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Review

A review on new bio-based constituents for natural fiber-polymer composites

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ABSTRACT

Composite materials based on renewable agricultural and biomass feedstocks are increasingly utilized as these products significantly offset the use of fossil fuels and reduce greenhouse gas emissions in comparison with conventional petroleum-based materials. However, the inclusion of natural fibers in polymers introduces several challenges, such as excess water absorption and poor thermal properties, which need to be overcome to produce materials with comparable properties to the conventional composite materials. Instead of using rather expensive chemical and physical modification methods to eliminate these aforementioned challenges, a new trend of utilizing waste, residues, and process by-products in natural fiber-polymer composites (NFPCs) as additives or reinforcements may bring considerable enhancements in the properties of NFPCs in a sustainable and resilient manner. In this paper, the effects of waste materials, residues or process by-products of multiple types on NFPCs are critically reviewed and their potential as NFPC constituents is evaluated.

Contents

1. Introduction and background

In response to the consumers' demands for lighter-weight, energy-efficient, carbon sequestering and more sustainable materials, industries are focusing more and more on materials based on renewable resources (Fiksel, 2003; Stokke et al., 2014). Ecological

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concerns such as environmental safety and recyclability have also resulted in an increasing interest in green materials (Sain and Panthapulakkal, 2004). Furthermore, the need to find new alternatives for materials derived from non-renewable resources is strongly present at the level of policy generation. The governmental considerations seem to be aligning to create an environment for producing more advanced products from various types of biomasses (Winandy et al., 2008).

Natural fiber-polymer composites (NFPCs) have a status of renewable and sustainable materials since they are composed of natural fibers embedded in a polymer matrix, which may be also of biological origin (e.g. polylactic acid, PLA) (Väisänen et al., 2016). Natural fibers are derived either directly from agricultural sources or as a processing or production residues when crops are processed for their primary uses, such as nutrition (Bassyouni and Waheed Ul Hasan, 2015). Examples of natural fibers used in NFPCs include wood, jute, hemp, kenaf, sisal, coir, flax, bamboo and fruit fibers. Matrix materials of NFPCs can be classified into thermosets and thermoplastics, and further into non-degradable and biodegradable polymers (Puglia et al., 2005). NFPCs with non-degradable thermoplastics cannot undergo biodegradation but they can be easily recycled compared to thermoset composites. In contrast, NFPCs consisting of a biodegradable polymer matrix can be broken down into natural degradation products after their intended use (Sain and Panthapulakkal, 2004).

Thermoplastics are the most commonly used matrix materials for NFPCs as they are, in contrast to thermosets, re-moldable, thus permitting more efficient use of raw materials through recycling (Clemons, 2008). Polypropylene (PP), polyethylene (PE), polystyrene (PS) and polyvinyl chloride (PVC) are examples of thermoplastics used in NFPCs. Examples of thermosets include epoxy, polyesters and polyurethane (PU). Commonly used biodegradable polymer matrices are PLAs, polyglycolic acid (PGA), poly-β-hydroxyalkanoates (PHA), which are thermoplastics, and polycaprolactone (PCL), which is a thermoset (Sain and Panthapulakkal, 2004).

The partial substitution of the polymer with natural fibers provides multiple advantages as natural fibers are inexpensive, typically biodegradable and have a low density. In addition, some properties, such as tensile strength and elastic modulus, of the resulting composite materials are better compared with the neat polymers (El-Shekeil et al., 2012; Mohanty et al., 2006; Mutje et al., 2007; Premalal et al., 2002; Rashed et al., 2006). More importantly, NFPCs have shown better performance in life cycle assessments (LCAs) when compared with conventionally reinforced composites (Joshi et al., 2004). Overall, NFPCs have an advantage in relation to toxicity, emission of effluent, energy consumption and abundance of disposal options (Patel et al., 2005).

There are also other factors contributing towards improved market development and opportunities for NFPCs (Pandey et al., 2015). The development of production and manufacturing processes with intentions to mitigate environmental damages are being supported by legislative provisions. Moreover, the dedication of research institutions and centers to find new ways to elevate the status on natural fibers to a new level while considering the balance between sustainability, economics and performance is also an important factor influencing the future prospects of NFPCs. The most important factors determining the commercial success of NFPCs are presented in Fig. 1.

To expand the use of NFPCs in a variety of applications, the properties of these composites should be somewhat comparable to the conventional materials like metals and petrochemical derivatives. If the density of the fiber is not taken into account, synthetic fibers have superior mechanical properties compared to natural fibers. However, the specific strength and modulus (Table 1) of natural fibers are similar to synthetic fibers. Furthermore, the price of natural fibers is considerably lower than that of synthetic fibers (Table 2).

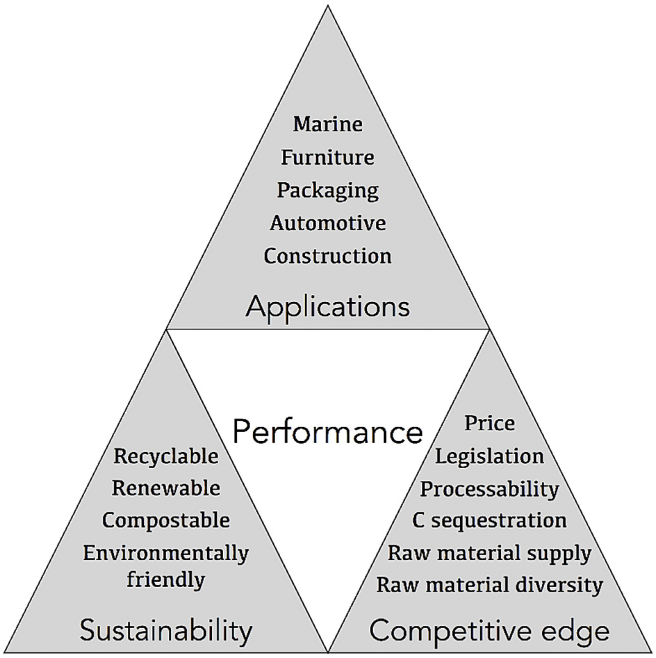

Fig. 1. The triangle of commercial success for NFPCs.

However, in many cases, NFPCs do not possess a similar level of performance as, e.g., glass fiber reinforced composites (Zini and Scandola, 2011), which is mainly due to the incompatibility between hydrophilic natural fiber and hydrophobic polymer matrix. Traditionally, this issue has been at least partially solved by adequate physical and chemical modifications. Physical modifications include sputtering, corona discharge, low temperature plasma, calandering, stretching, thermal treatment and the production of hybrid yarns (Adekunle, 2015; Dányádi et al., 2010; Moghadamzadeh et al., 2011; Mukhopadhyay and Fangueiro, 2009; Oporto et al., 2007). The aim of the physical methods is to alter the structural properties of the fibers and consequently improve the mechanical bonding between the matrix and fibers. Some methods also induce changes on the surfaces of the composite components, thereby affecting processability and the mechanical properties of the composites. Chemical modification methods, such as silane treatments, graft copolymerization, cyanate treatment, impregnation of fibers, and alkali swelling and substitution reactions, aim to improve the adhesion between fibers and the polymer matrix through generation of reactive functional groups on fiber surfaces (George et al., 2001).

Despite their positive effects on NFPCs, the physical and chemical modification methods increase the risk for chain degradation as well as lead to increment in the production cost (Pandey et al., 2015). Additionally, it is difficult to address all the problems associated with NFPCs with one single method (Das et al., 2015c). Another issue with some of these methods, such as using maleic anhydride grafted polypropylene (MAPP) as a coupling agent to introduce a covalent bond between fibers and the matrix, is that they are based on non-renewable sources and thus do not represent the modern aspects of developing future generation biocomposites based solely on renewable materials.

To simultaneously combat the challenges associated with NFPCs and the application of petroleum-based products and traditional waste treatment methods (e.g., landfilling), the utilization of bio-