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Review

Lignocellulosic Biomass to Automotive Manufacturing: The Adoption of Bio-Based Materials and Bio-Fuels

Zhiping Zhang, Yinggang Jiao, Yameng Li, Huan Zhang, Quanguo Zhang, and Bing Hu *

Henan Agricultural University, Henan International Joint Laboratory of Biomass Energy and Nanomaterials, Zhengzhou 450002, PR China

* Correspondence: hubing535@163.com

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Abstract: In order to meet the demand of automobile lightweight and reduce the automotive industry's dependence on non-renewable energy sources such as petroleum, the utilization of bio-based materials and bio-fuels has become a key link to realize the sustainable development of automotive manufacturing industry. Moreover, along with the coming of the era of Carbon Neutral, the evolution of automotive manufacturing has begun. Hence, in the paper, the alternative solutions of the body materials, related component, and vehicle fuel in which bio-products can be introduced into were reviewed. The types and preparation methods for bio-based materials and bio-fuels were mentioned, especially the discussion of bio-hydrogen production and its application in the automotive industry. The summary of the correlation between biomass and automobile manufacturing industry in this article has certain guiding significance for the energy industry, automobile manufacturing industry and biomass energy utilization field.

Keywords: biomass-derived products; bio-based materials; bio-fuels; automotive manufacturing

1. Introduction

For a long time, the automotive industry has failed to include sustainable practices in its production cycle. Traditional assembly lines and manufacturing processes still use huge amount of energy, metals, plastics, toxins, and manpower, leading to a massive carbon footprint. Hence, in the era of Carbon Neutral, reworking and adopting new methods to ensure the lighter, cleaner, sustainability, and ideally cost-efficiency are required in the automotive industry. With the emphasis of greener and lighter, a paradigm shift towards to biomass derived products adoption is necessary [1]. There are many kinds of biomass derivatives, and they have various physical and chemical properties [2]. Considering the properties of biomass and biomass-derived products, they can be introduced into the petroleum-driven industry as direct replacement, such as bio-based materials and bio-fuels [3]. Bio-based mateirals can be introduced into the automotive industry by direct replacement (bio-based materials) and functional replacement (bio-products have similar function). For instance, high strength bio-based carbon fiber can replace metal, which makes it an attractive option for meeting the requirement of lightweight and sustainability in automotive manufacturing. Bio-based plastic can replace petroleum-based plastic considering its properties of biodegradable, and environmental friendliness. All the alternative attempts realize the reduction of vehicle weight, lower cost and meet the high demands of the market.

Besides the bio-based materials, bio-fuels are also found easily blend in with the existing automotive engines and provide sustainable performance. Hence, the adoption of bio-based materials and bio-fuels offers a strategic measure to mitigate the carbon emission pressure and opens a chance to valorize the waste biomass materials [4,5].

Although the application of biomass-derived products has been discussed for many years, there are few

articles that discuss bio-based materials and bio fuels that may be used in the automotive industry together, because of the large span between bio-based materials and bio fuels. Therefore, this paper will comprehensively discuss the situation of biomass-based derivatives widely used in the automotive industry in recent years, and systematically discuss the development of biohydrogen energy and its future development in the automotive field based on the research advantages of the author's team in the field of biological hydrogen production.

2. Benefits of Adoption of Biomass-Derived Products in Automotive Manufacturing

Automotive manufacturing is one of the global pillar industries, which has attracted significant investment and research and development worldwide [6]. With the rapid development of electric vehicle, China has turned to be the largest automotive market in production and sales. About 150 kg of plastic and 1160 kg of steel are consumed in the automotive manufactured parts, which contribute a significant factor towards air pollution, greenhouse gas emission, and increasing demand for fossil fuel [5,7]. In addition to the manufacturing process of the automotive vehicle, it also emits enormous quantities of harmful gas, such as carbon dioxide, carbon monoxide, hydrocarbons, and nitrogen oxides during drive. The result is that automotive industry sector is responsible for 60%–70% of global air pollution [8]. Therefore, it is important to find alternative materials and fuels to minimize their reliance on petrochemicals and petroleum-based products, and replace them with bio-based alternatives. Biomass-derived materials and fuels have the advantages of lightweight, no-toxic emission, and low greenhouse gas emission; hence, more and more concern are paid in bio-based products and their utilization in automotive manufacturing.

Biomass is the most widely distributed substance on Earth, and includes all animals, plants and microorganisms as well as many organic matters derived, excreted and metabolized from these living substances. Among all kinds of biomass, lignocellulosic biomass, such as agricultural waste and forestry waste, can be transformed into bio-based materials and bio-fuels as valuable products, which show great significance to achieve carbon neutrality and green circular economy [9]. Bio-based poly-hydroxy-alkanoates (BioPHA), bio-based poly-butylene-succinate (Bio-PBS), bio-based poly-ethylene-terephthalate (Bio-PET), bio-based poly-amide (Bio-PA), conductive material and poly amino acids are the common bio-based materials, and bio-based materials may compete with conventional materials currently. Hence, bio-based materials are the key point of modern automotive bio-manufacturing industry development, since they can be directly applied in the automotive or conduct partial replacement.

3. Common Types of Biomass Derived Products and the Preparation Technologies

Lignocellulosic biomass is a remarkable alternative substrate to be bio-refinery and an excellent substitute for material preparing because of the complicate structure and richness in cellulose, hemi-cellulose and lignin [10,11]. The main high-value-added products from lignocellulosic biomass include bio-materials and bio-fuels [10,12]. The usage of biomass-derived products leads to a greener and sustainable automotive manufacturing industry, and hence, the search for bio-based materials and bio-fuels has been an active topic. The utilization of bio-based materials plays an important role in reducing weight and has direct impact on energy utilization efficiency [13]. There are several typical bio-based materials that can be used in automotive manufacturing, such as bio-plastic, wood-plastic composites, biolubricants, lignin-based foam, bio-based carbon fibers, and bio-polymers. To obtain the mentioned bio-based materials above, bio-transformation, chemical synthesis modification, resinification and composite molding methods are the common technologies.

Besides bio-based materials, bio-fuels have also been found to have a great potential for the replacement of fossil fuel. Bio-fuels can be produced from diverse substrates, such as the edible food crop, non-edible agricultural residues and microorganisms. Considering the demand of sustainability and the rule of “Do not use the land that grow food, do not use substrate that can be eaten”, researches in China are all focused on the bio-fuels production from lignocellulosic biomass [14]. Bio-ethanol, bio-butanol and bio-diesel are the typical liquid bio-fuels, biogas and bio-hydrogen are the typical gaseous bio-fuels. Fermentation, gasification, pyrolysis, and reforming.

The survey at Web of Science on September 14, 2023, using the topic "bio-based materials, and bio fuels", noted 10,465 articles about bio-based materials and 23,508 articles about bio fuels, with about 2000 highly cited papers. The trends of the quantity of articles can be found in Figure 1.

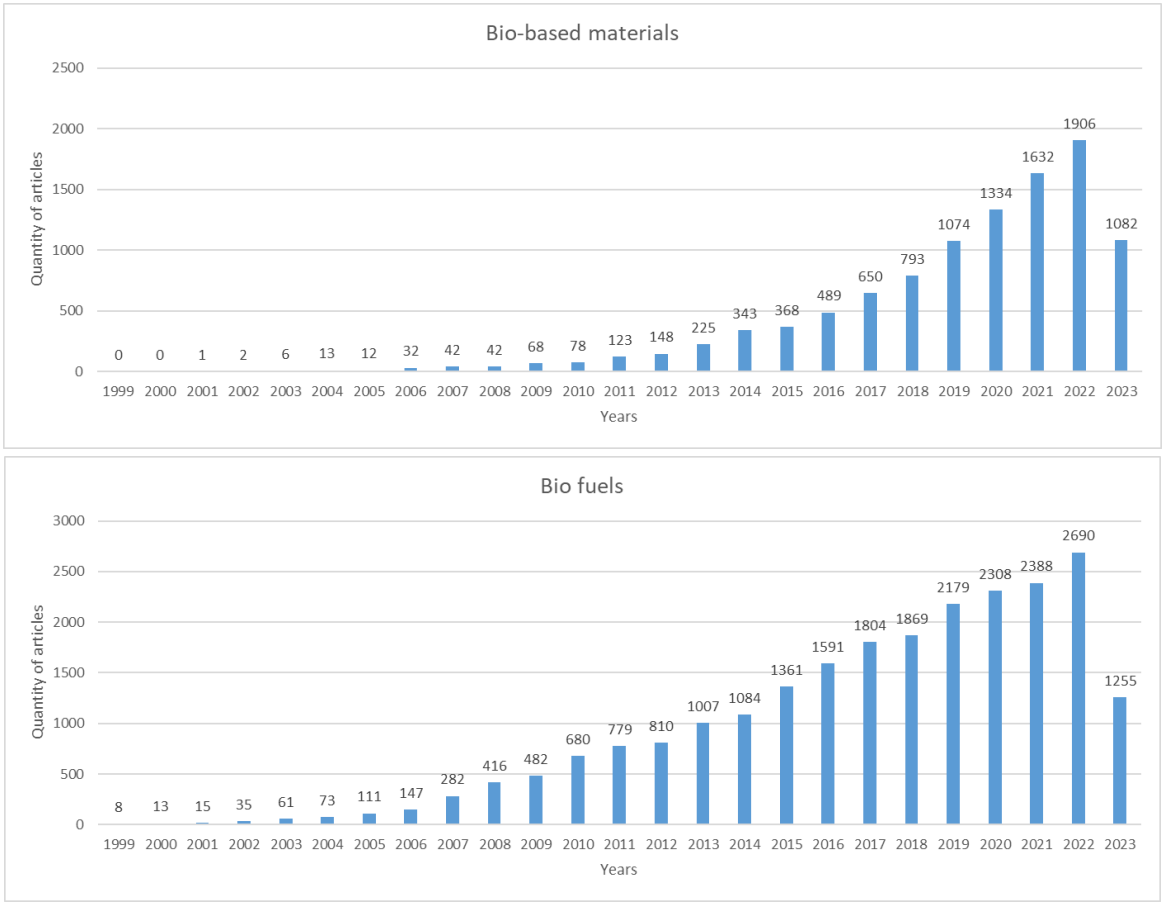

Figure 1. The trends of quantity of articles about bio-based materials and bio fuels.

From the data, it can be seen that in the past years since 1999, more and more researchers have been engaged in the research of bio fuels and bio-based materials. The number of related research papers published has also increased from less than 10 per year at the beginning to nearly 2000 and 3000 per year respectively at present, showing huge increase. The investment of more and more scientific research forces is strong evidence that these studies are currently hot spots.

When combining the searching scope of bio-based materials, bio fuels and automotive altogether, it can be seen that few literatures are found, with fewer comprehensive descriptions of bio-derived products applied in automotive manufacturing, especially the analyses containing bio-based materials and bio fuels together. It is found that the most typical representative of the transition from fossil- to bio-based materials is the utilization of bio-plastics [15], and the bio-ethanol is considered to be the first commercial alternative bio-fuels for replacing conventional fossil fuel resource [16]. Figure 2 shows the main topics discussed in this paper. Differing from the common opinion and considering the very hot research direction of hydrogen energy, in this paper, much concern was given to the bio-hydrogen. It is possible to provide a new way to explore the application of hydrogen energy in the field of automobile manufacturing.

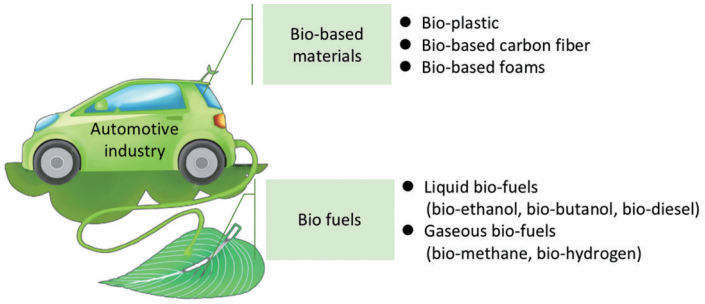

Figure 2. The scope of the topics discussed in this paper.

4. Materials Replacement of the Automotive Manufacturing by Bio-Based Materials

At present, bio-based materials are widely utilized in people's life and industry production for different purposes [17]. As listed above, bio-plastic, bio-based carbon fibers and lignin-based foams all can be applied in the automotive manufacturing for the reason of lightweight, low carbon emission, high mechanical strength, and sustainability. Take Ford as an example, Ford has been working on the use of biomaterials since the 1920s, when Henry Ford used wheat-grass in the Model T. Since then, soybean foam, seals, gaskets, castor foam, plastic, and natural fiber reinforced materials have been used by Ford and other automakers.

4.1. Bio-Plastic

Bio-plastic can be made from the lignocellulosic biomass, and showed better biodegradable property [18]. The annual output of bio-plastic has reached 2.1 million tons in 2020 [19]. Miller found that the use of metal accounts for 70%–75% of the total weight in automotive manufacturing, which encouraged researchers to find the replacement material which is lighter and greener [20]. Hence, bio-plastic gains more concern. Asia and Europe had the biggest bio-plastic markets [21]. Javaid and Gupta discussed the investment in the design and development of bio-plastic in the automotive manufacturing [22]. Naturally occurring fibers, such as hemp, soy, bio-poly amides and their composites, are most used bio-plastic in the automotive industry [23]. And almost all major automotive manufacturers use bio-plastic. Ford, Toyota, Lotus, Honda, Volvo and Audi are all planning to get rid of petroleum-based plastic in recent years, and mostly began with the replacement of door panels, headliner panel, seat backs [24–26].

Horacio reviewed the engineering, recyclable, and biodegradable plastics in the automotive industries, and found that there are several principles for bio-plastic selection according to the vehicle or component type [27]. For the section of processing and cost, it should be suitable for processing, optimal temperature and dwell time, have dimensional stability and water absorption. The cost should be lower during the raw materials and production. For the consideration of environmental friendliness and lightweight, it is better to have recycle ability, and lightweight. Moreover, it required high density and high fuel efficiency. For the products, it should have certain physical and mechanical properties, such as elasticity and stiffness, durability and flexibility, impact resistance, scratch resistance, heat resistance, odour and acoustic properties, corrosion resistance, and UV resistance. All these properties can be achieved by different preparing pathways. The mechanical properties change when the plastics are painted or blended, for instance, the lignin content has compatibility to meet the different requirement of tensile strength and tensile modulus with diverse load levels [28,29]. Maja and Ana also reviewed the challenges and opportunities of bio-plastic, especially focusing on the environmental advantages to the industry and consumers [30]. From the summary of Ryntz, the trends in alternative material development can be seen, which is from steel to plastic, and then to bio-plastic. For this sustainable development, the use of bio-plastic is a good investigation to cut our dependence on petroleum-based materials [31].

4.2. Bio-Based Carbon Fiber

Considering the compelling mechanical properties of carbon fiber, the U.S. Department of Energy's FreedomCAR program has made it the highest priority for material research in 2006 [32]. With the growing

demand for environmental protection and lightweight [1], and reducing the toxic emission, the usage of steel should be reduced. Replacement by carbon fiber is found to be an ideal choice with the same stiffness and modulus as steel. Carbon fiber can be prepared by controlled pyrolysis reaction with selected organic precursor [33]. Because of the high strength properties, it is suitable for reinforcement in automotive manufacturing.

BMW Group provides a good example of carbon fiber utilization in the automotive industry [34]. Carbon fiber is firstly utilized in less important components and then moving to the pressure tanks, especially carbon fiber reinforced polymer. Carbon fiber has the advantages of good surface and low weight; compared with the steel, carbon fiber has directional material properties and differs in fiber orientation. Several high-profile automotive applications are already in production, such as the front fenders, floor, rear deck lid inner structure in Corvette Z06, BMW 06, Fort GT, and etc. Recycled carbon fiber is utilized by BMW Group for the reinforcement of the C-pillar with sheet molding compound material and the roof of the BMW i3 [35]. Apart from BMW, carbon fiber can also be utilized by automotive industry as raw material for the manufacturing of the following parts: engine covers, anti-corrosion covers, fiber-reinforced plastic surfaces, interior parts, fiber-reinforced front and rear bumpers [36].

4.3. Bio-Based Foams

Due to the flexible structural form, open and closed cell, foams are adopted for making seats, bumper system, door panels, and coating in the automotive industry. Since open cell and closed cell displayed various properties, open cell foams are always applied for seating, while closed cell foams are utilized for interior coating, body making, and etc. [37]. Many kinds of foams existed all over the world, among them, the foams made from lignocellulosic biomass start to be the research hot spot for its sustainability and environmental friendliness. Lignocellulosic, especially lignin is made up of phenolic units that are chained together to form a giant polymeric structure, hence, it turned to be a potential substituent for the existing polyols [38]. Sonjui and Jiratumnukul studied the preparation process and physical properties of bio-based foams from bio-based succinate polyols. Results showed that the bio-based foam had smaller cell size, and more closed cell contents [39, 40]. Sarika found that the alkyl side chains of lignin provide a regular and uniform micro-structure to the foam which, in turn, improves its mechanical properties [41]. Because of the excellent characteristics of biomass-based foam, it has been used in the automotive industry, such as Ford.

Apart from bio-plastic, bio-based carbon fiber, and bio-based foam, the bio-based lithium-ion batteries and bio-based super-capacitors for automotive application also see an increase in demand for electronic vehicles. Carbon-based materials have good electrical conductivity, adjustable morphological properties and porosity, hence, it is considered as a potential replacement [42].

5. Applications of Bio-Fuels in Automotive Industry

Besides bio-based materials, bio-fuel is another main utilization pathway of lignocellulosic biomass derived products within automotive industry. Bio-fuels are sustainable, green, renewable and environmental friendly; many countries have favorable policies and goals for the preparation and utilization of bio-fuels [43,44]. As said before, there are diverse bio-fuels styles, such as solid bio-fuel, liquid bio-fuels, and gaseous bio-fuels. Around 50 countries have targets or requirements for blending bio-fuels with conventional fuels, and most have set targets for future bio-energy. Currently, bio-fuels account for 3% of the world's transportation fuel supply, but experts generally believe that with improved efficiency, lower production costs, and the commercial development of advanced bio-fuels, the share of bio-fuels in transportation fuel will exceed 25% by 2050. Considering the power system of the vehicles, the review is focusing on the liquid bio-fuels and gaseous bio-fuels in this section, and the relationship between bio-hydrogen production and the automotive industry was also discussed for the first time.

5.1. Liquid Bio-Fuels

The representative liquid bio-fuels are bio-ethanol, bio-butanol, and bio-diesel. Their combustion properties are equivalent to gasoline and diesel, hence, they can run the existing vehicles without major changes. Bio-fuels have higher oxygen content, for example, ethanol contains about 34.8% (w/w) oxygen in

its composition, which shows better combustion and helps in reduction of soot, un-burnt hydrocarbons, PM2.5, and other pollutants [45–47]. Among a variety of bio-fuels, bio-ethanol is the most widely used one, and the production of fuel ethanol has increased year by year since 2007 (49.68 billion liters) and reached its peak in 2019 (111.03 billion liters). Although there was a decline in 2020 and 2021 due to the COVID-19 epidemic, the production gradually rebounded after the recovery from the epidemic [48]. US and Brazil are the leading producers of bio-ethanol in the world. The main substrate of US and Brazil for bio-ethanol production is corn and sugarcane, which have very high yield compared with the lignocellulosic biomass that utilized by China [49]. At present, the production of fuel ethanol is not enough to support the replacement of all fuels such as gasoline, so the current use of fuel ethanol is often mixed with gasoline through different proportions. This form of utilization can also achieve carbon reduction targets in the automotive industry. The utilization of bio-ethanol enhances the performance of engines by increasing the compression ratio, and reduces the knocking phenomena in the internal combustion engine [50]. Sindhu found that a maximum ratio of 85% (v/v) ethanol blended gasoline can be directly used in the existing vehicle system without any modification [51]. Bio-butanol is also considered as an alternative bio-fuel for fossil fuel, even showing better physical properties than bio-ethanol. Many researchers have conducted series performance investigation of bio-butanol in vehicle engines. Butane blends were found to have the abilities to support the spark ignition, resuce the burning duration, and improve anti-knocking capacity [52]. Proper blend ratio is necessary when adopting bio-butanol. Lower concentration improved the brake-specific fuel consumption and lowered the emission rate, while, higher concentration was found to causing the unsteady working of engine because of the high viscosity of the mixture [53]. Although bio-butanol is considered as one of the fuel sources for automotive engines, it has not been produced on a large scale due to the problems such as many inhibitors, serious enzyme inactivation, low yield, and large water requirement during its preparation, so its commercialization has been hindered [54].

In addition to bio-ethanol, the related research of bio-diesel has also made significant breakthroughs, and bio-diesel has been successfully applied to vehicle fuel. Differing from the diesel whose elemental composition contains only carbon and hydrogen, bio-diesel is derived from long-chain fatty acid esters, thus, it contains carbon, hydrogen, and oxygen as their major element. Due to the presence of oxygen, when bio-diesel is used, the oxidation capacity of the fuel and the combustion performance of the engine are improved. Moreover, bio-diesel helps in the smooth running of components, hence, more encouraged policies have been made across the global [55]. Flashpoint, cetane number, iodine number, kinematic viscosity, oxidation stability, and etc, are some of the essential properties of bio-diesel too, just like the diesel [56]. Bio-diesel can be directly or blended with regular diesel, a blend of up to 5% bio-diesel can be used in the existing engine. Several studies have indicated that blending with bio-diesel can reduce the emission of soot, SO_x, PM 2.5, and un-burnt hydrocarbons, displaying environmental benefits [57].

5.2. Gaseous Bio-Fuels

The gaseous bio-fuels produced via bio-conversion are considered to be a green and clean bio-fuels, too [58]. Along with the rapid development of cars with new power strains, such as natural gas powered car series and electrical vehicles, natural gas (bio-methane) and hydrogen (bio-hydrogen) are found to be the reasonable gaseous bio-fuels that can be utilized as bio-fuels for automotive industry. Natural gas can be produced from anaerobic digestion of various organic matters, and hydrogen also can be produced by photo or dark fermentation of small molecular sugar or acid. Considering the carbon neutral demand and hydrogen development road maps, major automotive companies have been dedicated in the H_2 fuel cell powered electric propulsion vehicles (HFCV) nowadays. HFCV powered by hydrogen has shorter refueling time and longer battery life compared to battery electric vehicles [59,60], and is considered as an ideal alternative to internal combustion engine fuel vehicles [61, 62]. However, the current high cost of industrial hydrogen production technology increases the operating cost of HFCV system [63, 64], which limited the large-scale application of HFCV. In particular, the current hydrogen production mainly relies on the by-product hydrogen of fossil fuels, which is accompanied by the consumption of conventional energy and is not green enough. Hence, green hydrogen technology, which relies on renewable energy for hydrogen energy preparation, ushered in a development opportunity. Among the green hydrogen production technologies, bio-hydrogen

production from photo or dark fermentation are found to be the cleanest and most environmentally friendly way. Photo-fermentation bio-hydrogen production is using photosynthetic bacteria to decompose organic matter and produce hydrogen under light conditions. Dark fermentation bio-hydrogen production is using anaerobic bacteria to decompose organic matter in dark environment to produce hydrogen [65,66]. Due to the advantages of bio-hydrogen production, such as mild conditions (it can be carried out at room temperature and pressure), and a wide range of substrate sources (such as agricultural waste, forestry waste, and agricultural processing leftover), more and more researchers have been engaged into the study of bio-hydrogen production from dark or photo fermentation [67]. Academician Ren's team has made outstanding achievements in the field of bio-hydrogen production by anaerobic activated sludge dark fermentation [68, 69]. Academician Guo's team has made outstanding contributions in the screening of efficient hydrogen-producing bacteria, gene enhanced photosynthetic bacteria and hydrogen production model innovation [70, 71]. Long and Fan realized the efficient conversion of anaerobic microbial dark fermentation hydrogen production using agricultural and forestry wastes as substrate through efficient pretreatment of cellulosic biomass [72,73]. Zhang and Liao devoted themselves to the research of biological hydrogen production process of photosynthetic bacteria, and made important progress in multiple expansion of raw materials, process optimization and model establishment [74−81]. Cheng and Wang committed to the electrode combination of graphite carbon fiber anode and three-dimensional porous transition metal cathode as well as microbial flora regulation and other technologies, opening up a new field of research on microbial electrochemical hydrogen production [82, 83]. The exploration in the field of biological hydrogen production is gradually deepening, and its share in the field of hydrogen energy is gradually increasing, which will become one of the effective ways to ensure the supply of hydrogen energy.

6. Opportunities for Continued Expansion of Alternative Bio-Based Materials and Bio-Fuels

Carbon emission reduction involves all aspects of automotive manufacturing methods. In the field of materials, the application of bio-based materials in the automotive field has always been the direction of efforts of the automotive industry. In the field of energy, the preparation of bio-fuels also attracts increasing attention.

For the incremental and sustained adoption of alternative materials and fuels for automotive manufacturing into a minimally polluting industry, the replacement of vehicle component and fuel by bio-based materials and bio-fuels are most important. Ford has been working on the use of biomaterials since the 1920s, when Henry Ford used wheat-grass in the Model T. Since then, soybean foam, seals, gaskets, castor foam, plastic, and natural fiber reinforced materials have been used by Ford and other automakers. A wide variety of bio-based materials are used in all aspects of automotive manufacturing.

Bio-based materials are relatively lighter than those used in conventional cars, and chosen to produce more lightweight cars instead of steel. The replacement of traditional materials by bio-based materials is forced by the trend of environmental protection, and bio-based materials are known for their excellent properties such as environmental protection and non-toxic.

Utilizing green and renewable energy is also a key pathway for adopting lignocellulosic biomass into automotive manufacturing. It has two major directions: one is to use bio-fuels for commuting, using directly or blends. Around 50 countries have targets or requirements for blending bio-fuels with conventional fuels, and most have set targets for future bio-energy. Currently, bio-fuels account for 3% of the world's transportation fuel supply, but experts generally believe that with improved efficiency, lower production costs, and the commercial development of advanced bio-fuels, the share of bio-fuels in transportation fuel will exceed 25% by 2050. Another utilizing direction is providing fuel for electric vehicles, such as bio-hydrogen for fuel cell car. With the development of science and technology, the process of bio-hydrogen preparation can be optimized, making the manufacturing process more environmentally friendly and low-carbon, further reducing the cost of hydrogen storage, which can greatly stimulate the development of the hydrogen fuel cell vehicle market, and further help the realization of carbon neutral goals.

7. Conclusions

In the global trend of energy saving and environmental protection, it is essential to reduce overall

pollution and increase sustainability by adopting lignocellulosic biomass derived products instead of the petroleum-based products. This work reviewed the adoption of bio-based materials and bio-fuels into the automotive industry. Bio-plastic, bio-based carbon fiber, and bio-based foam have shown suitable physical properties. Bio-ethanol, bio-butanol, bio-diesel, bio-methane, and bio-hydrogen have shown better fuel properties. Bio-based materials can achieve the material replacement in the automotive manufacturing process, and bio-fuels can improve engine efficiency and emission quality when blended with regular fuels. Conclusion can be drawn that the investigation of bio-based materials and bio-fuels has been gradually accelerating over the last decades, and the adoption of biomass derived products has been spurred by government policies, capital investment, and consumer preferences. With the continuous improvement of the production process level of biomass-derived products in China, the future prospects can be predicted that more abundant product types, and continuous innovation breakthroughs in key industrialization technologies, the replacement rate of bio-based materials and bio-fuels for fossil raw materials and fossil energy in automotive industry will continue to increase. China's world-leading bio-hydrogen production technology will make a remarkable contribution to the future hydrogen car-related industries.

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