Waste Management xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Utilization of agricultural and forest industry waste and residues in natural fiber-polymer composites: A review

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ARTICLE INFO

Article history:
Received 10 February 2016
Revised 11 April 2016
Accepted 27 April 2016
Available online xxxx

Keywords:
Natural fiber-polymer composites
Biocomposites
Agricultural waste
Forest industry
Biochar
Sustainable development

ABSTRACT

Natural fiber-polymer composites (NFPCs) are becoming increasingly utilized in a wide variety of applications because they represent an ecological and inexpensive alternative to conventional petroleum-derived materials. On the other hand, considerable amounts of organic waste and residues from the industrial and agricultural processes are still underutilized as low-value energy sources. Organic materials are commonly disposed of or subjected to the traditional waste management methods, such as landfilling, composting or anaerobic digestion. The use of organic waste and residue materials in NFPCs represents an ecologically friendly and a substantially higher value alternative. This is a comprehensive review examining how organic waste and residues could be utilized in the future as reinforcements or additives for NFPCs from the perspective of the recently reported work in this field.

Contents

1. Introduction

The growing awareness of environmental issues and resource scarcity explains the increasing interest surrounding the use of bio-based materials in a wide variety of applications (Ashori and Nourbakhsh, 2010; Al-Oqla et al., 2015; Teuber et al., 2015). Furthermore, stringent legislative policies have forced many industries to seek new materials from renewable sources to take place of the traditional materials derived from non-renewable resources (Holbery and Houston, 2006; He et al., 2013).

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http://dx.doi.org/10.1016/j.wasman.2016.04.037
0956-053X/

At the level of policy generation, the principles embedded in the circular economy are now emphasized in process and product design. This has introduced several visionary concepts i.e. the bioeconomy, the bio-based society and the green economy that are now redirecting the strategic planning of many industrial companies (McCormick and Kautto, 2013). Due to the pressure of more stringent legislation and increased taxes throughout Europe, the policy of simply dumping industrial waste in landfills will not be the prevalent method for waste management. Today, wastes are either incinerated, or even better, some other higher value use is sought (Monte et al., 2009; Mendes et al., 2012; Alonso et al., 2011). For this reason, it is important to devise different applications for previous waste materials, while taking into account the environmental and economic factors of these waste treatments.

During the recent decades, there have been major developments in the properties of biocomposites meaning that these products are already interesting alternatives for conventional materials in a number of end uses. The ever-increasing market demand and production volumes of natural fiber based composites (Carus et al., 2015) means that not only should there be political incentives behind their manufacture but there also has to be a reasonable supply of feasible raw materials. As many natural fiber sources can be utilized by the traditional converting industries (clothing, paper, packaging, etc.) some availability and cost issues with native high-grade fibers are bound to arise. With crude oil market prices markedly lower than anticipated only a few years ago (Hass et al., 2012; U.S. Energy Information Administration (EIA), 2013), the competition with petroleum-based materials requires not only green values but also a good source of affordable biomass resources.

It is the combination of environmental awareness, financial drivers and global policies that provides the incentives to the recovery of organic waste components and then to their secondary utilization. These aspects are also present in multiple environmental certification programs, and many companies believe that the implementation of these programs can lead to an improved company image as well as generating a competitive advantage (González-Benito and González-Benito, 2005). However, NFPCs need to maintain a good market image as high-performance and ecological materials; i.e. the selection of these raw materials will not happen if they provide an inferior product performance.

The industrial recovery and reuse of secondary or tertiary fiber resources will ensure that there is a good supply of the raw material as well as promoting the products' competitiveness and also the efficiency of their logistics. Suitable raw materials can be obtained from chemical refining of wood (Weinert et al., 2010), local forest harvesting (Moriana et al., 2015; Agnantopoulou et al., 2012; Roy, 2006) and agriculture (Chaudhary et al., 2015; Chen et al., 2015; Faezipour et al., 2014; Ibrahim and Mahmoud, 2015; Prithivirajan et al., 2015; Reixach et al., 2015). There are cellulose containing residues or side streams (e.g. process rejects consisting of cellulose fibers and fines (Mäkinen et al., 2012; Kotanen et al., 2014), and pin chips (Smith, 2004; Hart, 2009) i.e. undersized chips that are produced during chipping) which are not yet being utilized on an industrial scale. In the future, these local tertiary cellulose resources and the fibers of municipal solid wastes may be used as biomass feedstocks taking the place of virgin pulp.

From this viewpoint, natural fiber-polymer composites (NFPCs) possess significant advantages over the conventional materials like petrochemical derivatives and metals. However, the use of recycled raw materials, especially plastics, in NFPCs can be challenging since recycled materials may exhibit different performances and contain many grades, colors and contaminants (Najafi, 2013).

Natural fibers are abundantly available and their specific properties are comparable to the other fibers used for reinforcement purposes. Moreover, natural fibers are inexpensive, have a low density and are typically biodegradable (Ku et al., 2011; Faruk et al., 2012). It is the increasing demand from the automotive, building and construction, electrical and electronic industries that are also driving forward the natural fiber composites market (Mohammed et al., 2015).

Although natural fibers have many advantages, there are certain drawbacks that reduce their potential as polymer reinforcements (Faruk et al., 2012; George et al., 2001). For example, the incompatibility between natural fibers and the polymer matrix or their poor dispersion may compromise the strength of the resulting composite. The low water resistance as well as the tendency to form aggregates during processing are also notable disadvantages associated with natural fibers (Saheb and Jog, 1999).

There are several different ways to overcome the limitations related to NFPCs. The compatibility between the polymer matrix and the fiber reinforcement can be improved by incorporating specific additives, such as coupling agents (George et al., 2001; Lu et al., 2000; Sobczak et al., 2013). Another approach is to utilize organic wastes or residues in the composite formulations. For example, the utilization of biochar in NFPCs is a rather new way to improve the properties of the composites (Das et al., 2015b, 2015a, 2016b, 2016a; DeVallance et al., 2015; Ayrilmis et al., 2015; Li et al., 2014). Organic wastes can be converted into biochar, liquids and non-condensable gases by treating the feedstock at high temperatures (~400–700 °C) through the process of pyrolysis (Cernansky, 2015; Das et al., 2015c). Biochar can also be used to combat pollution by binding the heavy metals in soils and liquids, and by reducing the nitrous oxide emissions because of its bulk surface area, pore size distribution, particle size distribution, packing and density (Cernansky, 2015). Biochar consists mainly of carbon (60–90%), hydrogen and oxygen (Nachenius et al., 2013). The physical and chemical properties of biochars vary according to the processing method and raw materials used in their manufacture, but the pyrolysis temperature is the most important parameter affecting the properties of biochar (Das et al., 2015c).

There are two alternative approaches to the utilization of organic wastes in NFPCs: organic waste materials can be used either to reinforce a plastic matrix or they can be included as an additive to improve the processability or the compatibility between the main constituents of the composite. Natural and affordable materials or waste can also be used as an inexpensive and widely available filler material. There are two clear advantages of utilizing organic wastes in NFPCs i.e. a reduction of raw material costs and less need for traditional waste management, especially in the long term. On the other hand, the properties of the resulting composite should be competitive with traditional composites, which means that there is a clear need for further developments of NFPCs.

According to directive 2008/98/EC, *waste* means "any substance or object which the holder discards or intends or is required to discard", and *by-product* is "a substance or object, resulting from a production process, the primary aim which is not the production of that item". International Energy Agency (IEA) defines *vegetal residues* as "biomass obtained from straw, vegetable husks, ground nut shells and other wastes arising from the maintenance, cropping and processing of plants". In this review, the term *residue* covers both *vegetal residues* and *by-products* for reasons of general consistency and clarity.

In this survey, recently reported studies concerning the utilization of organic wastes and residues in NFPCs are reviewed, and the most important issues in the development of novel composites are examined. Recently, the research activity around the NFPCs, and agricultural and forest industry wastes has been upsurging. This review summarizes the studies and provides insights to the most promising innovations in the field. The review focuses on polymer composites of virgin, non-biodegradable polymers as a matrix, hence excluding composites with biodegradable polymers.

Please cite this article in press as: Väisänen, T., et al. Utilization of agricultural and forest industry waste and residues in natural fiber-polymer composites: A review. Waste Management (2016), http://dx.doi.org/10.1016/j.wasman.2016.04.037