopolymers such as gelatin, soy protein, starch, and casein form malleable thin layers when accurately plasticized. Durable composites can be made based on *triglycerides* with a combination of synthetic fibers (glass and carbon) and/or plant fibers (flax, jute, hemp, kenaf, and sisal) [18]. They can potentially be applied in various areas, such as farm equipment, construction, and automotive industries. Low-cost biobased polymers can reduce our reliance on petroleum-based polymers and offer eco-friendly products (e. g., pharmaceutical carriers, food coatings, food packaging, and water purifier). Many studies have been conducted worldwide to improve the acceptability of bio-based polymers in terms of performance, ease of manufacture, biodegradability, and cost-effectiveness [17].

Recent developments of biopolymers in automobile applications

It is not easy to use biopolymers in automobile parts since anything that goes into a car must meet the high-quality benchmark of durability and strength. In short, car parts have to be long-lasting [19]. So, a vital query prevails whether biopolymers can meet these stringent requirements. The promising biopolymers with high durability and strength for use in automobile components are discussed in the following section.

Polylactic acid (PLA)

Polylactic acid is a frequently employed biopolymer in various applications. PLA production is the second-highest of any bioplastic, typically referred to as thermoplastic starch [20]. Plant starch, mainly sugar cane or corn, is used to make PLA. PLA is biodegradable and has better mechanical properties and low production cost relative to widely-used thermoplastic (e.g., polypropylene (PP)) in terms of elongation, flexural strength, and tensile strength. PLA also has a higher density than acrylonitrile butadiene styrene (ABS) and PP [2]. The PLA-based composites offer excellent properties making them a desirable biobased polymer for various applications [21, 22].

Different compatibilizers can improve the crystallinity of the PLA and its thermal resistance. For example, the impact strength of PLA-based composite can be enhanced using elastomeric additives (e.g., ethylene vinyl acetate (EVA)). Toyota used this approach to improve the mechanical properties of PLA further. FIAT also mixed PLA with polycarbonate to improve performance and fulfill or surpass all production requirements. The biodegradable bamboo-PLA composites have been shown to be a potential alternative to E-glass/epoxy composites, wood-strengthened materials, and aluminum alloys. The currently engineered PLA dissolves in two months, and the longer molding time required for PLA during production causes a significant barrier to its implementation. However, this PLA can be used to make protective packaging materials for automotive production and shipping [2].

Bio-polyurethane foam (PUF)

The proportion of polyol content substituted by natural oil polyol (NOP) during manufacturing distinguishes regular polyurethane foam (PUF) from bio-polyurethane foam (bio-PUF). Regular PUF has many applications, including automobile seats, cushioning materials, and construction materials [23]. The PUF manufacturing hazards (which may cause lung damage, asthma, and other respiratory problems) can be minimized using NOP. NOPs are mainly produced from agricultural feedstock material-derived fatty acids or triacylglycerols, as well as palm oil, soybean oil, and castor oil. NOPs (except castor oil) are bonded with hydroxyl groups to cater to their need to react with polyisocyanate using a process based on the chemical structure of the vegetable oil.

Over two billion pounds of PUF are produced annually in North America for commercial uses such as carpet underlayment, aircraft, packaging, and bedding [24]. Seating (back and cushion), sun visors, headliners, headrest and armrests, door panels, and underlayment are examples of bio-PUF automotive applications. However, the PU seat foam properties are the most strictly specified of all the PUFs used in the car interior [2]. Notably, a reaction injection molding machine is primarily used to manufacture bio-PUF components for automotive applications.

Polyhydroxyalkanoate (PHA)

Polyhydroxyalkanoate has the potential to be used as a biodegradable and renewable polymer. It can be extracted from microbial or plant-originated sustainable carbon sources. PHA is capable of accumulating intercellular inclusion of bacteria. This natural polyester may also degrade in soil and water under aerobic and anaerobic environments, rendering it a natural substitute for conventional petroleum-based plastic. A large variety of PHA is available, and it can be polymerized from thousands of possible monomers depending on the required applications. Poly((R)-3-hydroxybutyrate) (P(3HB) or PHB) is the most commonly used form of PHA. The PHB monomer has a short carbon chain that can be copolymerized and customized throughout the manufacturing process. As a result, the mechanical properties of PHB can be similar to those of commonly used plastics (e.g., PP).

Numerous studies have been conducted to control the chemical and thermal properties of PHAs due to their enormous potential for high mechanical properties. Manipulating the molecular weight, chemical composition crystallization, and microstructure are some processes to control the properties of PHAs. The tensile strength and crystallization of PHB can be improved and controlled by drawing and introducing nucleating agents, respectively, whereas the impact strength of PHB can be significantly improved by adding plasticizers and rubbery agents [2, 17]. Blending PHAs with nanoparticles, fibers, miscible molecules, and copolymers can also enhance their properties. PHA synthesis refers to the enzymes used in PHA biosynthesis and is the subject of critical research for potential future large-scale development. Moreover, PHA is a recent addition to commercial biopolymer applications equivalent to PLA.

Bio-based polyamides and copolyamides

Bio-polyamides (PAs)

Bio-polyamides have recently attracted attention from various end-users due to their recyclability, electromechanical resistivity, ductility, and creep resistance. The inclination of vehicle manufacturers toward increasing fuel efficiency and weight reduction is the primary driver for expanding bio-PA use. Several high-end carmakers such as BMW, Maserati, and Mercedes-Benz are anticipated to drive the bio-polyamide market in Europe in the next few years [25]. In partnership with Dupont (Germany), DENSO, a leading Japanese motor vehicle components supplier, has introduced the automobile cooling water box made of bio-based polyamide (PA 610), which can be considered the first biobased technical component in the engine compartment. It is highly durable even in long-term exposure to high temperatures and corrosive chemicals [26]. Arkema has recently produced Rilsan HT, a plant-based PA, to replace metal in tubing for high-temperature auto applications. Around 70% of this material can be made from renewable non-food crop vegetable feedstocks. The material also exhibits significantly higher flexibility than polyphthalamide, with outstanding fitting insertion and thermoformability. Rilsan HT has the potential to be a viable alternative to the rubber and metal used in tubular applications in car engines because of its temperature-withstanding capability of up to 150 °C [27]. Peugeot and Volkswagen also have used components similar to Rilsan HT to replace the metal hoses found under their car hoods. Similarly, Royal DSM N. V. developed EcoPaXX, a castor oil-based PA with high heat-resistant capability. It also performs almost equivalent to its traditional petroleum-based counterpart when it contains more than 50% biobased material. EcoPaXX is usually applied in the car engine compartment [27].

Bio-polyphtalamides (PPAs)

Polyphthalamide is a semi-crystalline, aromatic PA. In general, PPAs perform better than aliphatic PA 6,6 and PA 6 [28]. Indeed, the ring structure in the PA backbone offers the polymer several benefits, including higher melting temperature and decreased moisture absorption and solvents. These advantages lead to improved hydrolysis and solvent resistance, enhanced warpage, better dimensional stability, improved creep and fatigue resistance, and higher strength and stiffness at elevated temperatures [29]. Bio-based PAs with 50–70% bio content are now commercially available, and their combination with glass-fiber composite applications include automobile powertrains, charging air ducts for automobile engines, connections and connecting components for use with fuel, as well as those in direct contact with cooling water. Emerging bio-based PAs are eco-friendly materials that have the potential to substitute petroleum-based PAs in automobile applications. Their plastics can replace metal parts, reducing overall vehicle weight, thus leading to fuel economy and lower CO_2 emissions [30].

Bio-polyether-block-amides (PEBAs)

Polyether-block-amides have backbone chains comprised of alternating hard and soft segments, and they are comparable to other elastomers, such as polyesters and PUs. The soft segments made of polyether diols exhibit good flexibility over various temperatures. In contrast, the PA-based hard segments, their chains are joined by strong hydrogen bonds, have high tensile strength, good friction, and abrasion behavior, as well as high heat and weathering resistance. Bio-based PEBAs are available that either use block polymers made of PA or both kinds of block polymers made of renewable feedstocks (e.g., castor and canola oil). Bio-based PEBAs, like their petrochemical counterparts, can substitute traditional elastomers in various applications, such as high-end automotive ones that need high chemical resistance and retention of mechanical properties in harsh environmental conditions [30].

Bio-polyolefins

Bio-polyethylene (PE)

A bio-based ethylene monomer, produced by Braskem using bio-ethanol from sugar cane, can be used to create bio-based PE [31]. The chemical, physical, and mechanical properties of bio-based PEs are intended to be identical to those of their petrochemical counterparts. Braskem has polymerized various LLDPE, HDPE, and UHMWPE grades wholly made from renewable materials. The PE applications, like its petrochemical counterparts, range from fuel tanks, air ducts, and filler pipes (mostly made of HDPE) to noise abetment tapes for dashboards (made of UHMW-PE for squeak and rattling abatement) [30].

Bio-polypropylene (PP)

Over the decades, petroleum-based PP has been widely employed in producing tough and lightweight body components of contemporary automobiles. However, the joint venture between "Braskem" and "Novozymes" accomplished a large-scale production of bio-PP, using sugarcane as the raw material for the resin. At the same time, "Mazda" produced renewable PP derived entirely from cellulosic biomass [32]. Another method of producing bio-PP from biological resources involves butylene dehydrating bio-isobutanol made from glucose and then polymerizing it. This Bio-PP is capable of replacing traditional petroleum-based PP in all currently used automotive components [13, 33]. Car interiors and exteriors that use bio-PP include bumpers and spoilers, body panels, boot spoilers, chemical tanks, door panels, dashboards and pockets in various designs, battery covers, seat covers, indoor and outdoor carpets, and air ducts for under-the-hood uses.

Bio-based polyesters and copolyesters – apart from PLA

Bio-poly trimethylene terephthalate (PTT)

The non-biodegradable aromatic polyester poly trimethylene terephthalate (PTT) is formed by polycondensing 1,3-propanediol (PDO) with either dimethyl terephthalate or terephthalic acid. Bio-based PTT was made feasible by bio-based PDO (derived from corn sugar). Like its petroleum-based counterpart, bio-based PTT offers good stiffness, strength, toughness, and polyethylene terephthalate (PET) heat resistance combined with PBT processability, as well as better surface gloss and appearance [34]. As a result, PPT resins are suitable for critical automotive electronics and electrical parts [35]. Bio-based PTT fibers provide stain and softness resistance required for automobile carpets and plastic and fabric components, whereas PTT fabrics are designed for seat coverings, headliners, and door trims. PTT has a less moisture content that enables drying fabrics quicker, thus lowering the likelihood of mildew and odor. PTT seat biofabrics were launched by Honda in their "FCX" model automobile, while Mitsubishi "i-MiEV" model, a car for testing electric fleets, employed PTT floor mats [30].

Polybutylene succinate (PBS)

Polybutylene succinate plastic biodegrades into CO_2 and water with the aid of soil microorganisms. PBS has a higher heat resistance and excellent processability as opposed to other biodegradable resins. It is compatible with fiber and other biodegradable plastics, including PLA. BioPBS™ and other biopolymers can meet consumer requirements for a wide variety of properties [36].

Cellulose

Cellulose is an excellent fiber and the most abundant natural polymer. Wood, cotton, and hemp rope are made of fibrous cellulose. Different properties of this fibrous cellulose are affected by natural degradation [37], and various processes are required to use them in automobiles. The cellulose nanofiber plastic materials can change the traditional role of steel in car manufacturing processes, and product prices will reduce by 50% by 2030 [38]. Researchers at Oregon State University have examined the use of microcrystalline cellulose to partially replace silica as a reinforcing filler in rubber tires [39]. They found that replacing some silica with cellulose fiber reduces the energy required to manufacture the tire. It is also possible to make cellulose-based products using almost any plant fiber, which has long been used as a buttress in rubber and automotive products, such as hoses, belts, and insulation.

Current status of biopolymers in the automobile industry

In general, over 136 kg of 100 different plastic grades is used in the exterior, interior, under the hood, and electrical applications of a car. The use of bioplastics can be extended to automobiles since a vehicle typically comprises approximately 10% plastic on average. Some automakers, including Toyota, Ford, and Mazda, have been pioneers in this area, and they are seriously utilizing renewable, bio-based plastics for their car parts to make eco-friendly cars [27]. Figure 1 shows various parts of an automobile made from bioplastics.

Ford

Ford has aimed to use natural materials for manufacturing automobile interior parts that can decompose at the end of their lifespan. This company has long been a visionary in green interior design. From early 1930 to 1940, Henry Ford started attempting to create bio-composites from soybeans to employ in car production. In 1937, Ford produced 300,00 gallons of soy oil for car enamels [41]. It also manufactured soybean resin and fiber-reinforced body panels in that period. These body panels are significantly tougher than steel when subjected to an ax impact [42]. In 1941, Ford unveiled the futuristic vehicle known as the "Soybean car" [43], as shown in Fig. 2. While the exact materials used in this car are still unknown, it is assumed to be constructed of soybeans, wheat, hemp, flax, and ramie [44] and weighs one-third the weight of a comparable-sized steel car.

Unfortunately, the significance of Ford's concept was not fully appreciated during that time due to the lower petroleum oil price. However, by the end of the twentieth century, the idea gained popularity due to the unstable price of petroleum, advanced manufacturing process, and increasing demand for eco-friendliness [1]. Following the concept, Ford launched its concept vehicle, "Model U" in 2003 (see Fig. 3) as a soybean car's successor. Model U concept vehicle uses hydrogen fuel instead of fossil fuel, and many of its parts are made of polyester textiles, soy-based seating foams, and soy-based paint.

Ford's soy-based PU foam is by far the most promising biopolymer application. It also successfully introduced soy-based PU bio-foams in the Ford Mustang vehicle, used in six different Ford models. The use of soy foam in the seats and 75% of headrests of over five million Ford vehicles on the road today reduce annual petroleum consumption by 5 million lbs and CO_2 emissions by 20 million lbs. Bio-based nylon 11 is used in fuel tubes and derived entirely from castor bean oil. This product is applied in 95% of Ford vehicles, decreasing petroleum consumption by approximately 1 million lbs/yr and CO_2 emissions by 1.1 million lbs/yr. The Ford Escape has a headliner made of soy. The European Ford Fiesta initiated the use of corn-based Goodyear tires in vehicles. Injection-molded wheat straw PP is another notable Ford invention. Ford is the first organization globally that successfully replaced glass fiber or mineral reinforcement with wheat straw fiber-reinforced thermoplastic polymer composites. These biocomposites were used in making an internal storage bin for the 2010 Ford Flex model, as shown in Fig. 4.

Currently, Ford aims at making composites that use shape-memory polymers and natural reinforcing materials such as hemp, flax, jute, kenaf, and corn-based PLA. However, Ford's challenge is to offset the traditional plastics with PLA due to its fully compostable nature [27].

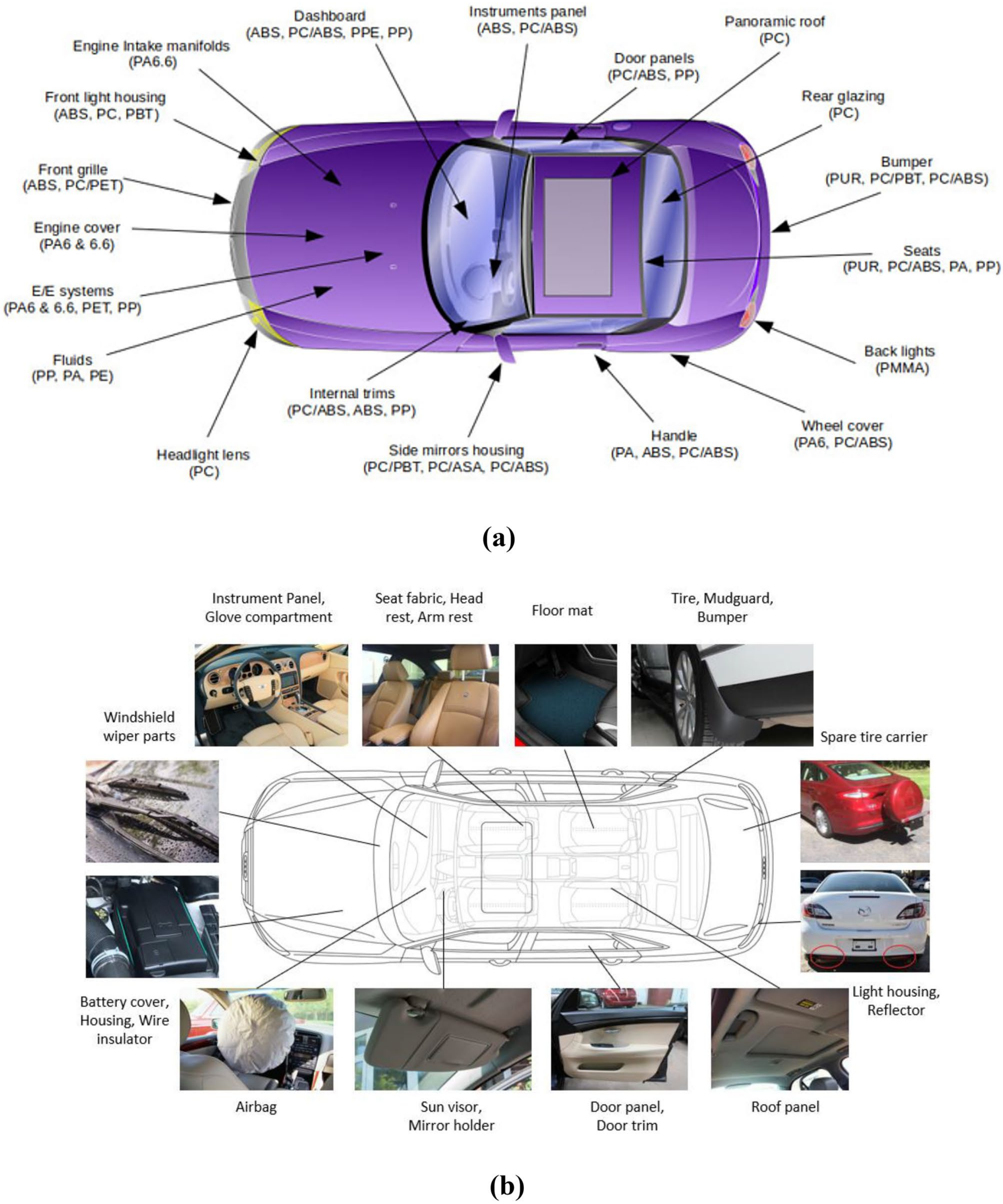

Fig. 1 **a** Bio-polymers for manufacturing different car parts [40] and **b** various components of a car manufactured using bioplastics

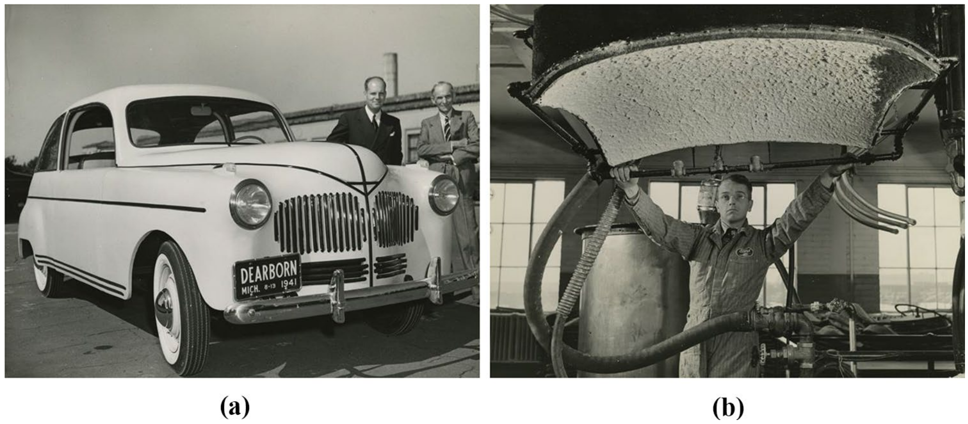

Fig. 2 **a** Ford experimental soybean car and **b** manufacturing of panel for soybean car [45]

Mazda

Mazda focuses on producing eco-friendly vehicles that are more fuel-efficient, emit less emissions, and utilize renewable fuels. It used biomaterials for the first time in 2011 for the Mazda Demio (overseas: Mazda 2), which featured a biomaterial-based radiator (Fig. 5a). Since then, Mazda has also introduced different biomaterial parts in its other vehicles. Mazda's breakthrough is a bio-based engineering plastic developed in 2014 that possesses a very high-quality finish and hence eliminates the need for paintwork. Since paint materials are derived from crude oil, removing the whole paintwork would significantly reduce the total carbon footprint. Later in 2017, Mazda further developed a new biomaterial that can be used for large and complex components such as the front grille [46]. Apart from these, Mazda launched the Premacy Hydrogen RE Hybrid vehicle in Japan, which featured the world's very first biofabric (i.e., biotech material) (see Fig. 5b) in its seat covers and door trims.

This biofabric is completely made up of PLA. It contains no additional petroleum-based materials and offers sufficient durability and quality for vehicle seat covers. Mazda acquired some technologies to control the molecular structure of raw resins to enhance fiber strength until it meets the benchmarks for abrasion resistance, strength, a lower degree of damage from sunlight, durability, and flame retardancy. These new technologies are likely to provide an excellent foundation for future bio-based materials to reduce the adverse environmental effect of non-renewable petroleum-based plastics [27, 48]. Mazda is currently attempting to make bioplastics from non-edible biomass such as plant garbage and wood chips. The aim is to develop multipurpose, environmentally sustainable plastics with significant strength, heat resistance, and endurance for vehicle instrument panels and bumpers.

Mitsubishi

In collaboration with Aichi Industrial Technology Institute, Mitsubishi manufactured a composite consisting of PBS and bamboo fibers to create green auto interiors. PBS is made from succinic acid (a result of corn/sugar cane fermentation) and 1,4-butanediol (a petrochemical).

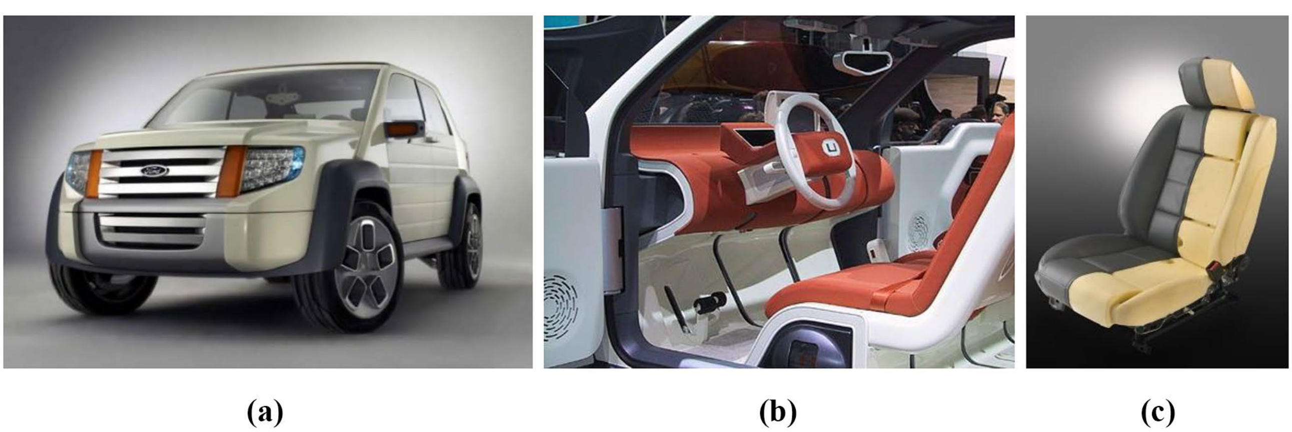

Fig. 3 **a** Model U concept vehicle, **b** model U concept vehicle interior design, and **c** soy-based PU seat used in the Ford Mustang vehicle [45]

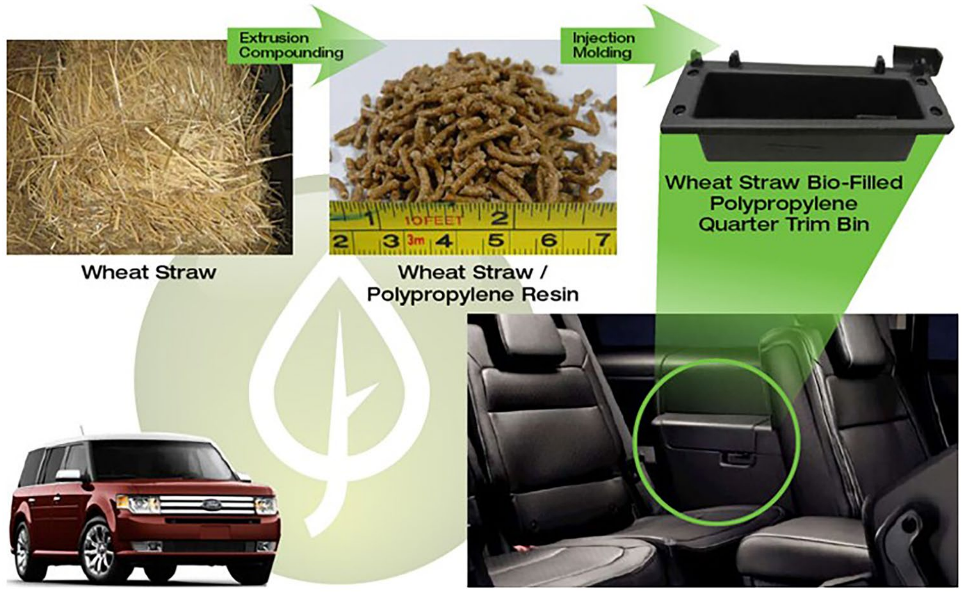

Fig. 4 Wheat straw-reinforced PP used in the 2010 Ford Flex model [28]

The fiber-reinforced composite exhibits high strength and rigidity [48]. In 2006, Mitsubishi announced to use PBS in the interior of its new mini car. Lifecycle tests showed that the PBS-bamboo fiber composites achieve a 50% cut in CO_2 emissions compared to PP. The levels of volatile organic compounds are also reduced by 85% over-processed wood hardboards [49]. In addition, Mitsubishi developed a new vehicle floormat using bio-PE produced from molasses and PP fiber [1].

Toyota

Toyota started producing biopolymers in 1999, and in 2003, Toyota launched a car (model: Toyota Raum 2003) with a reserve tire casing made of kenaf fiber and PLA. In 2008, Toyota reported a plan to supplant 20% of the polymers used in automobiles with biopolymers. It developed a floor mat that is entirely made of PLA. In addition, the sun visor, ceiling surface skin, and pillar garnish on Toyota's SAI model consist of Dupont's Sorona EP, a partly renewable polymer. Biopolymer-reinforced bamboo and kenaf fibers are used in the Lexus models of Toyota for internal components such as package shelves, luggage compartments, and floor carpeting. In 2011, Toyota launched a novel Lexus CT200h hybrid-electric compact car, which featured a luggage compartment lining composed of newly created bio-based PET derived from sugar cane [1], as illustrated in Fig. 6. Biocomposites are also used in the radiator end tank of the Toyota Camry Sedan. This component was manufactured from a 30% short glass fiber-reinforced Dupont's Zytel RS

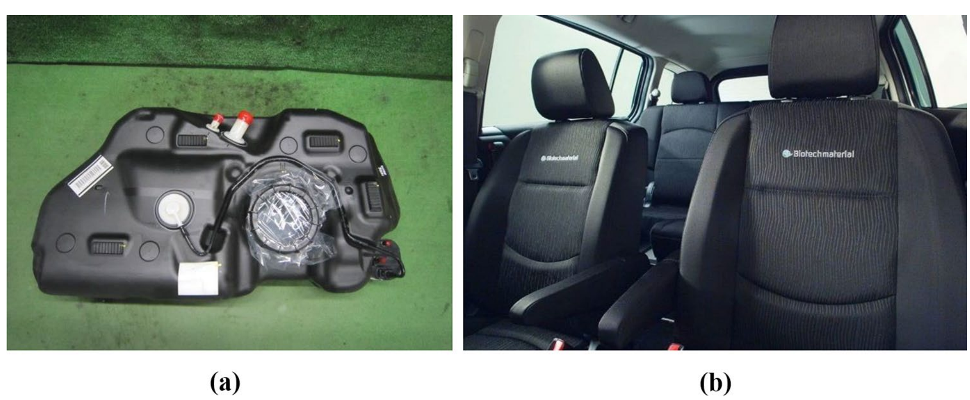

Fig. 5 **a** Mazda Demio fuel tank and **b** bio fabric used in the Premacy Hydrogen RE Hybrid vehicle [47]

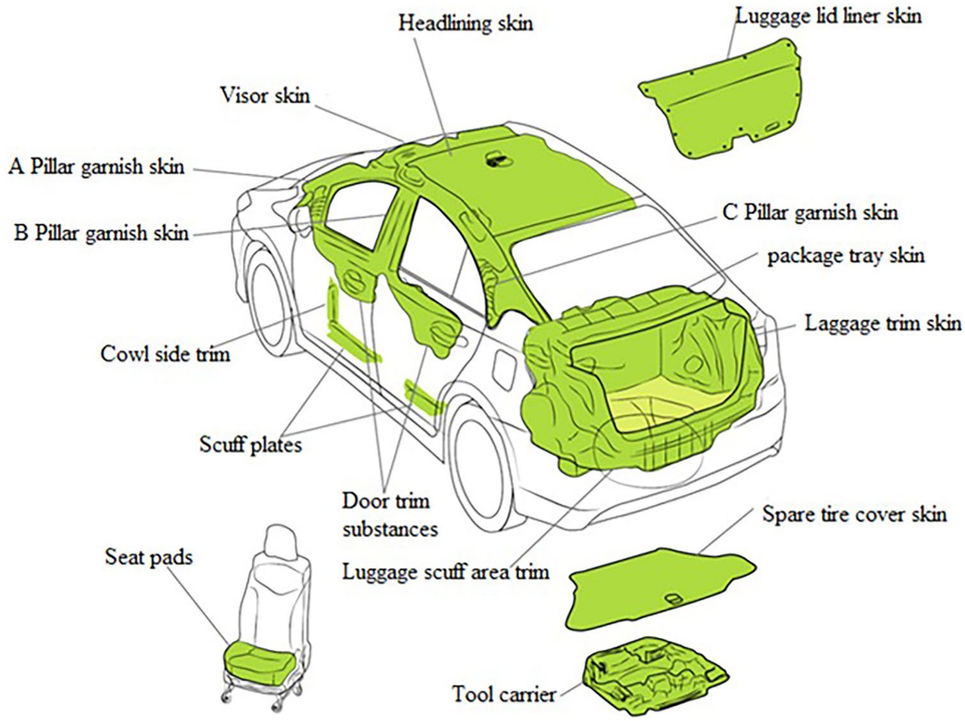

Fig. 6 Bio-based polymers used on different parts of the Lexus CT200h [50]

PA 1010 matrix using injection molding. About 40% of resin-biobased monomers are derived from castor beans [16]. Toyota Central Research and Development discloses the use of PLA composite as a surface component for automobile interiors, containing a plurality of PLA with different amounts of carbodiimide compounds bonded by thermo-compression using a solvent. Examples of this include ceiling material, package tray mounting, door trim, seat cover, floor mat, and trunk interior [16]. Toyota's Prius model, however, uses more eco-plastics in its structure by incorporating the PLA-PP blend in seven components, including the cowl side-trim board, front and rear door scuff plates, and rear-deck trim cover [26].

Fiat

In the European automotive industry, Fiat is a pioneer in applying bio-originated materials in manufacturing automobile parts. Fiat introduces PAs and PUs extracted from castor oil and soy, respectively, in some of their models to replace petroleum-derived plastics in vehicle components. Seat foams made of PU with a soy polyol content of around 5% are used in Fiat cars built for Brazil. This bio-foam is used in the armrests, headrests, and seats of various Fiat models such as Punto, Uno, Sadra, Idea Siena, and Palio [51]. Dupont's Zytel RS PA 1010 is also applied in diesel fuel supply lines. Furthermore, bio-based polymers are used in some parts of Fiat's Phylla solar car [52].

Honda

Honda introduced a bio-fabric in 2006 using bio-PTT and a corn-based replacement for 1,3-propanediol. The seat fabric of the 2010 Clarity FCX is composed of bio-fabrics. It also applied PLA for the roof, boot lining, and carpet, as well as PUR foams for the head and armrests.

Hyundai

Hyundai used PLA/PP composite and PA11 in the Blue-Will 2009 edition for interior trim, underhood engine cover, and headlamps. Interior trim made of PLA/PP composite is also used in the Elantra LPI Hybrid [2].

Goodyear

Goodyear developed tires from renewable sources using Bio-Isoprene™ technology; thereby, renewable biomass replaces petrochemically generated constituents in synthesized rubber production. Goodyear's Biotrend technology applies a bio-plastic (Mater-Bi) derived from starch to substitute carbon black. These tires use low energy in their production [38].

Mercedez Benz

German Federal Ministry of Education and Research centers have researched biobased PAs for automotive applications.

They envisage that new automotive components will be manufactured from biopolymers rather than high-performance plastics derived from fossil raw materials in the future. For the Mercedes Benz engine, an air filter is produced from PA 6,10 and 5,10. Moreover, other parts, including a cogwheel for the steering angle sensor, an accelerator pedal module, and a cooling fan, are tested and analyzed, in addition to the mass production of bio-PA-based components. In early 1994, Mercedez Benz introduced jute and renewable feedstock materials to manufacture door and door panels for its E-class sedan. It also started using flax fiber-reinforced polyester composites in the engine encapsulation of its several bus brands, such as Setra TopClass, EvoBus, and Travego, in 2000 [50]. Mercedes Benz applied abaca-banana fibers for the undercover panel and the spare tire cover, flax for the seatbacks, and castro for the engine cover in an A-class sedan. Biomaterials used in Mercedes Benz's E-class and S-class sedans are shown in Fig. 7.

In 2005, Mercedez Benz attempted to develop flexible tubing for brake and fuel systems using castor oil. Back cushions, seat bottoms, and head restraints are also produced from natural rubber (caoutchouc) and coconut fiber [38]. Additionally, Mercedes-Benz introduces bio-originated PP to manufacture engine/transmission casings for its Travego coach.

Volkswagen

Volkswagen developed a lightweight multipurpose crankshaft casing for its latest diesel engines using bio-PA 410 (EcopaXX). This bioplastic has superior toughness, a 70% renewable material content, a decreased weight due to low density, and outstanding performance at high temperatures [51].

BMW

BMW has used carbon fiber-reinforced plastics on a light aluminum chassis for the BMW i3 electric car. This car is featured for its lightweight and sustainability. Biopolymer derived from castor oil is the source material of the electric vehicle. The application of biopolymers in the automobile industry is summarized in Table 1, whereas Table 2 presents the mechanical and physical properties, estimated CO_2 footprint, and cost per kg of commercial polymers used in manufacturing automotive body parts.

Recent developments of biopolymers in aviation applications

Lightweight materials have recently drawn much attention in the aerospace industry to encounter the escalating expenses of aviation fuel. In aviation, fuel consumption accounts for around 50% of the operational cost. A bulkier system utilizes more fuel to elevate the aircraft, thus increasing the aggregated cost. In this regard, lightweight polymer materials can be very effective. Using polymeric materials in aviation can reduce weight by around 20%-40% while providing high specific mechanical properties (i.e., stiffness and strength). Though the commercial application of biopolymers in the aviation industry is not flourished yet, some recent advancements and thresholds are discussed in this section [48, 54, 55].

Biopolymers in aircraft interior panels

Interior sections of an aircraft must meet critical performance requirements as the parts have to provide dimensional

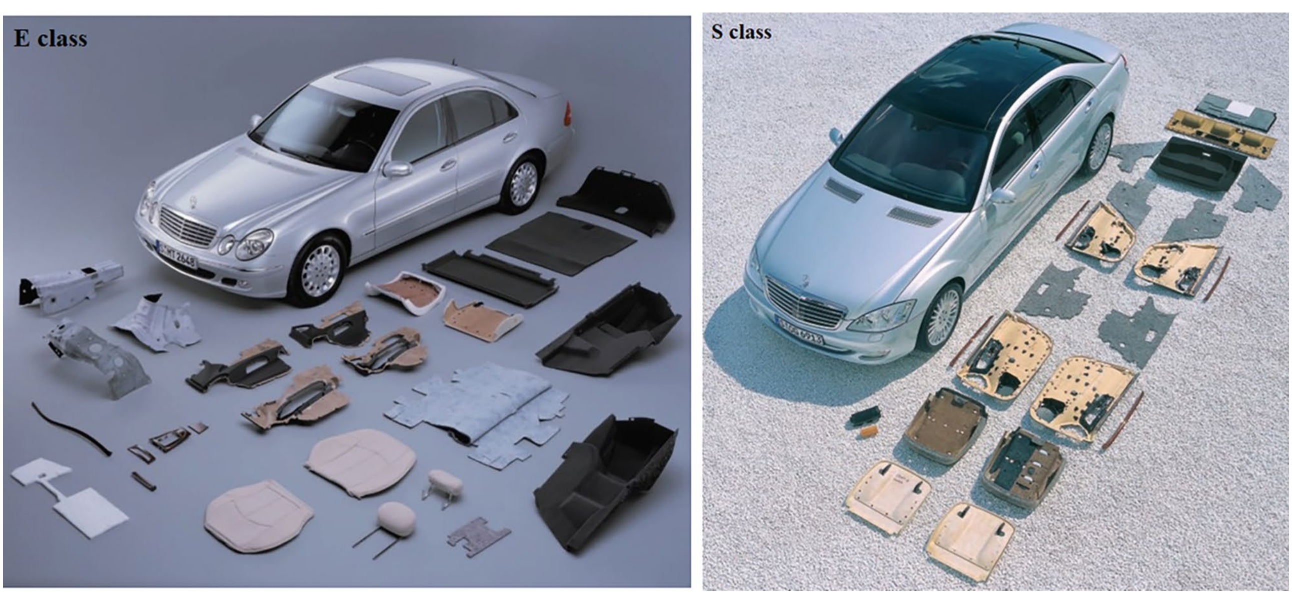

Fig. 7 Biomaterials in Mercedez Benz E-class and S-class sedans [50]

Table 1 Potential use of biopolymers in different automotive parts [52]

Biopolymers	Automobile parts		Automobile manufacturers
PLA, PBT, PBS, ABS, PHA, TPU, PCL, Bio-PU, Bio-PP, Bio-PET, and Bio-based polyester	Interiors	Carpet, seat cover, floor mats, door trim, door panel, instrument panel, ceiling material, sun visor, armrest, headrest, airbag, shock absorber, package tray mounting, sound insulation, and child seat	Beijing Automobile, Toyota, Mitsubishi, Hyundai, and Volkswagen
PLA, Bio-PC, and PHA	Exteriors	Bumper, side protection molding, mudguard, rear protector, spoiler, outer door handles, soft fascia hood, separable top, wiper parts, wind reflector, windshield washer, headlamp lens, mirror housing, nozzle, auto antenna parts, trim, lamp sockets, lamp reflectors, and lamp housing	Toyota, Mitsubishi, Hyundai, Volkswagen, and Mazda
PLA, PBS, PHA, Protein, Bio-PC, and Bio-PP	Door components	Water-resistant thin layer for vehicle doors, door panels, door pockets, door trim, pillar garnish, and privacy glass	Beijing Automobile, Mitsubishi, Mazda, and BMW
PLA, PCL, Bio-PP, and resin derived from castor oil	Electrical components	Electrical wire insulation, connector, lithium-ion secondary battery, battery casing, battery tray, battery cover, fuse cover, witches, and display unit	Nissan and Mazda
PPA and Bio-PA	Fuel and exhaust system	Exhaust gas recirculation system and fuel lines	Fiat
PPA, PLA, Bio-PP, Bio-PA, Bio-PET, and lignin	Engine, transmission, and radiator	Flexible tubing in the engine compartment, engine cover, engine splash shield, air filter housing, cooling fan, radiator end tank, air filter, brake disc core, casing swivel, and accelerator pedal module	Mercedes-Benz, Toyota, and Porsche
PLA, PCL, PBS, PVOH, Bio-rubber, cellulose acetate, and chitosan-cellulose-starch	Wheels	Tires, spare-tire carrier, cover, wheel cap, and tread pneumatic tire	Toyota, Goodyear, Ford, and Fiesta
Bio-PA, PA, PC, PBS, Bio-PP, and Bio-PA	Heating, ventilation, and air-conditioning	Air-filter, air guide element, ventilator and air-conditioner, fans, filter, case, vents, tubes, vent valves, air distributor, and air duct	Mercedes-Benz

PLA Polylactic acid, *PBT* Polybutylene terephthalate, *PBS* Polybutylene succinate, *ABS* Acrylonitrile butadiene-styrene, *PHA* Polyhydroxyalkanoate, *TPU* Thermoplastic polyurethane, *PCL* Polycaprolactone, *PU* Polyurethane, *PP* Polypropylene, *PET* Polyethylene terephthalate, *PC* Polycarbonate, *PPA* Polyphthalamides, *PA* Polyamide, *PVOH* Polyvinyl alcohol

Table 2 Mechanical and physical properties, estimated CO_2 footprint, and cost per kg of commercial polymers used in manufacturing automotive body parts [53]

	PP	PA	PMMA	ABS	PC	PU	PVC	PLA
Young's modulus (GPa)	0.896–1.55	2.62–3.2	2.24–2.8	1.1–2.9	2–2.44	1.31–2.07	2.14–4.14	3.55–3.75
Tensile strength (MPa)	27.6–41.4	90–165	48.3–79.6	28–55	60–72.4	31–62	40.7–65.1	65–70
Impact strength (J/m) at 24 °C	26.7–106.8	53.4–160.2	21.4–26.7	53.4–534	640.8–961.2	800	21.4–160.2	19–26
HDT (°C) load at 1.8 MPa	67	75	97	100	143	46–96	64	50–57
Density (g/cm^3)	0.89–0.91	1.12–1.14	1.16–1.22	1.1–1.2	1.14–1.21	1.12–1.24	1.3–1.58	1.25
CO_2 footprint (kg/kg)	2.6–2.8	5.5–5.6	3.4–3.8	3.3–3.6	5.4–5.9	4.6–5.3	2.2–2.6	< 1
Cost ($/kg)	1.2–1.3	3.3–3.6	2.6–2.8	2.1–2.5	3.7–4	4.1–5.6	0.93–1	~ 2

PMMA Polymethyl methacrylate, *PVC* Polyvinyl chloride, *HDT* Heat deflection temperature

stability, mechanical strength, and low smoke and heat produced during fire hazards while retaining the lowest possible aircraft weight for maximum efficiency. Lightweight materials in aircraft components can contribute to a greener environment by saving fuel and reducing greenhouse gas emissions. In response to these conditions, the Cayley project developed novel sustainable panels to substitute conventional ones free from harmful materials and address all mandatory technical property requirements concerning fire resistance and mechanical properties. Two such panels were developed using a renewable source-based organic resin (biopolymer panel) and a biodegradable polymer (PLA panel). The biopolymer resin matrix is processed from the polymerization of epoxidized acrylic acid (8 wt%) with linseed oil (90 wt%) in the presence of an initiator (2 wt%). PLA panel includes nanoparticles of graphene and nano-clay. These novel sustainable panels can save fuel during aircraft flight because of their relative lightness and lessened greenhouse gas emissions and other air pollutants. One square meter of the novel panels can reduce the emission of 6,000 kg of CO_2 equivalents. Moreover, the threat to maintaining a diversified ecological system, the safety of human health, and the availability of resources can be reduced by half relative to conventional panels [56, 57]. Recently, Airbus has signed a partnership with German biotech AMSilk to produce biocomposites based on spider silk that is expected to be lighter and stronger than currently used composites [58]. Boeing Research and Technology focused on using biomaterials for interior airplane components. Boeing applied biodegradable polymer or recyclable plastic with plant fiber (e.g., flax) for interior panels and is currently working on incorporating flax sandwich panels into the cabin interior [59].

Polyetheretherketone (PEEK)

Polyetheretherketone is an advanced biomaterial with a wide range of applications in aerospace. PEEK is a natural polymer of a semi-crystalline structure. It demonstrates superior mechanical and thermal properties, including low flammability, creep resistance, and high radiation-withstanding capability. It can also be subjected to high-pressure steam and water without the risk of deterioration. The PEEK's functioning temperature limit is about 450°F. This unique combination of properties, along with a wide operating temperature range, make it a preferable product choice in the aviation industry, especially in low-temperature and particulate-laden environments. In harsh ambient conditions, PEEK is a better substitute for fluoropolymers due to its high strength. The PEEK bears a V–O flammability rating and manifests very low toxic gas and smoke emissions when in contact with flame. Applications include aircraft interiors, wing ribs and panels, landing gear doors, valve seats, and pump gears. Again, the Ketron PEEK advanced material exhibits a unique combination of temperature resistance, high mechanical properties, and excellent chemical resistance, making it the most popular progressive plastics material. It is used in waste and drainage systems, as well as interior and engine components [60, 61].

Polymethyl methacrylate (PMMA)

Polymethyl methacrylate biopolymer has the potential to be a major market player in the aviation industry. It can be manufactured with many different functional properties and surfaces, including highly light-diffusing, light-transmitting, light-focusing, sight-screening, heat-resisting, heat-insulating, heat-reflecting, heat-shielding, scratch-resisting, and noise-reflecting. The PMMA sheets weigh only about half as much as glass and have more impact strength. Thus, it can be ideally used for the aircraft construction process. The material's machining and fabrication behavior are also useful. It is tough during handling and installation but can be routed, sawed, polished, and easy to form. Moreover, it is easy to maintain and highly suitable for long-term use. It forms no intensely toxic smoke gases and burns with almost no smoke, making it easy to find visible escape and rescue routes. During World War II, PMMA gained wide military aviation usage as an alternative to glass for aircraft windows. The PMMA sheets can be found on airplanes such as commercial, gliders, recreational, and military aircraft used in cockpits, portholes, windshields, exterior lighting, or helicopter windscreens [62].

Other applications of biopolymers in aviation

Many aircraft use natural rubber to make tires and inner tubes to reduce the certification cost for synthetic replacement [63]. For use in aircraft fuel storage tanks, polyglutamate (PGA) biopolymer has been developed and commercialized [64]. Aeronautics giant Airbus has the vision to introduce biomimicry for its future aircraft, as illustrated in Fig. 8. Instead of today's metal tube-shaped commercial aircraft, the Airbus concept plane features a bionic structure similar to a membrane, made of lightweight yet resistant biopolymers, and with many gaps that would ensure 360-degree views of the surroundings to the passengers [65].

Challenges and future prospects

For obtaining a foothold in the automotive industry, biopolymers must meet specific criteria of cost, property, production methodology, and continuous supply, in addition to the environmental benefits [48]. They must also compete with conventional plastics in the two major areas of performance and price. While biomaterials' progress is accelerating, they confront the harsh reality of insufficient production capacity, high prices, and a yet-to-develop infrastructure for composting, all of which negatively affect the growth curve. Biopolymer production is still inadequate to satisfy demand, and their prices cannot yet contend with petrochemical-based polymers [1]. The well-established petroleum-based polymer supply chain cannot successfully incorporate a biopolymer, significantly increasing its price. Petroleum-based polymers have widely been used

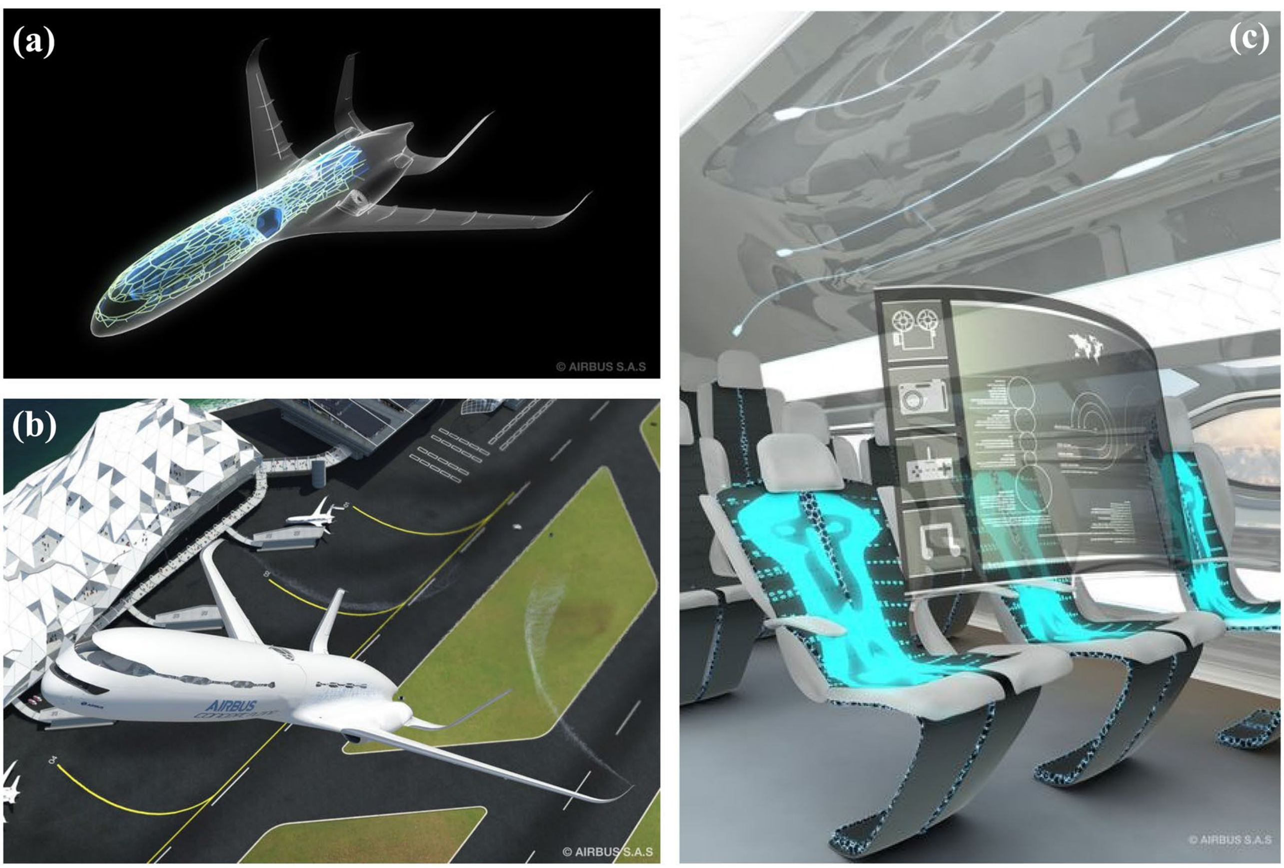

Fig. 8 Airbus's (**a**) membrane-like fuselage to mimic nature, (**b**) future aircraft, and (**c**) smart seat technology — the seat that understands you [65]

for years, resulting in highly effective manufacturing and supply chain challenging to compete. However, the cost of bio-based plastics has recently become less unstable than that of petroleum-based plastics. They are projected to get cheaper in the long run as technology advances, and demand scales up [27, 66]. Despite the fact that biopolymers are still constrained in meeting certain stringent requirements, new materials and modifying agents are expanding their uses and scope. More focus should be given to improving the thermal and mechanical properties of biopolymers to make them equivalent to more cost-effective basic materials. Innovative additives for enhanced endurance, reduced degradation, and fiber reinforcement can greatly expand biopolymer applications. It is reasonable to state that to begin as a commonly used and globally accepted eco-friendly product, there may be no better industry for bio-materials than the automotive industry. So, these environmentally benign and renewable materials are expected to gradually expand their applications in a wider range of industries, including the automotive industry [67, 68].

For more demanding property requirements, the prospective applications of biopolymers in aviation are minimal. Optimizing performance relating to durability and processing is a daunting task. However, progress in biopolymeric materials would continue to integrate with other emerging technologies to meet the aviation industry's precise requirements. Biopolymers can gain a stronger foothold in the aviation industry as the manufacturing technology for polymer materials improves. These advancements can result in enhanced biopolymeric materials for a wide range of applications, including ultra-light aerostructures or thin films, shape memory polymers for space vehicles, electrochromic polymers for thermo-optical applications, and electroactive polymers for space operations [69].

Conclusions

Introducing a new material, specifically biobased material, into the automotive and aviation industries is complex. However, bio-degradable materials can take precedence over those derived from non-renewable sources. The present status of PLA and other bio-based polymers in the automobile industry is just a single step toward the sustainable, eco-friendly automotive sector. Airlines are prone to acquiring the cheapest aircraft to offset high fuel costs and mounting demand to reduce ticket rates. With their lightweight, high-temperature capability, and corrosion resistance, plastic materials can be an excellent alternative to components conventionally made of rubber or metallic alloys. Plastic tails and wings are expected to be seen on aircraft in the coming decades. Reducing petroleum dependence is the major driving factor for the aviation industry to consider advanced eco-friendly polymeric materials. Given this, it can be inferred that advances in biopolymers and their composites can pave the way for the next generation of futuristic cars and beyond.

Declarations

Conflict of interest This is to confirm that there is no conflict of interest to disclose.

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