Polypropylene-Based Biocomposites and Bionanocomposites

Edited by Visakh P.M. and Matheus Poletto
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Preface

This book, *Polypropylene-Based Biocomposites and Bionanocomposites*, summarizes many of the recent research accomplishments in the area reflected in the title. In addition to the state-of-the-art and new challenges and opportunities in this area, an effort has been made to discuss many other topics related to polypropylene-based biocomposites and bionanocomposites. Included are subjects such as PP/cellulose-, PP/starch-, and PP/polylactic acid-based biocomposites and bionanocomposites; PP-based hybrid biocomposites and bionanocomposites; the biodegradation and flame retardancy of PP-based composites and nanocomposites; PP single-polymer composites; PP/plant-based fiber biocomposites and bionanocomposites; the development method, properties and application of PP/oil palm fiber composite; and the interfacial modification of PP-based biocomposites and bionanocomposites.

This book will be a very valuable reference source for university and college faculties, professionals, post-doctoral research fellows, senior graduate students, and researchers from R&D laboratories working in the area of polypropylene biocomposites and bionanocomposites. The various chapters in this book were contributed by prominent researchers from industry, academia and government/private research laboratories across the globe, resulting in an up-to-date record of the major findings and observations in the field.

The scope of the introductory first chapter ranges from the state-of-the-art and preparation methods of polypropylene biocomposites and bionanocomposites to environmental concerns about them. A thorough review of PP/cellulose-based biocomposites and bionanocomposites is presented in Chapter 2. The authors have divided this chapter into three parts: preparation, characterization and applications. Thermal, morphological, X-ray diffraction, rheological, viscoelastic, electrical and mechanical characterization methods are among those discussed in the characterization part of the chapter. The last part of the chapter is divided into automotive, packaging, structural, fire retardant, electrical and electronic areas of application.
In Chapter 3, various preparation and characterization methods of PP/starch-based biocomposites and bionanocomposites are discussed by the authors. The application of these biocomposites and bionanocomposites in biomedical, packaging, automotive, military, coating, fire retardant, aerospace, and optical fields are also covered. Recycling and lifetime studies conducted on these biocomposites and bionanocomposites are equally highlighted.

Chapter 4 on polypropylene/polylactic acid (PP/PLA)-based biocomposites and bionanocomposites first introduces their preparation methods, including melt blending, melt spinning and some other newly emerging methods like autoclave preparation. Then the morphology, compatibility and crystallization of the PP/PLA-based biocomposites and bionanocomposites are discussed in order to obtain resultant materials with uniform distribution and good compatibility among different components. Also summarized are the rheological, electrical, mechanical, thermal, gas barrier, and flame retardant properties of these biocomposites and bionanocomposites, and how each of these properties is dependent upon the composition of the biocomposites and bionanocomposites.

Summarized in Chapter 5 are many of the recent research accomplishments in the area of hybrid biocomposites based on polypropylene. In this chapter, the author discusses the preparation, characterization and applications of PP-based hybrid biocomposites and bionanocomposites. Specifically discussed are their mechanical, thermal, and weathering properties and their role in improving durability, flame retardancy and thermal stability.

A good basis for understanding the biodegradation and flame retardancy of polypropylene composites and nanocomposites is provided in Chapter 6. This chapter summarizes information obtained from highly ranked journals published during the last two decades about the flame retardancy of these biocomposites and nanocomposites. The chapter begins with a short description of the specific flammability of PP, followed by an overview of fire retardants and flame testing methods and standards. Preparation principles, processing methods, properties and applications of polypropylene single-polymer composites are discussed in Chapter 7.

In Chapter 8, different subsections are devoted to topics such as types of natural fibers, the processing of plant-based fiber bionanocomposites with polypropylene, the characterization of plant fiber reinforced polypropylene, applications of plant fiber reinforced PP-based biocomposites and bionanocomposites and future perspectives in the global market. Polypropylene composite with oil palm fibers, its method of development, properties and applications, are discussed in Chapter 9. In this chapter,
the authors explain pretreatment methods, cellulose extraction, composite development, characterizations, composite properties and applications. The last chapter of this book focuses on the interfacial modification of PP-based biocomposites and bionanocomposites. First, the nature of fiber-matrix interface is introduced and then the qualitative and quantitative methods for the determination of interface strength are outlined. Finally, the interface modification of PP-based biocomposites and bionanocomposites are presented in light of the existing literature.

In conclusion, the editors would like to express their sincere gratitude to all the contributors to this book, whose excellent support aided in the successful completion of this venture. We are grateful to them for the commitment and sincerity they have shown towards their contributions. Without their enthusiasm and support, the compilation of this book would not have been possible. We would also like to thank all the reviewers who have taken their valuable time to make critical comments on each chapter. We also thank the publisher John Wiley and Sons Ltd. and Scrivener Publishing for recognizing the demand for such a book, for realizing the increasing importance of the area of polypropylene-based biocomposites and bionanocomposites and for starting such a new project, which not many other publishers have handled.

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Polypropylene (PP)-Based Biocomposites and Bionanocomposites: State-of-the-Art, New Challenges and Opportunities

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Abstract
This chapter presents a brief account of various topics concerning polypropylene (PP)-based biocomposites and bionanocomposites, including their preparation and state of the art. Among the topics discussed are polypropylene/cellulose-based, polypropylene/starch-based, polypropylene/polylactic acid-based and polypropylene-based hybrid biocomposites and bionanocomposites. In addition, biodegradation and flame retardancy of polypropylene-based composites and nanocomposites, easily recyclable polypropylene single-polymer composites, polypropylene/natural fiber biocomposites and bionanocomposites, and polypropylene composite with oil palm fibers are also discussed, along with method development, properties and applications and interfacial modification of polypropylene-based biocomposites and bionanocomposites.

Keywords: Polypropylene, biocomposites, bionanocomposites, cellulose, bionanomaterial, biodegradation, polypropylene, natural fiber, single polymer

1.1 Polypropylene (PP)/Cellulose-Based Biocomposites and Bionanocomposites

Composites of polypropylene with cellulose or cellulose content materials are prepared either by the treatment of cellulosic fibers or by the addition of a third component, e.g., coupling agents or compatibilizers or both,
to improve compatibility of the composite components PP and cellulose. Masterbatch of a composite is prepared in this way and diluted with PP matrix in melt-mixing processing equipment. A typical example of solvent casting process is the preparation of PP/kenaf fiber composite using polypropylene graft acrylic acid (PP-g-AA) as compatibilizer [1]. First, PP, PP-g-AA, and divinylbenzene (crosslinker) are dissolved in boiled xylene and then stirred for one hour after adding kenaf fibers. Finally, the xylene solvent is removed by evaporation from the mixture product to form composite. Bagheriasl et al. [2] prepared PP/nanocrystalline cellulose (CNC) nanocomposites via masterbatches. They produced masterbatches of CNC and the compatibilizer poly(ethylene-co-vinyl alcohol) (CO) via melt-mixing and solution mixing.

Iwamoto et al. [3] prepared PP/microfibrillated cellulose (MFC) nanocomposite via solvent casting followed by melt-mixing process. They dissolved PP and maleated polypropylene (MAPP) in toluene at 100 °C, and then added the toluene dispersion of surfactant-coated MFC into the resulting hot solution. Haque et al. [4] studied the thermal degradation behavior of PP composite with candelilla bagasse fibers (CF) and reported that thermal stability was slightly improved when using CF in PP compared with neat PP. Jang and Kim [5] carried out SEM analysis of the fracture surfaces of the PP composite with hydrophobized cellulose powder by soybean oil.

They observed that the hydrophobization induced much stronger interfacial bonding between the PP matrix and cellulose powder. Nekkaa et al. [6] studied the morphologies of the fractured surfaces of PP composites with silane treated Spartium junceum fibers. They also found higher interfacial adhesion between treated fibers and PP matrix compared with untreated fibers. Krishnan et al. [7] carried out the morphological analysis of bionanocomposite based on PP, CNF and polystyrene (PS) by transmission electron microscopy (TEM). To find out about the dispersion and location of CNF in polymers, TEM is an effective technique. Yeo and Hwang [8] characterized the morphology of PP composites with MAPP-g-MFC and pristine MFC as control by SEM. They noticed that the fractured surface of the PP composites with MAPP-g-MFC was smoother than that obtained from the PP composites with pristine MFC.

Morales-Cepeda et al. [9] also studied the crystallinity of PP/cellulose composites by X-ray analysis. They also reported that the crystallinity of PP/cellulose with MAPP was slightly higher compared with uncompatibilized composite. Doumbia et al. [10] also studied the rheological properties of PP and PP/flax fiber composites with the same variety and volume fraction of flax fiber and also with a similar type and amount of compatibilizer.
Qiu et al. [11] studied the viscoelastic properties of PP/cellulose composites using MAPP as compatibilizer. The storage moduli values were increased with cellulose content. Franco-Marquès et al. [12] carried out mechanical characterization of lignocellulosic fiber reinforced PP composites with and without MAPP as compatibilizer. Moscoso-Sánchez et al. [13] also studied the mechanical properties of cellulose reinforced PP composites using MAPP as compatibilizer. They also observed similar results for compatibilized composites.

Applications of PP/cellulose composites are used in different industries such as automotive, packaging, structural, flame retardants, electrical, electronics, etc. Hao et al. [14] developed kenaf fiber reinforced PP composites for automotive application. They studied the open-hole and pin filled-hole effects on the tensile properties of the composites in production of automotive interior parts. Panaitecu et al. [15] developed PP/hemp fibers treated with silane and potassium permanganate composites for automotive parts. It is reported that potassium permanganate treatment is a cheap and effective treatment of hemp fibers which is easily applicable industrially. Hung et al. [16] developed composites of PP with acetylated wood particles for structural application. The composites of PP with acetylated wood particles exhibit excellent reinforcing effects on the mechanical properties and creep resistance compared with unmodified wood particle composites. Liao et al. [17] developed PP separators coated with cellulose aerogel based on hydroxyl ethyl cellulose via ice-segregation-induced self-assembly for improving the ionic conductivity of PP separators.

1.2 Polypropylene (PP)/Starch-Based Biocomposites and Bionanocomposites

Hamdan et al. [18] used this technique to prepare sago starch/polypropylene blends. It was found that blending starch with propylene using a bar blender reduced the overall mechanical properties (Young’s modulus and tensile strength) with a small increase in the dynamic property (storage modulus) of the composite. The results of Tănase et al. [19] revealed that upon incorporation of starch into the polymer matrix, the torque of the physical blends was highly increased due to an increase in the viscosity of the starch phase. This behavior would lead to an increase in melt viscosity and power consumption during processing. The extrusion process has been widely employed in the synthesis of PP/starch biocomposites and bionanocomposites, particularly with twin-screw extruders [20, 21], although a few authors have also reported the use of single-screw extruders [22].
The barrel temperature is an important parameter as it controls the melting process. Authors have reported barrel temperature ranging from 160–180 °C for the preparation of PP/starch composites. Beckermann and his coworkers [23–25] comprehensively studied hemp fiber reinforced PP composites prepared by injection molding process. Their studies included fiber treatments and modifications, model predictions of micro-mechanics and strengths, the optimization of hemp fiber quality, and the influence of bag retting and white rot fungal treatments. Panthapulakkal and Sain [26] studied the influence of water absorption on the tensile properties of injection molded short hemp fiber/glass fiber reinforced polypropylene hybrid composites. Swelling of natural fiber as a result of prolonged exposure to water was found to lead to reduction in the stiffness of the fibers.

Liu et al. [27] successfully prepared starch/PP blends with improved mechanical properties by a one-step reactive compatibility technique using maleated polypropylene (MAPP) as the interfacial agent and diethanolamine (DEA) as a reactive plasticizer for starch.

In the investigation of Rosa et al. [28] on recycled PP blended with thermoplastic starch (TPS), addition of 30% of TPS was found to reduce tensile strength of the polymer at break. Researchers have deployed several ways in enhancing these properties in starch/PP composites. DeLeo et al. [29] observed that addition of clay can greatly improve the mechanical properties of PLS/polypropylene blends at high starch content.

Gupta and Alam [30] reported that addition of MAPP to potato starch/polypropylene composite improved the tensile and flexural strengths of the composite while the impact strength remained the same. The study by Obasi et al. [31] on the utilization of thermoplastic starch obtained from cassava starch and potato starch prepared using glycerol as a plasticizer showed that plasticized starch content exhibited an inverse relationship with the tensile strength, elongation at break and was directly related to the Young’s modulus of the starch/PP blends. Liu et al. [32] found that addition of starch to PP improved bending strength, bending modulus, and Young’s modulus but to different extents decreased yield strength, tensile strength, and elongation at break. Pure starch/PP composites should be electrical insulator. However, when fillers are added, the biocomposite can be made conductive or semiconductive.

In the work of Haydaruzzaman et al. [33, 34] on starch-treated coir/jute-based hybrid PP composites and 2-hydroxyethyl methacrylate + starch treated PP composites, the maximum value of dielectric constant (the measure of the ability of a material to store electrical energy) was found
to be 289.39 and 335.46 respectively. The flame retardancy of starch/PP biocomposites is almost unexplored. A few reports [35] have shown that starch/PP biocomposites are better retardants than pure PP. Nie et al. [36] assessed the flame retardant properties of starch containing polypropylene (SCP) semi-biocomposites by limited oxygen index, UL-94 test, and cone calorimeter test.

1.3 Polypropylene (PP)/Polylactic Acid-Based Biocomposites and Bionanocomposites

Polylactic acid (PLA) is a sustainable aliphatic polyester derived from polymerization of the renewable monomer lactic acid. Besides its well-known biodegradability and renewability, the physical and mechanical properties of PLA are comparable or even better when compared with some petrochemical polymers such as polyethylene, polypropylene, polystyrene and polyethylene terephthalate. In addition to PLA/PP phases, various types of nanofillers have also been incorporated into PP/PLA biocomposites as synergists in order to develop bionanocomposites with additional functionalities like reinforcement. The main focus is on the properties of PP/PLA-based biocomposites and bionanocomposites in relation to their rheological and viscoelastic properties, mechanical and thermal properties, gas barrier properties and flame retardant behavior, etc. PP/PLA-based biocomposites and bionanocomposites can be prepared through mixing PP, PLA and/or other additives using melt blending, extrusion or spinning. Most of the PP/PLA-based biocomposites have been prepared for specimens or films through conventional melt blending, and a few studies have been reported to produce PP/PLA-based biocomposite fibers. Wojciechowska and co-authors developed a melt-spinning method for preparing PP/PLA biocomposite fiber [37]. Through optimizing the processing temperatures, PP/PLA biocomposite fibers of good quality were obtained within the whole range of component concentrations. Similar to PP/PLA-based composites, most of PP/PLA nanocomposites were prepared by melt blending, but this method is not effective enough to destroy the aggregates of nanomaterials just through mechanical shearing force.

For semicrystalline PP/PLA biocomposites, incorporation of nanofiller can also result in an altered crystallization temperature, crystallization rate and degree of crystallinity. PP/PLA-based biocomposites are electrically insulating. In order to improve their electrical conductivity, some
Polypropylene-Based Biocomposites and Bionanocomposites

Conductive nanofillers are incorporated into PP/PLA-based biocomposites. Carbon nanotube is such a conductive nanofiller that possesses exceptional electrical conductivity as well as ultrahigh mechanical strength/modulus and outstanding thermal stability/conductivity [38, 39].

The thermal degradation behavior of PP/PLA biocomposites clearly exhibited two mass loss stages, indicating the immiscibility between the two phases. The first stage is ascribed to the thermal decomposition of PLA, and the second one is assigned to the thermal degradation of PP. The incorporation of nanoclay (Cloisite 15A) into the PP/PLA composites resulted in a notable improvement in tensile modulus, but the tensile strength and elongation at break values were reduced with the addition of the nanoclay [40]. The incorporation of PP into PLA led to an increase in the impact strength of the resultant PP/PLA composites compared to neat PLA, due to the toughening effect of PP droplets. One emerging research direction for PP/PLA-based biocomposites and bionanocomposites is focused on biomedical applications. Tanaka and coworkers used a new PP/PLA (10/90) composite mesh for groin hernia repair [41]. In comparison to PP meshes (commercial product: Prolene®), this new composite biomaterial showed reduced inflammation and cell-mediated immune responses, indicating a better tolerance, which was probably due to the low mesh shrinkage and decreased tissue adhesion.

1.4 Polypropylene (PP)-Based Hybrid Biocomposites and Bionanocomposites

Hybridization allows designers to tailor the composite properties according to the desired structure under consideration [42]. Hybrid fillers combining two or more different types of fillers for polymer composites are sometimes very useful because they possess different properties that cannot be obtained with a single type of reinforcement [43]. In a study published by Uawongsuwan et al. [44] pultrusion process was used to produce long fiber pellets of jute fiber/PP and glass fiber/PP. For the making of pellets from long fiber jute and PP, four jute yarns were twisted together and passed through the impregnation die. PP-based hybrid biocomposites and bionanocomposites underwent processing at temperatures corresponding to the processing temperature of PP. The temperatures were varied in the range of 160–195 °C, depending on equipment used for shaping and composition of hybrid material. The melt temperatures did not exceed 195 °C to prevent wood degradation. This may be attributed to the improved resistance offered by the glass fibers in the composites. The mechanical properties of
injection-molded short hemp fiber/glass fiber reinforced polypropylene hybrid composites were investigated by Panthapulakkal and Sain [45].

According to Uawongsuwan et al. [46], the effectiveness of glass fiber hybridization is highest when combined with RP-JF/PP pellet composites for tensile strength (64%), flexural strength (74%) and impact strength (948%), respectively, when comparing at 20 wt% total fiber content. Turku and Kärki [47] have also found that tensile strength and modulus of hybrid biocomposites made with softwood fiber increased as compare to biocomposite made without addition of glass fibers. However, in this case, an addition of glass fiber was found to decrease the impact strength of biocomposites.

Väntsi and Kärki [48] and Huuhilo et al. [49] have studied the extruded PP-based hybrid biocomposites containing 20% of mineral filler: mineral wool fibers, talc, calcium carbonate and wollastonite. In PP/bamboo fiber and PP/sisal fiber composites reinforced with glass fibers, it was found that incorporation of fibers and MAPP interrupts the linear crystallizable sequence of the PP and lowers the degree of crystallization [50, 51]. Martikka et al. [52] showed that the microsized mineral fillers added in concentration of 20% did not have any noticeable effect on the degree of crystallinity of PP/wood fiber composites. On the other hand, nanowollastonite [53], organoclay [54] and nanosilica [55] acted as efficient nucleating agents for the crystallization of the PP matrix. The nanofillers accelerated the crystallization of the PP matrix remarkably.

The increase of heat deflection temperature upon addition of glass fibers to PP/hemp fiber or PP/sisal fiber composite was reported by Panthapulakkal and Sain [45] and Birat et al. [56], respectively. According to Panthapulakkal and Sain [45] the HDT value of neat PP was 53 °C and was increased twice by the incorporation of hemp fibers. Gwon et al. [57] have found that water absorption of PP/wood fiber composites increased with addition of mineral filler; the composite made with zinc borate had highest water absorption. Increase in the water absorption of zinc borate-containing composite is attributed to the increased void fractions during the compounding process as well as high hydrophilicity of the filler.

1.5 Biodegradation and Flame Retardancy of Polypropylene-Based Composites and Nanocomposites

Biodegradable materials can be defined as materials susceptible to being assimilated by microorganisms such as fungi and bacteria. Some non-biodegradable plastics are erroneously believed to be biodegradable because
they often contain biodegradable additives. Strömberg and Karlsson studied the biodegradation of polypropylene, recycled polypropylene and polylactide biocomposites exposed to a mixture of fungi and algae/bacteria in a microenvironment chamber [58]. Suharty et al. have shown that the addition of diammonium phosphate increased the water absorption and weight loss of a recycled PP/kenaf fiber/nano-CaCO₃ composite significantly [59]. Islam et al. have shown that the water absorption (measured in a water immersion test) of kenaf/PP and coir/PP composites increased with the addition of montmorillonite (MMT) [60]. The durability or resistance of biocomposites to various types of degradation has been the object of many studies in the field of composites. The question of the durability of the composite is inseparable from the question of degradability. Durability determines the usefulness of composite materials in a particular environment. The degree of degradation can be evaluated by estimating the change of color and appearance of the composites. In a work published by Butylina and Kärki, a comparison was made between natural and artificial weathering of PP biocomposites containing carbon black [61].

Cellulosic fibers are composed of carbon, hydrogen (fuels) and oxygen (supporter of combustion), and they are thus highly flammable and burn easily. Cellulosic fibers, being char forming material, can significantly reduce the flammability parameters of PP, including peak of heat release (pHRR), mass loss rate (MLR), total heat release (THR) and others [62–64]. However, composites have a lower decomposition temperature and shorter time to ignition [65]. Stronger interaction between the polymer and the reinforcing filler improves the thermal stability of the composite [66–68]. The crosslinking and dehydration tendency of the sulphur-containing amino acids in wool can improve char formation under combustion, making wool fibers not melting and dripping. Conzatti et al. report that wool fibers (20–60%) improved the thermal stability of PP especially in the presence of a compatibilizer [69]. Kim et al. studied the fire retardancy of a PP/wool (30%) composite containing 20% of ammonium polyphosphate (APP) [70].

Thus, the multilayered char formed during burning worked as a mass transfer barrier, slowing the escape of the volatile products generated during decomposition [52, 71]. The role of a compatibilizer in the flame retardancy of clay/PP nanocomposite is described by Gilman [72]. Tang et al. used a combination of organo-modified clay and a nickel catalyst (Ni-Cat) to enhance the carbonization of PP during burning [73]. The nickel catalyst is known as a good catalyst for the synthesis of CNTs. This combination was found to increase the fire retardancy of the composite significantly, which was reflected in the decreased peak of HRR and increased residue amount.
1.6 Polypropylene Single-Polymer Composites

Due to the need for environmentally friendly composite materials with good adhesion properties, single-polymer composites (SPCs) are of interest. SPCs refer to the class of composite materials in which the matrix and the reinforcement come from the same polymer. These materials have also been denoted as one polymer composites, homocomposites, all-the-same polymer composites, homogeneity composites, self-reinforced composites, or mono-materials. During the manufacture of PP traditional composites, the reinforcement is little affected in the preparation process. However, because the reinforcement in PP SPCs also comes from PP, the preparation methods for PP traditional composites are not suitable for PP SPCs. Injection molding and extrusion molding are the most popular processes in the industrial production of polymer composites, which are used to create many things. Injection molding is suitable for volume production of products with complex geometries such as packing, bottle caps, automotive parts and components, toys, etc.

Kmetty et al. [74] introduced thermoplastic elastomers (TPEs) into the injection molding of PP SPCs. A significantly wide processing window (about 90 °C) can be obtained. TPEs have been applied as matrix materials to produce discontinuous natural and man-made fiber reinforced composites. Abo El-Maaty et al. [75] were the first to prepare PP SPCs. Since then, different methods have been developed for preparing PP SPCs, including hot compaction, film tacking, coextrusion, injection molding, and a combination of them. In fact, the classification of these methods is mainly based on the main key process, since they all include many processes. Hine et al. [76] established the important parameters that control the hot compaction behavior of five woven oriented PPs. The five materials studied used different shaped oriented components (fibers and tapes), different molecular weight polymers and various weave styles, allowing the importance of these factors on hot compaction behavior to be studied. Hine et al. [77] described a route for manufacturing SPCs by combining the processes of hot compaction and film stacking. The idea is to use an interleaved film, preferably of the same polymer, placed between the layers of woven oriented elements, thereby delivering additional matrix material to the rougher interlayer region. The homoisotactic PP fibers are sandwiched between the PP-PE random copolymer films. The stacking material was introduced between the female and the male molds. Then, the fiber bundles of polymer are put between the polymer films at a given pressure and temperature.

Bárány et al. [78] prepared the real PP SPCs by film stacking method based on the principle of copolymer and used carded PP as the reinforcement and
random PP copolymer as the matrix to manufacture PP SPCs with film stacking. Izer et al. [79] continued to investigate the film stacking of PP SPCs with β nucleated homo- and copolymer matrices. Woven PP fabric (woven from highly stretched split PP homopolymer yarns) with melting temperature of 172.4 °C was selected as reinforcement and incorporated into ca. 50% in the corresponding PP SPC. Alcock et al. [80] investigated the interfacial properties of the highly oriented coextruded PP tapes, the T-peel strength of PP SPCs for a given homopolymer/copolymer combination is determined by the tape draw ratio, the compaction temperature, and the drawing temperature of the tape. In Alcock's research, the temperature processing window was seen to be > 30 °C, allowing PP SPCs to be consolidated at a range of temperatures. Thus the interfacial properties of the composite can be tailored during production to suit the final application.

Khondker et al. [81] used injection-compression molding method and realized the production of PP SPCs. Although the injection-compression molding method has the limitations of the compression process, it also has some of the benefits of injection molding such as short cycle time. Before the injection-compression, weft-knitting technique was adopted to produce plain knitted textile fabric. In accordance with insert injection molding, the woven fabric was pre-placed like an insert on the half cavity of the moving mold plate. After mold closing the woven fabric was fixed in the middle of the whole mold cavity, and the clamping force could press the sandwiched woven fabric tightly. Injection-compression molding and insert-injection molding for SPCs are all limited by the fabric setting, and they are still not suitable for products with complex shapes. Three-dimensional parts with complex geometry cannot be produced and thus the most design-friendly and versatile processing advantages of injection molding cannot be adapted.

### 1.7 Polypropylene/Plant-Based Fiber Biocomposites and Bionanocomposites

PBFs are natural composites in which the reinforcement constituent is distributed within a flexible matrix. Each fiber at the macroscopic level is a bundle of microfibers with the diameter in the range of 20–40 μm [82]. Injection molding is one of the most versatile processing methods for manufacturing of natural fiber PP composites. This process is usually used for producing interior parts of automobiles with the thickness of 2–5 mm like instrument panel components, consoles, door handles, and load floors. Natural fiber-PP composites are used in injection-molded products like
home and office furniture, lawn and garden products, toys, housewares, power tools, sporting goods, and storage containers.

Natural fiber and PP improves interfacial adhesion, resulting in better mechanical properties. The aim of chemical treatments is to substitute some of the hydroxyl groups in the natural fiber surface with these bi-functional materials. Based on the coupling agent introduced into the fibers, there are various chemical treatments such as silane treatment, acetylation, and so on [83, 84]. Maleic anhydride is the most common coupling agent used in natural fiber-PP biocomposites. The main difference of maleic anhydride with other coupling agents is that it is mostly used to modify PP instead of natural fibers. Nowadays, different grades of maleic anhydride grafted polypropylene (MAgPP) are in the market, which are utilized to compatibilize PP with not only natural fibers, but also other reinforcements like glass fibers. However, they are highly limited by their high moisture absorption and weak interfacial adhesion between polar-hydrophilic fibers and nonpolar-hydrophobic petroleum-based plastics. The recent studies indicate an improvement in wood fiber–PP matrix bonding in the presence of compatibilizers or coupling agents [85–87].

In addition, different chemical treatments on fibers aimed at improving the adhesion between the fiber surface and matrix may not only increase the mechanical properties but also modify the surface of the fibers. Moreover, results have shown that the water absorption of natural fiber reinforced biocomposites is decreased significantly due to such chemical modifications on natural fibers as acetylation, alkali, acrylation, silane, benzoylation, permanganate, and isocyanates [88–90]. Several studies have been conducted on physical and/or chemical treatments and modification of the surface of jute fibers for improving the mechanical and physical properties of the biocomposite materials [91, 92].

For instance, a systematic study of the effect of surface treatments on the properties of PP/jute fiber has been carried out by Wang et al. [93]. Karmaker et al. have shown that swelling of an embedded jute fiber in PP, caused by water absorption, is able to fill the gaps between fibers and matrix, which were mainly formed because of the thermal shrinkage of PP melt. The fill-up of such gaps results in a higher shear strength between jute fibers and PP, and increases the mechanical properties accordingly [94]. Joseph et al. [95] comprehensively delved into the effects of processing parameters on the mechanical properties of sisal fiber reinforced PP biocomposites. Such biocomposites were prepared by both melt-mixing and solution-mixing methods. In addition, biocomposites containing longitudinally oriented fibers presented better mechanical properties than those with random and transverse orientations. The influence of chemical
treatment on the tensile properties of sisal/PP biocomposites was carried out by such treatments as sodium hydroxide, urethane derivative of PPG, maleic anhydride, and permanganate [96].

The recycling of hemp fiber reinforced PP has been studied extensively for many years [97]. As expected, the length of fibers, molecular weight, and Newtonian viscosity have been decreased by reprocessing of composite. Despite the number of reprocessing cycles, the mechanical properties of recycled hemp fiber/PP biocomposites remain well preserved. Natural fibers are often considered for nonstructural applications that require low costs, low energy for processing, biodegradability, and light weight. For example, non-load-bearing indoor components in civil engineering are successfully produced with natural fiber reinforced composites because of their vulnerability to environmental attack [98].

1.8 Polypropylene Composite with Oil Palm Fibers: Method Development, Properties and Application

Chemical pretreatment involves the dissolution of lignin, hemicelluloses and crystalline part of oil palm lignocellulose with the help of mineral or organic compounds. The depolymerization is achieved by hydrolysis brought by acid or alkali. Acid hydrolysis is normally associated with the use of phosphoric, sulphuric, formic, peracetic or hydrochloric acid [99]. The effective autoclaving treatment not only disinfects, but also opens up lignocelluloses for penetration of reagents and for hydrolysis to take place.

Delignification and cellulose extraction from oil palm fibers (empty fruit bunches, mesocarps, frond and trunk) is challenging because of its inert nature and compact structure. Very strong acid and alkali may have to be used to treat the fibers and often it takes a long time to achieve the desired result. To speed up the process, multipronged approaches can be adopted such as the combination of different solvents, reactive species and assistance of electromagnetic radiations or ultrasonic and mechanical treatments. The natural plant fibers with higher cellulose content appear to potentially show better mechanical properties [100]. Cellulose whiskers (CWs) extracted from grass used as filler to fabricate polymer composite show improved composite mechanical properties and thermal stability after alkali treatment on the whiskers. Better mechanical properties are observed at 5% filler but any further loading reduces thermal stability and also the elongation due to phase separation [101]. The palm and coir fiber reinforced PP composites fabricated through injection molding show