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Life cycle assessment of wood-plastic composites: Analysing alternative materials and identifying an environmental sound end-of-life option

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ABSTRACT

In the drive towards a sustainable Bioeconomy, a growing interest in the development of composite materials made of plastics compounded with wood particles, known as wood-plastic composites (WPC), can be observed. Wood is seen as one of the cornerstones for sustainable economic growth, while the use of thermoplastics from hydrocarbon fossil resources and additives for WPC potentially cause severe environmental impacts along the entire life cycle. In this study, the life cycle stages of raw material supply and end-of-life pathways of WPC were assessed environmentally from different perspectives with life cycle assessment (LCA). The utilization of alternative raw materials reflected the WPC producer's point of view. Harmonized product LCA standards were applied and combined with physical parameters of actually produced composites to give credit to substitution potentials in terms of resource quality. The downstream pathways of post-consumer WPC products reflected the recycler's perspective. A system LCA approach was needed where systems with equal functions were generated to secure a comparison of end-of-life (EoL) treatment systems. Results showed that WPC produced from secondary materials is the ecologically and technically superior alternative. Recycling of the composites would be the ecologically preferable pathway, but the recycled WPC content in novel WPC is a sensitive issue when comparing both EoL treatment systems. Yet, incineration of the composites is the predominant EoL pathway due to current recycling directives and lack of markets for secondary WPC material.

1. Introduction

The European Bioeconomy Strategy highlights the use of wood as one of the cornerstones for a sustainable economic growth (EC, 2012). The manifold alternatives for using wood led to a competition between the various utilization pathways as a renewable energy carrier, as a renewable precursor for the chemical industry and in the biofuel industry in context of promoting Sustainable Development (UNCED, 1992; UNFCCC, 1998; UN, 1998). This raised concerns of wood availability, especially due to direct and indirect incentives for wood used as an energy carrier (Geldermann et al., 2016; Höglmeier et al., 2014). Mantau et al. (2010) concluded that there will be not enough wood from sustainably managed forests for the competitive markets of material use and fuelwood in 2030.

A potential solution to overcome resource scarcity is seen in the cascading use of biomass and in using by-products more efficiently in the wood-based products sector. Sirkin and Houten (1994) stated that "*resource cascading has been utilized as a method for achieving resource conservation in contexts where resources have been regarded as precious or vital*". The cascading principle is to some extent manifested in national acts of the European member states with the execution of the European Waste Framework Directive 2008/98/EC (EC, 2008). This directive prioritizes the end-of-life (EoL) alternatives of waste by demanding the so-called waste management hierarchy: (1) prevention, (2) preparing for re-use, (3) recycling (without any kind of incineration), (4) other recovery (i.e., energy recovery) and (5) disposal. In addition to cascading, various strategies and concepts, such as the Circular Economy on European level (EC, 2011; EP, 2015; Haas et al., 2015) and ProgRess on German level (BMUB, 2015), have been developed to strengthen recycling and circulating materials aiming at an efficient utilization of resources.

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1.1. Wood-plastic composites

In pushing towards a Bioeconomy, a growing demand can be observed in composite materials made of plastics compounded with a significant share of wood particles, forming the so-called wood-plastic composites (WPC) (Partanen and Carus, 2016). The modifiable affinity of the molecular structure of the polymer matrix of thermoplastics in combination with various kinds of fillers, additives and reinforcement materials results in a functional improvement of the neat polymer matrix (Klyosov, 2007). WPC is defined "*as a material or product made thereof being the result of the combination of one or several cellulose-based material(s) with one or several thermoplastics, intended to be or being processed through plastic processing techniques*" (CEN, 2014a).

According to Carus et al. (2015), about 260 kt of WPC were produced in the year 2012 in Europe. The European WPC production represents approximately 9% of the globally produced WPC. The outdoor deckings market is the biggest distribution channel for products made of WPC. In Germany, about 80% of the distributed WPC deckings are in accordance with the "Quality and test specifications for production control of deckings" of Qualitätsgemeinschaft Holzwerkstoffe e.V. (Qualitätsgemeinschaft Holzwerkstoffe e.V., 2016). According to this voluntary commitment, WPC should be derived from FSC-certified wood from sustainably managed forests or waste wood categorized as untreated, natural wood – class A I (German Government, 2003) – with more than 50% wood content. The plastics shall be derived from primary or post-industrial production (Qualitätsgemeinschaft Holzwerkstoffe e.V., 2016).

1.2. Wood-plastic composites and the environment

WPC products replace either solid wood products (i.e., outdoor deckings and wall claddings in the building and construction sector) or neat plastic products (i.e., decorative claddings in the automotive sector). Geldermann et al. (2016) stated that WPC cannot compete with solid wood with regard to the low environmental impact of wood, but is an environmentally friendly alternative to neat plastics. Teuber et al. (2016) stated that WPC tend to be a possible step in a cascading use of biomass before energy recovery of the biomass.

The environmental assessment of products and services is conducted based on quantitative data by the life cycle assessment (LCA) methodology, which is standardized in ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b). The technical feasibility of producing WPC from secondary or cascaded resources has been intensively analysed since the early 1990s, for instance by Yam et al. (1990), Youngquist et al. (1992), Adhikary et al. (2008), Ashori (2008), Sommerhuber et al. (2015) and Sommerhuber et al. (2016). To the best of the authors' knowledge, an ecological analysis based on quantitative data is missing in all of these studies. Studies exist reporting on WPC produced with virgin raw materials on a laboratory scale for which an LCA was conducted ex ante (Hesser, 2015; Mahalle et al., 2014; Qiang et al., 2012, 2014; Xu et al., 2008), with the focus on different alternative materials (Väntsi and Kärki, 2015) or focusing on integrating durability issues of WPC into LCA (Miller et al., 2015).

The following studies used the LCA methodology to compare WPC deckings to solid wood deckings. Bolin and Smith (2011) and Bergman et al. (2013) conducted an LCA of solid WPC outdoor deckings with PE and HDPE as the plastics matrix with wood particles from co-products. Both authors considered also recycled plastics and concluded that WPC from recycled plastics is environmentally better than WPC from virgin plastics, but inferior to solid wood deckings in the North-American context. However, a consideration of technical functions and the application context is missing. Stübs et al. (2012) conducted an LCA of solid and hollow WPC outdoor deckings, comparing the results to solid wood deckings from tropical Bilinga (*Nauclea diderrichii*) and Scots pine (*Pinus sylvestris*). The authors concluded that WPC had better environmental performance due to a prospective higher service life and less maintenance than the solid wood deckings. In addition, Environmental Product Declarations (EPD) were published for WPC products in a German context, stating a reference service life of 30 years for deckings and 40 years for claddings according to manufacturers' specifications (IBU, 2015a,b). A combination of the functional unit and service life should be seen critically, not only because WPC is facing durability challenges under outdoor conditions, which depends on macro and micro-climate conditions as well as on the application context (Catto et al., 2016; Ibach et al., 2013). Methods for potential durability improvements can be linked to, for instance, changing processing conditions or adding additives (Stark and Gardner, 2008). The possibility of using additives in WPC is one reason why these composites are often promoted to be comparable or even better than solid wood deckings. However, the additives in synthesized products and plastics are problematic for human health and the environment along the entire life cycle (Thompson et al., 2009).

Considering the EoL of WPC, the separation of wood particles and thermoplastic polymers from the composite is technically challenging. During the compounding process of WPC, the thermoplastic matrix is heated to the crystalline melting point (T_m). Then, wood particles are added to the melted thermoplastic and mechanically irreversibly bonded to the plastic-matrix. The WPC matrix is cooled until the thermoplastic molecules solidify, which is known as the glass transition temperature (T_g) (Klyosov, 2007). Recycling of post-consumer thermoplastic to secondary materials is possible in comparison to thermosets or elastomers, but recycling of the constituents of WPC to secondary materials for cascading and improvement of resource efficiency is currently economically unfeasible (Meinlschmidt et al., 2014; Sommerhuber et al., 2015).

Among the LCA studies of WPC, Thamae and Baillie (2008) investigated the replacement of glass fibre reinforced polypropylene (PP) car door panel with a wood fibre reinforced PP panel. The EoL was modelled using the avoided burden approach, which allocates the potential credits of energy generation of waste incineration to the manufacturing of a product. Allocation of EoL processes is of major importance for the LCA results and is discussed critically within the LCA community (Bergman et al., 2014a; Heijungs and Guinée, 2007; Nicholson et al., 2009; Sandin et al., 2014). In the context of applying the waste management hierarchy (EC, 2008) on post-consumer WPC, an ecological comparison is needed. The study of Väntsi and Kärki (2015) is an example of assessing the environmental profile of alternative materials for WPC (recycled mineral wool and polypropylene) and its end-of-life treatment options (incineration with energy recovery versus landfill).

1.3. Aim and objectives of the study

The upstream processes (resource alternatives) as well as the downstream processes of WPC need to be thoroughly ecologically analysed. With the underlying assumption that it is technically feasible to produce WPC completely from secondary materials (recycled wood and plastics), we ask the first research question (*RQ 1*):

(1) What is the ecological difference of WPC made from virgin vs. secondary materials?

The focus is on the ex-ante LCA analysis of WPC compounds, as manufactured and analysed prior in Sommerhuber et al. (2015) and described in Section Product LCA. The thermoplastic matrix is HDPE compounded essentially with softwood particles (Table 1).