

REVIEW

Carbon Fiber from Biomass Sources: A Comprehensive Review

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ABSTRACT

Global energy demand is rising, fossil fuel prices are rising, fossil fuel reserves are running out, and fossil fuel use contributes to the greenhouse effect. As a clean alternative source of energy to fossil fuels, biomass is becoming more and more essential. Carbon fiber (CF), often known as graphite fiber, is a thin, strong, and adaptable material utilized in both structural (capacity) and non-structural applications (e.g., thermal insulation). Precursors are the raw materials used to create carbon fiber, which is mostly derived from fossil fuels. Because of the high cost of precursors and manufacture, carbon fiber has only found employment in a few numbers of high-performance structural materials (e.g., aerospace). To reduce the price of CF and reliance on fossil fuels, numerous alternative precursors have been studied throughout the years, including biomass-derived precursors such as rayon, lignin, glycerol, and lignocellulosic polysaccharides. This study's goal is to present a detailed study of biomass-derived CF precursors and their market potential. The authors look into the viability of producing CF from these precursors, as well as the state of technology, potential applications, and cost of production (when data are available). We go over their benefits and drawbacks. We also talk about the physical characteristics of CF made from biomass and contrast them with CF made from polyacrylonitrile (PAN). Additionally, we go into bio-based CF manufacturing and end-product concerns, logistics for biomass feedstock and plant sites, feedstock competition, and risk-reduction techniques. This paper offers a comprehensive overview of the CF potential from all biomass sources and can be used as a resource by both novice and seasoned professionals who are interested in producing CF from non-traditional sources.

Keywords: Carbon fibre; Polyacrylonitrile; Biomass; Lignocellulosic

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1. Introduction

Carbon fibers are fibrous carbonaceous materials having a diameter of 5-10 μm . Carbon fibers are filaments, lines, or reels that contain more than 92 percent carbon and are normally in a nongraphite condition, according to the International Union of Pure and Applied Chemistry (IUPAC) ^[1]. This means that carbon is defined as a two-dimensional long-range arrangement of carbon atoms in planar hexagonal networks with no crystalline structure in the third direction except for some parallel stacking ^[2]. Graphite fiber, often known as carbon fiber (CF), is a strong, lightweight material that can be used for both structural and non-structural applications (e.g., thermal insulation). Most carbon materials demonstrate excellent stability and high power density when used as supercapacitor electrodes; nevertheless, their specific capacitance and energy density are relatively low, which cannot meet the high energy requirements for practical applications ^[3]. In this case, carbon materials with a high specific surface area, a reasonable pore size distribution, and desired nanostructure are critically demanded ^[4]. Carbon fiber, a newly developed synthetic material that is commonly utilized in the production of advanced composites has a wide range of applications in the automotive, aerospace, and electronics industries ^[5]. Carbon materials have long been suitable materials in energy storage due to their superior electrical conductivity, easy fabrication, physical and chemical sustainability, and high surface area among several supercapacitor electrode materials ^[6]. Carbon fibers have great stiffness, high durability, light weight, strong chemical stability, high-temperature tolerance, and minimal thermal expansion as its key characteristics ^[7]. To make a composite, carbon fibers are frequently mixed with other materials. It generates carbon-fiber-reinforced polymer (commonly referred to as carbon fiber) when penetrated with a plastic resin and baked. It has a very high-grade ratio and is exceedingly rigid, but slightly brittle. Carbon fibers can also be combined with other materials like graphite to create reinforced

carbon-carbon composites with a feverish temperature tolerance. However, when compared to similar fibers such as glass fiber, basalt fibers, or plastic fibers, they are quite pricey ^[8]. To make a carbon fiber, carbon atoms are bonded together in crystals that are aligned parallel to the fiber's long axis, resulting in a fiber with a high strength-to-volume ratio (in other words, it is strong for its size). Thousands of carbon fibers are bundled together to create a tow that may be used alone or woven into a fabric ^[9].

2. Synthesis of carbon fiber

Organic polymers, which are long chains of molecules linked together by carbon atoms, are used to make carbon fiber. The polyacrylonitrile (PAN) method produces most of the carbon fibers (about 90%). A minor percentage (about 10%) is made using rayon or the petroleum pitch method ^[10]. The effects, properties, and grades of carbon fiber are created by the gases, liquids, and other components employed in the manufacturing process. Carbon fiber makers create materials using proprietary formulas and combinations of raw components, and they treat these compositions as trade secrets in general. Pitch, obtained from petroleum or coal, and polyacrylonitrile have been the most popular types of precursor materials used to make carbon fiber commercially since the 1960s. All the non-renewable materials are discussed in the following sub-section.

2.1 PAN

PAN-based carbon fibers with poor mechanical qualities were first manufactured in 1959 in Osaka, Japan, boosting the carbon fiber industry's development. Despite facing numerous challenges in generating high-strength and high-modulus carbon fiber, the Japanese business TORAY has reached world-leading levels of performance in this industry ^[11]. PAN is petroleum-based linear polymer carbon fibers made from PAN are primarily made in two processes. The first stage is to make polyacrylonitrile precursor, which consists mostly of monomer polymer-

ization and the preparation of spinning liquid, which is then spun further. This is an important first step in the manufacture of carbon fiber since the quality of the precursor dictates the carbon fiber's performance. The precursor is pre-oxidized and carbonized in the second stage^[12]. Carbon fiber made from PAN, on the other hand, is expensive, thus its use is confined to high-performance structural components^[13]. For example, due to their outstanding mechanical properties and high production, CFs based on PAN precursor are the most important in the market^[14]. However, as fossil energy is rapidly exhausted, not only will the cost of CFs based on non-renewable energy rise, but environmental pollution from the production of toxic gases (e.g. hydrogen cyanide) using PAN as a precursor will also rise^[15]. Most carbon fibers used are made from polyacrylonitrile (PAN) precursor fibers, which are the best precursors for high-performance carbon fiber production^[16]. Thermal stabilization and carbonization are the two processes in the manufacture of carbon fiber from PAN precursor fiber^[17]. In an oxygen environment, the stabilization procedure is usually carried out under stress at temperatures ranging from 200 to 300 degrees Celsius^[18]. Various exothermic chemical events, such as cyclization, dehydrogenation, oxidation, and cross-linking, cause PAN to undergo chemical modifications that result in an increase in density during this process. The cyclization process converts a linear polymer into an infusible ladder polymer, which gives the polymer thermal stability and prevents melting during the subsequent carbonization process (which takes place at temperatures between 700 and 1500 degrees Celsius in a nitrogen atmosphere)^[19]. As a result, the stabilization process is the most important factor in determining carbon fiber's mechanical properties^[20]. To date, most studies on the PAN stabilization process have mostly focused on thermal stability, with only a few researchers actively investigating the effect of radiation on the PAN precursor's thermal stabilization. Furthermore, when the PAN precursor fiber is stabilized by electron beam irradiation (EBI) and heat treatments, the stabilization period (2-3 h) can be decreased because

of pre-stabilization by EBI and thermal treatments^[21].

2.2 Pitch

Pitch is the common name for a tarry substance with a high carbon content that is particularly viscous at ambient temperature. It's a complicated mix of hundreds of aromatic hydrocarbons and heterocyclic molecules with a molecular weight of 300-400. It can be made from natural sources such as petroleum and coal by destructive distillation, or from synthetic sources such as polyaromatic chemicals and polymers by pyrolysis. Pitch composition varies greatly depending on the tar source and processing circumstances. Pitch can contain more than 80% carbon, and the quality of the result CF improves as the aromaticity rises. The bottoms of catalytic crackers, steam cracking of naphtha and gas oils, and wastes from other refinery processes can all be used to make petroleum pitch^[22]. Before being used in the CF sector, crude products normally go through several refining processes. Coal tar is produced as a by-product of the coking of bituminous coals to make cokes. Distillation and heat treatment are used to extract coal-tar pitch from coal tar. The pitch is the residue left over after the heavy oil fractions have been removed. Coal-tar pitch has a higher aromatic content than petroleum pitch^[23]. It does, however, have a significant solid content, which leads to filament breakage during extrusion and heat treatment. As a result, petroleum pitch is favoured for the manufacturing of CF. Isotropic and mesophase pitch are the two primary forms of pitch used in the pitch-based precursor business. The GP grade of pitch CF is made with isotropic pitches^[24]. They are not graphitic, and their characteristics are inferior to those of the HP grade. A unique treatment technique is required to convert the pitch to mesophase grade in order to make HP grade. Mesophase grade is graphitic in nature and optically anisotropic. To make a product appropriate for melt spinning, the isotropic pitch must be processed, filtered to eliminate solid particles, and have low volatility^[25]. The low volatility components of the pitch are removed using a wiping film evaporator, and the molten pitch

is filtered to remove solid contaminants. Domains of very parallel, platelike molecules develop and consolidate during the creation of the mesophase until 100 percent anisotropic material is formed. Several strategies for the synthesis of mesophase pitch have been researched over the years: (a) pyrolysis of pitch, (b) solvent extraction, (c) hydrogenation, and (d) catalytic modification. For the best control of the processing parameters and pitch quality, the catalytic technique is preferred in pitch pre-treatment [26]. It is claimed that a spinning pitch should contain 40%-90% mesophase with domain sizes greater than 200 nm, resulting in a fiber with a highly orientated structure. Domain sizes of less than 100 nm have been found to be unsuitable for spinning. Melt spinning in an extruder produces pitch-based predecessors. Because of the rheological qualities of molten pitch, melt spinning is challenging, and very precise processing conditions are necessary. The viscosity of the mesophase is very temperature-dependent, and the jet temperature should be precisely regulated, as a change of 3.5 °C at the jet face causes a 15% change in diameter [27]. Due to poor viscosity, too high a temperature causes thermal deterioration of the pitch or dripping. Melting the precursor, extrusion via a spinneret capillary, and drawing the fibers as they cool are the three phases in the melt-spinning process. Solid pitch chips have been fed into the hopper of a screw extruder with off-gassing apertures and evenly heated, resulting in a uniform feed of molten pitch to the filter and then spinneret at the extruder's outlet. To avoid interfilamentous fusing, pitch spinnerets have a 130 Fiber Technology for Fiber-Reinforced Composites multiplicity of holes, which must be spaced roughly 1.1 mm apart. As the molten pitch flows through the capillaries, some initial orientation occurs. It is cooled by quenching air after coming from the capillaries [28]. The solid fiber is pulled before windup while it is still hot to produce a highly oriented precursor fiber. Any subsequent carbonizing procedure will not require a further drawing of this precursor fiber. Due to the low strength of the as spun mesophase pitch, fiber handling in the windup is challenging (tensile strength around 0.04 GPa).

Mesophase carbon fibers have a diameter of 10-15 μm, whereas PAN carbon fibers have a diameter of 5-7 μm. This is due to the preference for bigger diameter mesophase precursor fibers for easier handling and higher carbon yield, resulting in a lower size decrease in the carbonization process. It is claimed that a processing speed of up to 1000 m/min can be achieved [29].

The microstructure of spun mesophase pitch precursor fibers is made up of microdomains of well-oriented polyaromatic molecules. Discotic nematic liquid crystal microstructures are the name given to these microstructures.

2.3 Carbon fiber from renewable biomass sources

Carbon fiber made from biomass could be less expensive to produce and have more environmental benefits than carbon fiber made from natural gas or petroleum [30]. Consequently, developing a process for producing low-cost CFs based on renewable, non-toxic, and sustainable resources is both essential and realistic in the context of climate change mitigation and adaptation. Because of the advantages of renewable and low-cost properties, bio-mass resources such as cellulose, lignin, Glycerol, Lignocellulosic Sugars and wood are attractive precursors for the preparation of CFs [31]. Scientists and engineers are motivated to create these novel materials because the use of biomass resources for a variety of electrode materials shows that a sizable portion of the intricate functionality of living systems is founded on an intricate hierarchical organization from the nanometer to the macroscopic scale. Because of their abundant availability and added value gained from their renewable and biodegradable nature, biomass sources are becoming increasingly essential. Various bio-renewable resources have been developed as alternative materials for CFs in recent years [32]. All of these are discussed in the following sub-sections.

Cellulose

The manufacture of cellulosic fibers is well known; rayon, the first CF to hit the market in the 1960s, is made from cellulose-based natural materials (such as wood pulp, cotton linters,

leaves, and the inner pith of bamboo plants) that are chemically processed to create semi-synthetic fibers^[33]. All three of these rayon types—viscose, modal, and lyocell—are made differently and have different properties. Lyocell is frequently marketed under the brand name TENCEL and is produced by the Lenzing Group in Austria. PAN-based CF has superseded rayon-based CF in most applications due to its superior performance in various areas, particularly tensile strength^[34]. Furthermore, although having a cheaper raw material cost, rayon-based CF has a higher total cost due to a low char yield (20%-25%) following carbonization. These qualities can be improved by stress graphitization at elevated temperatures, but this raises the cost of the fiber even more, making it less appealing. Despite not being used for structural purposes, rayon-based CF is still used in the rocket and missile industries for ablative purposes like re-entry vehicle nose tips, heat shields, solid rocket motor (SRM) nozzles, and exit cones^[35]. Rayon-based CF can endure the elevated temperatures and corrosive gases of SRM operation, as well as the feverish temperatures created by missile re-entry systems' aerodynamic heating. Due to low demand, commercial manufacturing of rayon-based CF is limited (approximately 1%-2% of overall CF production). RUE-SPA-Khimvolokno in Belarus is the world's largest rayon-based CF producer. Precursor stabilization (low-temperature oxidation), carbonization (longitudinal orientation and crystalline ordering development), and graphitization (optional for high modulus) are the three basic steps in the production of rayon-based CF^[36]. Natural fibers like cotton and ramie have not been chosen for the production of CF due to their complicated structure, discontinuous filament structure, low degree of orientation, and related pollutants^[37]. Advanced processing technology and a search for renewable sources, on the other hand, may open new possibilities for natural fibers as CF precursors in the future. Because of its tremendous flexibility, cellulose (the most prevalent biological macromolecule in nature) is an appealing alternative material for electrospinning to manufacture submi-

cron-diameter CFs. However, due to the low thermal stability of cellulose, direct carbonization of biomass-based CFs is problematic^[38]. The typical viscose process is likewise slow, arduous, and complex in the cellulose-based CFs business. It also produces CS₂, H₂S, and heavy metals, all of which are detrimental to the environment^[39]. As a result, finding a cost-effective and ecologically friendly technique to create regenerated cellulose fibers is desirable. CFs manufactured from regenerated cellulose fibers, such as Lyocell fibers, have been attempted using the CarbaCell method. The Lyocell process uses N-methyl-morpholine-N-oxide (NMMO) as a cellulose solvent, resulting in better fiber qualities such as tenacity, crystallinity, and modulus. High-spinning temperature and solvent recovery are two technical issues with this method^[40]. The CarbaCell technique is an alternate approach for reducing hazardous compounds. In this procedure, cellulose carbamates (CC) are stable at room temperature and can be stored for more than a year without losing quality^[41].

Lignin

Lignin, which has a high carbon content, exceptional thermal stability, and a huge number of benzene ring structures, is another excellent bio-renewable resource^[42]. Furthermore, lignin is a cheap and easily available coproduct of the pulp and paper-making process. However, due to lignin's nonlinear chemical structure and limited flexibility, preparing CFs by spinning independently remains a significant difficulty. Physical blending with petroleum-based polymer or bio-macromolecular as spinning auxiliaries has been used to manufacture lignin-based CFs in a variety of ways^[43]. However, during the carbonization process (high-temperature heating under a nitrogen atmosphere), cellulose and lignin molecules containing a considerable amount of oxygen have a high oxidation process weightlessness, resulting in the morphological collapse of biomass-based CFs. When these monolignols polymerize in natural biomass, they produce a racemic, cross-linked, and highly heterogeneous aromatic macromolecule. The proportions of syringyl (S), guaiacyl (G), and p-hydroxyphenol (H) monomers, molecular weights,

degree of branching, isolation methods, and purity all influence the physical and chemical properties of lignin separated from biomass^[44]. Most of the lignin produced by the Kraft pulping process and the biofuel business are currently used as low-cost fuel. Future development of processes for biomass utilization may involve a “biorefinery” concept in which wood (biomass) is brought to a mill site and further converted to pulp and paper or, alternatively, to energy, biofuels, and chemicals through processes such as prehydrolysis-kraft, organosolv pulping, steam explosion, autohydrolysis or acid hydrolysis. The alternative techniques, unlike the classic kraft pulping process, are not suited for creating pulp and paper, but they can be developed for other purposes such as cellulose, hemicelluloses, and lignin synthesis. Chemical modification of the lignin might be done during the process or afterward. Lignin will most likely be widely available in vast amounts in the future^[45]. Although lignin is a great biofuel, new applications in higher-value-added products are appealing because lignin isolation and refining need processing stages that can be combined with structural alterations such as membrane fractionation, derivatization, and others. With more than 50 years of research and significant investments, lignin is the most studied biogenic CF precursor^[46]. Lignin-based CF has a potentially significant manufacturing cost advantage over current technologies, with commercial scale prices estimated to be around \$4-\$6 per pound against \$10 per pound for petroleum-based CF (in 2010 dollars)^[47]. PAN precursors cost \$4-\$5 per pound, whereas lignin costs \$0.25-\$0.70 per pound. Most possible production cost savings can be attributed to this significant reduction in precursor costs. However, possible cost-cutting opportunities in other aspects of the process have been studied as well. Due to performance difficulties and manufacturing limitations, the lignin-to-CF route is not commercially viable^[48]. Various entities have been active in lignin-based CF research, but the work undertaken by the Oak Ridge National Laboratory (ORNL) and Innventia, which both manufacture CF for testing reasons, have gotten the most attention in the last

ten years^[49]. In order to meet goals for finished fiber strength and stiffness, these organizations strive to address commercialization challenges associated with lignin-based CF manufacturing, such as “melt processability (especially for softwood lignins); long heat treatment time (especially for hardwood lignins); variability in the feedstock and unproven scale of operation.” These difficulties arise from the heterogeneous molecular weight, functionality, and thermal characteristics of lignin, which vary depending on the source and isolation procedure^[50].

Glycerol

With regards to being used in food, cosmetics, and pharmaceuticals, glycerol (also known as glycerine or glycerin) also has the potential to be used as a renewable chemical source. It is doable to be utilized in the production of ACN, which may then be polymerized and spun into PAN, which can then be utilized in a variety of applications CF was converted. The literature describes two glycerol-to-ACN conversion processes: Direct synthesis in the gas or liquid phase employing microwave heating in the latter case and ammoxidation in the former^[51]. Indirect synthesis via acrolein—glycerol is dehydrated to generate acrolein, which is then ammoxidized to ACN—or allyl alcohol—glycerol can be converted to allyl alcohol using iron oxide as a catalyst, followed by ammoxidation of allyl alcohol to ACN as intermediates^[52]. In the past, synthetic methods were mostly used to produce glycerol from petroleum. Yet, as a byproduct of numerous industrial processes, such as the production of biodiesel, the hydrolysis of fatty acids, and the production of soap, glycerol from plant and animal sources became readily accessible. Biodiesel production now accounts for most of the glycerol production, accounting for around 63 percent of the market in 2013. In 2013, global glycerol consumption was 2.2 million tonnes, with 3.5 million tonnes projected by 2020^[53]. Given the better lifestyle in emerging nations, which leads to higher consumption of processed and packaged goods, this demand is predominantly driven by the food and beverage industry. As a result, rather than producing surplus steam in the mill, removing a portion of the

dissolved wood polymers should be a realistic option that also opens new product areas. Glycerol (also known as glycerine or glycerin) is utilized in cosmetics, pharmaceuticals, and food items, but it also has the potential to be used as a renewable chemical source. It can be used to make ACN, which can be polymerized and spun into PAN, which can then be turned into CF^[54].

Lignocellulosic sugars

The use of biomass-derived sugars (e.g., glucose, fructose, and xylose) generated from the cellulose and hemicellulose portions of biomass is another mechanism for producing ACN^[55]. Laboratory testing has revealed that this route may be used to directly replace conventional ACN with mechanical qualities that are comparable. Recognizing this prospect, the US Department of Energy approved two projects in 2014 to improve the production of low-cost, high-performance CF using sustainable, non-food-based biomass feedstocks^[37]. For the conversion of sugars from non-food biomass to ACN, the Southern Research Institute (SRI) in Birmingham, Alabama, will use a multi-step catalytic process. Multiple metabolic pathways to ACN will be investigated and optimized at the National Renewable Energy Laboratory (NREL) in Golden, Colorado.

Biomass-based goods made from natural resources have recently gotten a lot of interest in academics and industry^[56]. Biomass materials, as a vast resource pool, have become a popular area of research, with biomass resources such as agricultural wastes and other renewable resources being used to create biomass-based porous carbon compounds^[57]. Porous carbon materials such as rice, fiber, wood, proliferata, cattle bone, coconut shells, silk, egg whites, and cigarettes have all been employed in supercapacitors, lithium batteries, and fuel cells. There are few investigations on activated carbon fibers employing natural plant fibers as raw materials in current research, and industrial production has yet to be established^[58]. As a result, using biomass as a raw material to make activated carbon fibers and using them in supercapacitors has more practical value and significance^[59]. This is owing to benefits such as sustainability, recy-

clability, cost, efficacy, environmental friendliness, and so on^[60]. Although the fibers are not discontinuous, limited in fiber length, and have relatively low mechanical properties in comparison to conventional rayon-based and PAN-based carbon fibers, it would be desirable and useful if carbon fibers or activated carbon fibers could be made from biomass-based natural fibers, which are abundant in nature and less expansive^[61].

3. Carbon fiber from other biogenic sources

Glutamic acid, which may be produced from a variety of waste streams including dry distiller's grains and solubles from the manufacturing of ethanol from corn and wheat, is another biogenic source that has been investigated for the creation of ACN. A palladium catalyst is used in a two-step process that starts with an oxidative decarboxylation of 3-cyanopropanoic acid in water and ends with a decarbonylation-elimination reaction. Another method for producing CF has been suggested: Genetic manipulation of biomass. This route comprises (1) employing CO₂ or carbon nanotubes via yet-to-be-developed technologies and (2) engineering plants to generate lignin or other natural polymers that could be transformed into PAN-like compounds. Additionally, the University of Delaware researchers have looked into the use of chicken feathers as a raw material for the synthesis of CF. They created chicken feather fibers with low modulus and low to medium strength; they want to raise these parameters, but recent years have seen a decline in their research in this area.

4. Advantages of increased sustainability

Utilizing CF made from biomass could give some companies a competitive edge. For instance, many current athletic goods incorporate CF to lighten and strengthen their construction. Many of these producers also emphasize the environmentally friendly qualities of the goods they produce. Some snowboards have certified sustainably obtained wood cores that have a minimal environmental impact.

A common component of snowboards is CF, which enhances performance. For some businesses, being able to sell sustainable CF generated from biomass rather than fossil fuels could have a positive competitive advantage and be a differentiation, potentially making the risk associated with switching materials worth it. Many merchants and producers are making efforts to lessen the environmental impact of the goods they produce or sell. For instance, many merchants put pressure on their suppliers to save costs and environmental impact. Switching materials might be encouraged if CF made from biomass could save costs and have positive environmental effects for a product like a tennis racket. Additionally, many businesses, particularly those in Europe, are facing greater pressure to lessen the environmental impact of the goods they produce. Sustainability professionals, activists, or shareholders may encourage the use of low-impact materials like biomass-based CF.

4.1 Recyclability

The recyclability of CF at the end of its useful life has been identified as a known concern by numerous ongoing research efforts, although few current workable solutions have been offered. Beginning in 2015, each car must include 85% recyclable elements by weight in accordance with the End-of-Life Vehicle (ELV) Directive 5 of the European Union (Gardiner 2014). Metals and other plastics used in automobiles are recyclable, but CF is currently not. CF must be recyclable if it is to become a key automotive component in Europe. Similar problems are faced by the European aircraft sector, and Airbus has set a goal to recycle 95% of its CF-reinforced plastic by the years 2020-2025. Biomass-based CF might become more popular if it offered a better route to recycling. This would provide it with a significant supply chain advantage. However, if CF made from biomass were chemically equivalent to CF made from petroleum, it would have the same problems with recycling and probably not be more advantageous. For a better understanding of the process and possibilities for recycling, more research is needed to examine the recyclability of biomass-based CF.

4.2 Biomass feedstock competition

There are additional existing or potential uses and applications for biomass resources that might be used to make CF. These include the production of heat and electricity, as well as chemicals and other materials from lignocellulosic material. Glycerol is currently primarily used in personal care and pharmaceutical products, as was already mentioned. However, between now and 2020, food and beverage are expected to see the fastest growth in terms of application. This is due to improving lifestyles in emerging economies, which have led to an increase in the consumption of processed and packaged foods. There is ongoing research into the synthesis of liquid fuels, aromatic compounds, and polymers as well as other value-added commodities from lignin. The capacity to secure a supply of raw materials at a reasonable price will be a critical factor for the industry's long-term success. The potential risk to feedstock supply is increased by competition from other sectors for biomass. For instance, CF is just one of 43 possible lignin-derived compounds listed in a paper from the Pacific Northwest National Laboratory. CF is a high-value product and would probably compete advantageously for lignin with many other commodities, but price increases due to the competition may lessen the cost savings from CF made from biomass.

4.3 Plant siting and feedstock logistics

The location of CF manufacturing facilities has been determined by a few variables, such as closeness to customers or affordable energy. Since most of these current facilities are close to biomass sources, there may be a chance to incorporate these alternative sources into the production of CF. With only one or two exceptions, solid biomass resources and pulp and paper mills, which serve as a stand-in for lignin production, are located close to the CF manufacturing factories (e.g., crop residues, forest residues, or both). The economic analysis of biomass-based CF must appropriately account for and take into consideration the logistics of packing and delivering these

raw materials. The bulk of CF manufacturing facilities in the United States already imports raw materials for CF production, such as PAN or ACN, from other nations. These facilities might perhaps switch to importing biomass or precursors generated from biomass, such as ACN or PAN. Some biomass resources can cost up to \$100 per dry ton, and in some situations even more, to purchase (for example, lignocellulosic biomass, which includes crop leftovers). In comparison to the current price of ACN, which is about a dollar per pound, even at the high end of expenses, this is only a few cents per pound.

5. Conclusions

As of right now, no biomass-based CF has been created that possesses the structural qualities needed for use in the main CF applications (such as aerospace, wind, and automotive). The appropriate application or exploitation of the many forms of CF that can be produced from biomass sources depends on the physical qualities (mainly tensile strength, as well as other factors). The market share of CF made from rayon is modest. Since the strength of this form of CF is less than that needed for structural purposes, it is generally employed in insulating and ablative applications. CF made from lignin is still in the research and development (R & D) stage. Current research is concentrated on non-structural uses like insulation because based on current experimental efforts, the modulus and strength of lignin-based CF are too low to meet the criteria of structural applications. Although glycerol is cheap and widely available, straight ammoxidation from this resource to produce acrylonitrile (ACN) has been shown to be uneconomical at the current moment; it costs around 67% more than ammoxidation based on propane. Although other conversion routes have been looked into, it is still unclear whether they are cost-effective. In addition to its techno-economic viability, biomass-based CF will have other ramifications and difficulties that must be taken into account for man-

ufacturing, feedstock supply, and end products. They include raw material availability, plant locations, raw material certification, product warranties, product competitiveness, and raw material availability.

Conflict of Interest

There is no conflict of interest.

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