VOL 5

Handbook of Composites from Renewable Materials

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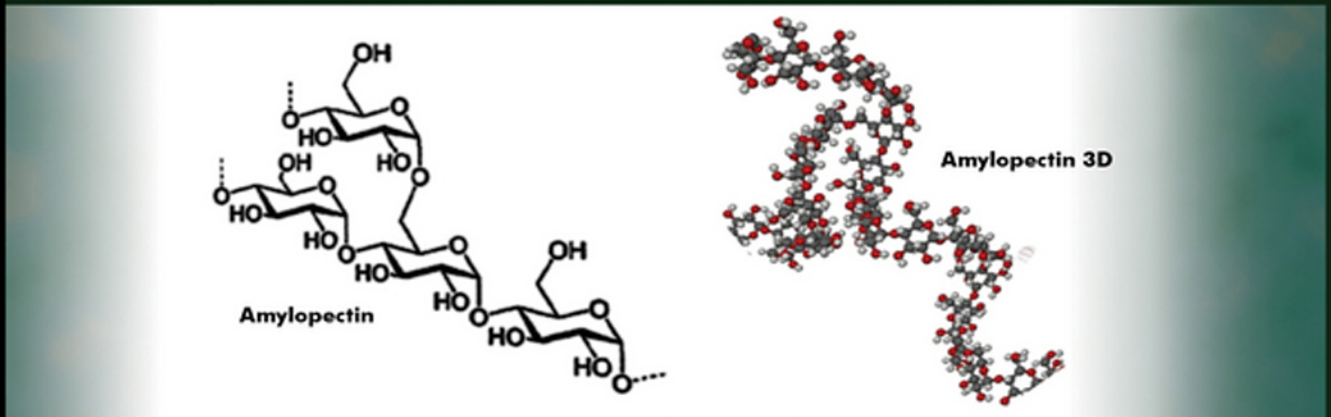

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To my parents and teachers who helped me become what I am today.

Vijay Kumar Thakur

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Preface

The concept of green chemistry and sustainable development policy impose on industry and technology to switch raw material base from the petroleum to renewable resources. Remarkable attention has been paid to the environmental-friendly, green, and sustainable materials for a number of applications during the past few years. Indeed, the rapidly diminishing global petroleum resources, along with awareness of global environmental problems, have promoted the way to switch toward renewable resources-based materials. In this regard, biobased renewable materials can form the basis for a variety of eco-efficient, sustainable products that can capture and compete markets presently dominated by products based solely on petroleum-based raw materials. The nature provides a wide range of the raw materials that can be converted into a polymeric matrix/adhesive/reinforcement applicable in composites formulation. Different kinds of polymers (renewable/nonrenewable) and polymer composite materials have been emerging rapidly as the prospective substitute to the ceramic or metal materials, due to their advantages over conventional materials. In brief, polymers are macromolecular groups collectively recognized as polymers due to the presence of repeating blocks of covalently linked atomic arrangement in the formation of these molecules. The repetitive atomic arrangements forming the macromolecules by forming covalent links are the building block or constituent monomers. As the covalent bond formation between monomer units is the essence of polymer formation, polymers are organic or carbon compounds of either biological or synthetic origin. The phenomenon or process of polymerization enables to create diverse forms of macromolecules with varied structural and functional properties and applications. On the other hand, composite materials, or composites, are one of the main improvements in material technology in recent years. In the materials science field, a composite is a multiphase material consisting of two or more physically distinct components, a matrix (or a continuous phase) and at least one dispersed (filler or reinforcement) phase. The dispersed phase, responsible for enhancing one or more properties of matrix, can be categorized according to particle dimensions that comprise platelet, ellipsoids, spheres, and fibers. These particles can be inorganic or organic origin and possess rigid or flexible properties.

The most important resources for renewable raw materials originate from nature such as wood, starch, proteins, and oils from plants. Therefore, renewable raw materials lead to the benefit of processing in industries owing to the short period of replenishment cycle resulting in the continuous-flow production. Moreover, the production cost can be reduced by using natural raw materials instead of chemical raw materials. The waste and residues from agriculture and industry have also been used as an alternative renewable resources for producing energy and raw materials such as chemicals,

cellulose, carbon, and silica. For polymer composites applications, an intensifying focus has been directed toward the use of renewable materials. Biobased polymers are one of the most attractive candidates in renewable raw materials for use as organic-reinforcing fillers such as flex, hemp, pine needles, coir, jute, kenaf, sisal, rice husk, ramie, palm, and banana fibers, which exhibited excellence enhancement in mechanical and thermal properties. For green polymer composites composed of inorganic-reinforcing fillers, renewable resources-based polymers have been used as matrix materials.

Significant research efforts all around the globe are continuing to explore and improve the properties of renewable polymers-based materials. Researchers are collectively focusing their efforts to use the inherent advantages of renewable polymers for miscellaneous applications. To ensure a sustainable future, the use of biobased materials containing a high content of derivatives from renewable biomass is the best solution.

This volume of the book series '*Handbook of Composites from Renewable Materials*' is solely focused on the '*Biodegradable Materials*'. Some of the important topics include but not limited to rice husk and its composites; biodegradable composites based on thermoplastic starch and talc nanoparticles; recent progress in biocomposites of biodegradable polymer; microbial polyesters: production and market; biodegradable and bioabsorbable materials for osteosynthesis applications; biodegradable polymers in tissue engineering; composites based on hydroxyapatite and biodegradable polylactide; biodegradable composites; development of membranes from biobased materials and their applications; green biodegradable composites based on natural fibers; fully biodegradable all-cellulose composites; natural fiber composites with bioderivative and/or degradable polymers; synthetic biodegradable polymers for bone tissue engineering; polysaccharides as green biodegradable platforms for building up electroactive composite materials; biodegradable polymer blends and composites from seaweeds; biocomposites scaffolds derived from renewable resources for bone tissue repair; pectin-based composites; recent advances in conductive composites based on biodegradable polymers for regenerative medicine applications; biosynthesis of PHAs and their biomedical applications; biodegradable soy protein isolate/poly(vinyl alcohol) packaging films; and biodegradability of biobased polymeric materials in natural environment.

Several critical issues and suggestions for future work are comprehensively discussed in this volume with the hope that the book will provide a deep insight into the state of the art of '*Biodegradation*' of the renewable materials. We would like to thank the Publisher and Martin Scrivener for the invaluable help in the organization of the editing process. Finally, we would like to thank our parents for their continuous encouragement and support.

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Rice Husk and its Composites: Effects of Rice Husk Loading, Size, Coupling Agents, and Surface Treatment on Composites' Mechanical, Physical, and Functional Properties

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Abstract

Among the many natural fibers used as reinforcements/fillers in the manufacture of natural fiber composite materials, rice husk (RH) has not been attracting the deserved attention despite its significant annual yield of tens of million tons due to the huge worldwide rice-consuming population. This chapter presents an introduction to natural fibers and their composites with an emphasis on RH and its use in the manufacture of composite materials. A thorough review has been carried out on the manufacturing of RH composites with various polymers and manufacturing processes. The effects of RH loading, size, surface treatment, and the use of coupling agents on mechanical, physical, and functional properties of RH composites have been discussed in detail. Although RH has also been used in the form of ash in manufacturing different composites, this chapter only focuses on RH used in its natural form and its resulting composites.

Keywords: Rice husk, coupling agents, surface treatment, composites manufacturing, mechanical, physical and functional properties

1.1 Introduction

By definition, natural fibers are fibers which are not artificial or manmade (Ticoalu *et al*., 2010). Natural fibers can be plant based such as wood, sisal, flax, hemp, jute, kenaf, and ramie or animal based, e.g., wool, avian feather, and silk or mineral based such as basalt and asbestos. They have been used as reinforcements with a variety of materials for over 3000 years (Taj *et al*., 2007) and have demonstrated immense potential to replace synthetic fibers, such as glass and carbon fibers, because of their eco-friendly and biodegradable characteristics.

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There is a large variation in the properties of natural fibers, which is affected by several factors such as fiber's place of growth, cultivation conditions, growth time, moisture content, and form (yarn, woven, twine, chopped, and felt) (O'Donnell *et al.*, 2004; Ochi, 2008; Pickering *et al.*, 2007). Table 1.1 shows various plant-based natural fibers and their regions or countries of origin.

The mechanical and physical properties of natural fibers are greatly affected by their chemical composition and structure (Taj *et al.*, 2007). The majority of plant-based natural fibers have cellulose, hemicellulose, and lignin as their main constituents along with pectin and waxes (John & Thomas, 2008). The reinforcing ability of natural fibers depends on cellulose and its crystallinity (Bledzki & Gassan, 1999, John & Thomas, 2008), whereas biodegradation, micro-absorption, and thermal degradation of natural fibers depend on hemicelluloses (Taj *et al.*, 2007), which is hydrophilic in nature (John & Thomas, 2008). On the other hand, lignin which is hydrophobic in nature plays a critical role in protecting the cellulose/hemicellulose from severe environmental conditions such as water (Thakur & Thakur, 2014), and is thermally stable but prone to UV degradation (Olesen & Plackett, 1999); pectin gives plants flexibility, while waxes consist of various types of alcohols (John & Thomas, 2008). Each of these constituents of natural fibers plays an important role in determining the overall properties of natural fibrous materials (Thakur *et al.*, 2014b).

These fibers are chemically active and decompose thermo-chemically between 150 °C and 500 °C (cellulose between 275 °C and 350 °C; hemicellulose mainly between 150 °C and 350 °C; and lignin between 250 and 500 °C) (Kim *et al.*, 2004).

The relative percentages of cellulose, hemicellulose, and lignin vary for different fibers (John & Thomas, 2008). Table 1.2 shows the chemical composition of some natural fibers.

Table 1.1 Fibers and their origin (Taj *et al.*, 2007; Kim *et al.*, 2007).

Fibers	**Regions/countries of origin**
Flax	Borneo
Hemp	Former Yugoslavia, China
Sun hemp	Nigeria, Guyana, Sierra Leone, India
Ramie	Honduras, Mauritius
Jute	India, Egypt, Guyana, Jamaica, Ghana, Malawi, Sudan, Tanzania
Kenaf	Iraq, Tanzania, Jamaica, South Africa, Cuba, Togo
Roselle	Borneo, Guyana, Malaysia, Sri Lanka, Togo, Indonesia, Tanzania
Sisal	East Africa, Bahamas, Antigua, Kenya, Tanzania, India
Abaca	Malaysia, Uganda, Philippines, Bolivia
Coir	India, Sri Lanka, Philippines, Malaysia
Rice husk	Asia, Pacific rim, North America

Table 1.2 Chemical composition of some natural fibers (Malkapuram *et al.*, 2009).

Fiber	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Pectin (wt%)	Wax (wt%)	Moisture content (wt%)
Wood	40–50	15–25	15–30	–	–	8–16
Jute	61–71.5	13.6–20.4	12–13	0.4	0.5	12.6
Hemp	70.2–74.4	17.9–22.4	3.7–5.7	0.9	0.8	10
Kenaf	31–39	21.5	15–19	–	–	–
Flax	71	18.6–20.6	2.2	2.3	1.7	10
Sisal	67–78	10–14.2	8–11	10	2.0	11
Coir	36–43	10–20	41–45	3–4	–	8
Bamboo	26–49	15–27.7	21–31	–	–	–

Generally, an increase in the cellulose content increases tensile strength and Young's modulus of fibers, whereas stiffness also depends on the micro-fibrillar angle. Fibers are rigid, inflexible, and have high tensile strength if the micro-fibrils have an orientation parallel to the fiber axis. If the micro-fibrils are oriented in a direction spiral to the fiber axis, the fibers are more ductile (John & Thomas, 2008). This variation of material properties does cause some concerns about the use of such materials in the more advanced and critical applications such as composite components for automobiles, infrastructure, aeronautical, and aerospace industries.

Agricultural wastes such as RH, wheat straw, rice straw, and corn stalks also come under the category of natural fibers. Researchers are now increasingly looking toward these by-products for manufacturing composite materials (Panthapulakkal *et al.*, 2005b; Nourbakhsh & Ashori, 2010; Ghofrani *et al.*, 2012). The use of these agricultural by-products provides a great opportunity to start a natural fiber industry in those countries which have little or no wood resources (Ashori & Nourbakhsh, 2009). The chemical components and contents of these materials are similar to those of wood and they can be used in the form of fibers or particles (Yang *et al.*, 2004; Yang *et al.*, 2006b). With the comparatively large quantity of agro-wastes from annual crops, Table 1.3, there is a potential that wood can be substituted by these alternative materials (Ashori & Nourbakhsh, 2009). These agro-residues are normally used as animal feed or household fuel and a large proportion is burned for disposal, which adds to environmental pollution (Ashori & Nourbakhsh, 2009). These agricultural waste fibers can be formed into chips or particles similar to wood (Yang *et al.*, 2003), and their exploration and utilization will contribute to rural agricultural-based economies in a positive way (Sain & Panthapulakkal, 2006).

1.2 Natural Fiber-Reinforced Polymer Composites

Composite materials consist of two or more ingredients in which one component acts as the matrix material and the other as the reinforcement (Pappu *et al.*, 2015) and their

Table 1.3 Annual production of natural fibers and sources (Taj *et al.*, 2007).

Fiber source	World production 10^3 tons	Origin	Fiber source	World production 10^3 tons	Origin
Abaca	70	Leaf	Nettles	Abundant	Stem
Bamboo	10,000	Stem	Oil palm fruit	Abundant	Fruit
Banana	200	Stem	Palm rah	–	Stem
Broom	Abundant	Stem	Ramie	100	Stem
Coir	100	Fruit	Roselle	250	Stem
Cotton lint	18,500	Stem	Rice husk	Abundant	Fruit/grain
Elephant grass	Abundant	Stem	Rice straw	Abundant	Stem
Flax	810	Stem	Sisal	380	Stem
Hemp	215		Sun hemp	70	Stem
Jute	2,500		Wheat straw	Abundant	
Kenaf	770		Wood	1,75,000	
Linseed	Abundant	Fruit			

overall properties depend on the individual characteristics of the polymer matrix and the reinforcement (Thakur *et al.*, 2014a).

Although research on natural fiber-reinforced polymer composites (NFRCs) began in 1908 (John & Thomas, 2008), it has not received much attention until from about three decades ago (Westman *et al.*, 2010). Nowadays, both the academic and industrial sectors are showing a significantly increased interest in the use of NFRCs due to their low cost, environmental friendliness, lightweight, biodegradable, and nonabrasive nature (Rozman *et al.*, 2000). Moreover, they have high electrical resistance, good acoustic insulating properties, low energy consumption, less dermal and respiratory irritation, good chemical and corrosion resistance, and are safe to handle (Ticoalu *et al.*, 2010; Taj *et al.*, 2007; John & Thomas, 2008; Malkapuram *et al.*, 2009; Ashori, 2008; Mavani *et al.*, 2007).

With the reported advantages of NFRCs and the growing awareness on the depletion of petroleum-based resources as well as global environmental issues, the demand of NFRCs has predicted to grow 15–20% annually with a growth rate of 15–20% in automotive applications (Malkapuram *et al.*, 2009), and 50% or more in building and construction applications. North America is known as the leading region of NFRC applications in the building and construction sectors with mainly wood fiber-based composites, whereas Europe is the leading region of NFRC applications in the automotive industries with mostly nonwood fiber-based composites (Lucintel, 2011). Of course, there are other NFRC applications emerging in the other regions of the globe. The earlier forecast for the NFRC market was with a compound annual growth rate

(CAGR) of 10% to reach $3.8B by 2016 (Lucintel, 2011); interestingly, it has shown that RH is emerging as an alternative for wood fibers in the applications of the building and construction sectors.

Despite the promising forecast, NFRCs do have some inherent issues which need to be addressed properly before their full potential can be realized for widespread industrial applications in various sectors. Along with the nature of the fibers, the properties of the resulting composites are also influenced by the type of polymer matrix used and the amount and dimensions of the fiber. One of the critical issues is the weak adhesion and poor interfacial bond strength between natural fibers and the matrix (Lee *et al*., 2004; Hristov *et al*., 2004), and formation of aggregates during their processing (Taj *et al*., 2007; Ashori, 2008), leading to inferior mechanical properties. Natural fibers are polar and hydrophilic in nature and polymer matrix is nonpolar and hydrophobic, which form the heterogeneous systems for NFRCs. Surface tension as well as polarity of matrix and the fibers should be the same in order to have good interfacial adhesion in NFRCs (Mwaikambo & Ansell, 2002), and a suitable adhesion is required between the matrix and the filling material in order to improve mechanical properties of the composites (Yang *et al*., 2004).

Due to the hydrophilicity of natural fibers, NFRCs could absorb water when used in moist conditions which leads to the poor compatibility between fibers and hydrophobic polymer matrices (Yang *et al*., 2006a). The water absorption (WA) is due to the hydrogen bond developed between the hydroxyl groups (OH) in the natural fibers and water molecules present in the environment. Therefore, it is essential to prevent such moisture infiltration so that swelling and/or permanent damage can be avoided for effective usage of these cellulosic composites in wet conditions (Ishak *et al*., 2001).

In order to enhance the performance of NFRCs, the compatibility between hydrophilic fibers and hydrophobic polymers can also be improved by using coupling agents and/or surface modification of fibers. These measures can create efficient interfacial bond strength between the fibers and the polymer matrices so that the effective load transfer can be achieved when NFRCs are subjected to loading during applications.

Coupling agents, who have both the hydrophilic and hydrophobic properties necessary to bond well with the fiber and the polymer matrix, make polymers more reactive toward the surface of the natural fiber (Panthapulakkal *et al*., 2005b; Ershad-Langroudi *et al*., 2008; Ahmad Fuad *et al*., 1993; Stark & Rowlands, 2003; Toro *et al*., 2005; Park *et al*., 2004; Sombatsompop *et al*., 2005). They chemically link with the hydrophilic fiber on one side and the hydrophobic polymer chain on the other to facilitate the wetting of polymer surrounding the fibers. The interfacial region between the fiber and the matrix has two types of interaction, i.e., primary and secondary bonding represented by covalent bonding and hydrogen bonding, respectively (Rozman *et al*., 2005a; Rozman *et al*., 2003).

1.3 Rice Husk and its Composites

Rice is a source of primary food for the majority of the population worldwide. Around 20 wt% of paddy received is husk which is separated from the rice grain during milling process (Chand *et al*., 2010); therefore, rice husk (RH) is abundantly available

in significant quantity. The annual production of rice in 2012 was approximately 718 million tons according to the Food and Agriculture Organization of the United Nations (FAO, 2012). RH is biodegradable, abundant, cost effective, lightweight, easily available, reduces the density of the finished product, has no residues or toxic by-products, is environmentally friendly, low density, and recyclable (Yang *et al*., 2004; Yang *et al*., 2006a; Ibrahim and Kuek, 2011; Rahman *et al*., 2010a; Premalal *et al*., 2002).

RH is mainly used as fuel, fertilizer in agriculture, landfill, and animal bedding (Kim & Eom, 2001; Park *et al*., 2003; Mano, 2002), but the majority of RH is burnt for disposal because of its resistance to decomposition in the ground, and its difficulty to digest and low nutritional value for animals (Piva *et al*., 2004). In the past few years, researchers have looked into the possibility of using RH, which is mostly an unwanted material, for making composite materials (Razavi-Nouri *et al*., 2006).

Similar to other natural fibers, RH has cellulose, hemicelluloses and lignin as its main constituents (George and Ghose, 1983), noticeably it also contains significant amount of silica (20 wt%), which is present on its outer surface in the form of silicon–cellulose membrane (Yoshida, 1962). RH has a cellulose content (35 wt%) similar to that of wood (Martí-Ferrer *et al*., 2006; Rosa *et al*., 2009b) but has lower contents of lignin (20 wt%) and hemicellulose (25 wt%) than those found in most other natural fibers including wood. Since the thermal degradation of RH occurs due to the degradation of hemicellulose and lignin (Kim *et al*., 2004), a similar mechanism to that of wood, the lower content of lignin and hemicellulose allows RH-filled polymers to be processed at higher temperatures as compared to wood polymer composites. While wood has thermal stability issues at temperatures over just 200 °C, RH degrades and decomposes at temperatures around 250 °C which enables the manufacturing of RH composites to be performed at higher temperatures up to 250 °C (Martí-Ferrer *et al*., 2006) without concern of losing material properties.

RH as reinforcement/filler in polymer-based composite materials has proven to be a good option, provided there is good compatibility between RH and base polymer matrix (Chand *et al*., 2010). Like other plant-based natural fibers, RH is hydrophilic and its use with hydrophobic thermoplastics results in poor compatibility and adhesion between the counter parts (Panthapulakkal *et al*., 2005a; Dhakal *et al*., 2007; Sain & Kokta, 1993; Lai *et al*., 2003; Kazayawoko *et al*., 1999; Sain *et al*., 1993; Li & Matuana, 2003). One of the reasons for poor adhesion is the presence of silica, which is present in the form of a silicon–cellulose membrane on the outer surface of RH (Vasishth, 1974). Removal of silica and other surface impurities can result in a better adhesion between the fiber and the matrix and in turn improve properties of composites (Sain & Panthapulakkal, 2006). Fiber matrix adhesion can also be improved by introducing coupling agents (Panthapulakkal *et al*., 2005a; Dhakal *et al*., 2007; Kazayawoko *et al*., 1999, Lai *et al*., 2003; Sain *et al*., 1993; Sain & Kokta, 1993).

RH is also more resistant to WA and fungal decomposition because it contains 20 wt% amorphous silica in combination with 30 wt% of a phenyl propanoid structural polymer called lignin (Rahman *et al*., 2010b). As mentioned earlier, common NFRCs have a major disadvantage of WA mainly due to diffusion or infiltration (Czél & Kanyok, 2007). In the case of RH, the percentage of cellulose is very low and the waxes contained also make it comparatively less prone to water uptake.

Composites made from RH have better dimensional stability under moist conditions, good termite resistance, and high resistance to biological attack as compared to wood-based materials (Kim *et al*., 2007). These RH composites have reasonable strength and stiffness, no residues or toxic by-products when burnt, are recyclable, and low CO_2 emissions when compared with inorganic-filler-reinforced polymer composites (Kim *et al*., 2007; Yang *et al*., 2006a; Razavi-Nouri *et al*., 2006; Kim *et al*., 2005).

Flammability is another problem faced by natural fiber composites. Synthetic polymers are petroleum based and are highly flammable. Various flame-retardant materials such as halogen and phosphorus-based compounds can be used with polymers to improve flame retardancy, but these flame retardants have a negative impact on the environment and raise health concerns as well (Zhao *et al*., 2009). RH could prove to be a good flame-retardant material in composites as it contains silica as one of the main constituents. Silica is mainly responsible for the improved flame retardancy by providing thermal shielding and diffusion barrier effects during the combustion process (Zhao *et al*., 2009; Arora *et al*., 2012).

RH has been used both in thermoplastics and thermosets. The following subsections discuss a wide range of research undertaken in the area of RH composites. The main focus of discussion is the type of polymers and manufacturing processes involved in the manufacture of RH composites. The effects of RH loading and coupling agents on mechanical, physical and functional properties of RH composites are also discussed.

1.3.1 Polymers Used in the Manufacturing of RH Composites

Over the past two decades, although both thermoplastics and thermosets have been used as matrices in manufacturing of RH composites, yet thermoplastic polymers have been the primary candidate for RH composites. Among the commonly available thermoplastic resins, PE and PP of different densities (i.e., low, medium, and high) have been used the most. On one hand, PE is primarily used as an exterior building component. Low-density polyethylene (LDPE) has properties such as fluidity, flexibility, transparency, and a glossy surface and has been used mainly as a food packing material in the forms of sheet and film; whereas, high-density polyethylene (HDPE) has toughness, stiffness, solvent resistance, and electrical insulation and is mainly used as an insulating material for electric wire and for producing various types of containers (Yang *et al*., 2007b). The manufacturing of composites with RH as reinforcement and PE (low, medium, and high densities) as polymer matrix has been carried out by quite a number of researchers (Yang *et al*., 2007b; Kim *et al*., 2004; Panthapulakkal *et al*., 2005b; Ghofrani *et al*., 2012; Yang *et al*., 2006a; Rahman *et al*., 2010a; Panthapulakkal *et al*., 2005a; Rahman *et al*., 2010b; Zhao *et al*., 2009; Khalf & Ward, 2010; Najafi & Khademi-Eslam, 2011; Fávaro *et al*., 2010; Syafri *et al*., 2011; Rahman *et al*., 2011; Bilal *et al*., 2014a-c).

On the other hand, PP is one of the most widely used packaging materials (George *et al*., 2007). It is also commonly used in the automotive industry and recently has been studied for use as building profiles (Razavi-Nouri *et al*., 2006). Similar to PE, composites manufactured with PP (low, medium, and high densities) and RH has also been widely researched (Kim *et al*., 2007; Kim *et al*., 2004; Ashori & Nourbakhsh, 2009; Yang *et al*., 2004; Yang *et al*., 2006a,b; Ishak *et al*., 2001; Ershad-Langroudi *et al*., 2008;

Table 1.4 Manufacturing processes used in the manufacture of RH composites.

Manufacturing process	Reference
Injection molding	Kim *et al.*, 2007; Ashori & Nourbakhsh, 2009; Yang *et al.*, 2004; Yang *et al.*, 2006b; Yang *et al.*, 2006a; Ishak *et al.*, 2001; Ershad-Langroudi *et al.*, 2008; Rahman *et al.*, 2010a; Razavi-Nouri *et al.*, 2006; Rahman *et al.*, 2010b; Czél & Kanyok, 2007; Yang *et al.*, 2007b; Fávaro *et al.*, 2010; Rahman *et al.*, 2011; Bilal *et al.*, 2014b; Bilal *et al.*, 2014c; Bilal *et al.*, 2014a; Yang *et al.*, 2007a; He *et al.*, 2011; Yussuf *et al.*, 2010, de Carvalho *et al.*, 2011; Nourbakhsh *et al.*, 2014
Compression molding	Chand *et al.*, 2010; Premalal *et al.*, 2002; Rosa *et al.*, 2009b; Zhao *et al.*, 2009; Syafri *et al.*, 2011; Rosa *et al.*, 2009a; Santiagoo *et al.*, 2011
Extrusion	Aminullah *et al.*, 2010; Wang *et al.*, 2014; Panthapulakkal *et al.*, 2005a; Panthapulakkal *et al.*, 2005b
Hot press	Ghofrani *et al.*, 2012; Rozman *et al.*, 2000; Rozman *et al.*, 2005a; Rozman *et al.*, 2003; Khalf & Ward, 2010; Najafi & Khademi-Eslam, 2011; Nordyana *et al.*, 2013; Zuhaira *et al.*, 2013; Zurina *et al.*, 2004; El Sayed *et al.*, 2012; Ndazi *et al.*, 2007; Rozman *et al.*, 2005b; Bakar & Muhammed, 2011
Others	Arora *et al.*, 2012; Sheriff *et al.*, 2009; Ahmad *et al.*, 2007; Hua *et al.*, 2011; Sharma & Chand, 2013

Premalal *et al.*, 2002; Razavi-Nouri *et al.*, 2006; Rosa *et al.*, 2009a,b; Czél & Kanyok, 2007; Santiagoo *et al.*, 2011; El Sayed *et al.*, 2012; Aminullah *et al.*, 2010; Yang *et al.*, 2007a; He *et al.*, 2011).

Apart from PE and PP, phenol formaldehyde (PF) (Bhatnagar, 1994; Ndazi *et al.*, 2007), polyurethane (PU) (Sheriff *et al.*, 2009; Rozman *et al.*, 2003), polyester (Rozman *et al.*, 2005a; Ahmad *et al.*, 2007, Rozman *et al.*, 2005b), polymer lactic acid (PLA) (Yussuf *et al.*, 2010, Hua *et al.*, 2011), polyvinylchloride (PVC) (Chand *et al.*, 2010), polyvinyl alcohol (PVA) (Arora *et al.*, 2012), polystyrene (Rozman *et al.*, 2000), urea formaldehyde (UF) (Bakar & Muhammed, 2011), and epoxy (Ibrahim & Kuek, 2011) have also been used to manufacture composites with RH.

Injection molding, compression molding, extrusion, and hot press are the most commonly used techniques to manufacture RH-reinforced composite materials. The manufacturing of composites with different manufacturing processes using RH is shown in Table 1.4.

1.3.2 Effects of RH Loading on the Properties of RH Composites

RH has been used with different percentages for the manufacturing of composites, as shown in Table 1.5. The effect of RH loading on mechanical, physical, and functional properties has been widely investigated.