Journal of Cleaner Production xxx (2015) 1–13

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Influence of carbon feedstock on potentially net beneficial environmental impacts of bio-based composites

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ARTICLE INFO

Article history:
Received 19 July 2014
Received in revised form
9 September 2015
Accepted 20 November 2015
Available online xxx

Keywords:
Bio-based composite
Life cycle inventory
Carbon-neutral composite
Natural fiber
Textile

ABSTRACT

Natural fiber composites are of increasing interest in research because of their potential to provide a low environmental impact material for applications, such as in the construction industry. In this analysis, fully bio-based composites with varying natural fiber reinforcement in a biosynthesized polymer matrix were assessed. The biopolymer was analyzed with two different carbon feedstock sources: simple carbohydrates and biogas. While both carbon feedstock sources result in the ability to cultivate rapidly renewable polymers, biogas as a feedstock source allows for use of a waste greenhouse gas emissions flow to produce a commodity. The bio-based composites were compared both on constant volume and for a decking application relative to a type of natural fiber filled petrochemical based polymer composite. When material properties and end-of-life considerations were incorporated, the biogas carbon feedstock biopolymer composites showed the potential to have a net beneficial global warming potential as well as favorable fossil fuel consumption and acidification relative to the conventional decking material, depending on natural fiber reinforcement selected. In terms of eutrophication impact, however, if byproducts from simple carbohydrate processing are considered, the simple carbohydrate feedstock biopolymer composites had the most beneficial impacts, suggesting consideration of the most critical environmental impact for the regions of production and use may be drivers for processing and selection of the bio-based composite constituents.

1. Introduction

Designing rapidly renewable, fully biodegradable construction materials has been of interest in current research because such materials could aid in alleviating burdens associated with use of landfill space. Current construction practices result in significant use of landfill space: an estimated 325 million tons of construction and demolition waste are generated annually in the U.S. (USEPA, 2004). Roughly 27% of this waste is from wood and wood based products (D&R International Ltd., 2011), which are not fully degradable due to lignin content (Micales and Skog, 1997). Additionally, 35% of the global construction market is polymer composites (Humphreys, 2003), which commonly resist microbial decay (Wessel, 1964). Poly (β-hydroxybutyrate)-co-(β-hydroxyvalerate) (PHBV) is a co-polymer of poly (β-hydroxybutyrate) (PHB), one of the most common types of poly (hydroxyalkanoates) (PHAs). PHAs are produced as intracellular granules in certain strains of bacteria that have access to excess carbon, but are starved of an essential nutrient, such as phosphorus (Anderson and Dawes, 1990). PHBV has the benefit of having a short residency in anaerobic conditions and the inclusion of natural fibers has been shown to expedite degradation (Morse, 2009). In addition to disposal benefits, PHBV/natural fiber composites have benefits associated with production. Unlike polymer composites that require petroleum resources and woods that have depleted resources in certain regions (Whiteman and Brow, 2000), the constituents for PHBV bio-based composites are renewable and can be harvested globally. Natural fibers, such as jute and hemp, have similar specific stiffness to E-glass fiber reinforcement (Wambua et al., 2003) and can be cultivated in a matter of months (Turunen and van der Werf, 2006), so they have been the focus of some interest for their potential environmental advantage over non-renewable composite reinforcement.

Previous life cycle assessments (LCAs) of short fiber filled bio-based composites and natural fiber reinforced petrochemical

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http://dx.doi.org/10.1016/j.jclepro.2015.11.047
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based polymers revealed the potential to improve environmental performance of products by replacing synthetic materials (Patel et al., 2003; Pietrini et al., 2007). Xu et al. (2008) showed adding natural fibers could reduce environmental impact compared to neat polymer. Wötzel et al. (1999) and Corbière-Nicollier et al. (2001) found that incorporating natural fibers as reinforcement in petrochemical based polymers could provide a beneficial greenhouse gas emissions profile in automotive applications. While LCAs of PHB composites are not as common, the use of this polymer has been shown to have potential environmental benefits in terms of both non-renewable energy use and global warming potential (GWP) depending on application (Pietrini et al., 2007).

Although PHBV commonly uses a carbohydrate feedstock (Grabowski et al., 2015), the application of energy and feedstock sources from renewable waste streams can provide for a novel subset of bio-based composites that demonstrates the potential to have a carbon-neutral life cycle. The envisioned closed-loop carbon life cycle of the bio-based composites includes a matrix formed in bacteria under nutrient deprivation using biogas as a carbon feed source. The cultivation of natural fibers removes carbon dioxide from the atmosphere during photosynthesis. Together, these constituents can be combined to form composite materials. Upon disposal in anaerobic conditions, such as a landfill, the materials decompose into methane and carbon dioxide (Morse, 2009) – the principal carbon sources for the constituents. While incorporation of this biogas feedstock PHBV to the bio-based composite life cycle inventory does not fully exemplify a potentially industrial scale closed carbon-loop composite, it provides an initial representation and for that reason has been incorporated into this analysis.

When designing materials, such as bio-based composites, with intended reduction in environmental impact relative to conventional materials, it is necessary to quantitatively assess the environmental burdens accrued during the material life cycle and compare the results to environmental burdens accrued during conventional material life cycles. This research performed such a quantitative assessment of energy and material flows through LCA of several PHBV/natural fiber composites currently in the research and development phase through an attributional approach. Environmental impacts of fully bio-based composites, composed of PHBV/natural fiber, were compared to a type of wood flour filled polyolefin composite (WPC), based on constituents and processing techniques used in common decking materials (Klyosov, 2007). This comparison was chosen because of the desired potential for fully bio-based composites to offer an alternative to materials used in similar applications to WPC.

PHBV/natural fiber composites were selected to be examined in this research based on this potential to have fully rapidly renewable composites and, theoretically, closed-carbon loop composites. Five textile reinforcements were considered for the bio-based composites, which were selected to represent some potential differences in fiber species, level of processing, and differences in textile production. To investigate the influence of fiber species, both hemp and jute textiles were examined. While there are a variety of species of natural fibers used in bio-based composites, hemp and jute were selected for their high specific moduli (Mohanty et al., 2002). To examine the influence of the degree of processing on the environmental impacts associated with the composites, a highly processed hemp linen textile was examined as was a less processed hemp burlap textile. In addition, recycled jute burlap (i.e., jute burlap that has already served one service life) and jute processed without hydrocarbons (i.e., jute burlap that is manufactured without using lubricating oils during textile processing) were considered to examine the influence of textile production methods. The constituents and composites assessed in this research can be found in Table 1. A subset of the material and mechanical properties of the composites necessary for this research can be found in Table 2. While the properties of the bio-based composites and the WPC vary slightly, they fall within a similar range to materials such as wood or engineered wood products (Miller et al., 2013).

Table 1
Constituents and composites considered in this analysis.

Name	Definition
PHBV-C	Poly (β-hydroxybutyrate)-co-(β-hydroxyvalerate) from simple carbohydrate feedstock
PHBV-B	Poly (β-hydroxybutyrate)-co-(β-hydroxyvalerate) from biogas feedstock
HL	Hemp linen
HB	Hemp burlap
JB	Jute burlap
NJB	Jute burlap processed without hydrocarbons
RJB	Recycled jute burlap
P-HL-C	PHBV-C reinforced with hemp linen
P-HL-B	PHBV-B reinforced with hemp linen
P-HB-C	PHBV-C reinforced with hemp burlap
P-HB-B	PHBV-B reinforced with hemp burlap
P-JB-C	PHBV-C reinforced with jute burlap
P-JB-B	PHBV-B reinforced with jute burlap
P-NJB-C	PHBV-C reinforced with jute burlap processed without hydrocarbons
P-NJB-B	PHBV-B reinforced with jute burlap processed without hydrocarbons
P-RJB-C	PHBV-C reinforced with recycled jute burlap
P-RJB-B	PHBV-B reinforced with recycled jute burlap
WPC	Wood flour filled recycled high density polyethylene

2. Goal and scope

The intent of this analysis was to determine the influence of using alternative carbon feedstock sources for biopolymer production in PHBV/natural fiber composites. To do this, LCA, an assessment tool for accounting material, energy and waste flows through a material or product's life cycle, was implemented. This study analyzed bio-based composite production: resource consumption during cultivation of natural fibers and feedstock for bacteria that produce biopolymers, as well as energy and material flows during growth, refinement processes, and manufacturing. Additionally, atmospheric and aqueous emissions during cultivation through production as well as land use considerations were included. End-of-life approximations were made based on predictions for anaerobic decomposition in a landfill with methane recapture capability. A schematic of the flows considered is shown in Fig. 1.

As this investigation was meant to be representative of a general industrial production of bio-based composites and associated impacts, average material and energy inputs from the literature were used; additionally, energy sources and transportation were based on the most common regions for production. Transportation distance calculations, polymer production, composite manufacture, and composite disposal were based on composite production and use in Palo Alto, California. Production of the textile reinforcement was considered to be located in the countries with the largest production of the analyzed fibers (China for hemp textiles and India for jute textiles). The type of technology modeled for production of the textile reinforcement was based on general industry practice. The type of technology modeled for polymer production was based primarily on pilot scale manufacture. The type of technology used for production of the composites was based on classic techniques, however, performed a laboratory scale. Machinery depreciation was considered to be minimal and excluded from the assessment based on the findings of Heijungs et al. (1992). Waste streams that could not be directly recycled within a process stream were modeled as undergoing decomposition in an anaerobic landfill