Wood polymer composites and their contribution to cascading utilisation

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Abstract

Due to a shortage of resources and a growing competition of land use, sustainable and efficient resource utilisation becomes increasingly important. The application and multiple, cascading utilisation of renewable resources is aimed at to ensure an allocation and future availability of resources. Wood polymer composites (WPCs) are a group of innovative materials consisting of mainly renewable re-sources. By means of summarizing recent research, it is shown how WPC can potentially contribute to an enhanced cascading utilisation. For the production of WPC, waste materials and by-products from wood and agricultural industry, e.g. offcuts, sawdust, residues from board manufacturing, pulping sludge, can serve as a raw material. Furthermore, the cited literature presents the use of recycled polymers and biopolymers as a potential alternative for the polymer component of WPC. By using biodegradable polymers, a fully biodegradable composite can be formed. In addition to using recycled materials and potentially being biodegradable, it is pointed out that WPC furthermore offers the possibility of being recycled itself, therefore being considered as a "green composite". Although the influence of contami-nated waste streams and mixed filler and polymer types on the properties of WPC made with such recyclates is yet not fully understood and no collection systems exist for post-consumer WPC, in-house recycling on the production sites is identified as a promising option as it reduces production costs and enhances resource efficiency and cascading utilisation. On the basis of cited life cycle assessments, the eco friendliness of WPC is assessed resulting in the conclusion that WPC cannot compete with solid wood with respect to environmental impact but is an environmentally friendly alternative to neat plastics in several applications.

Introduction

A continuously growing demand for resources makes a sus-tainable and efficient resource utilisation more and more important (Brown et al., 2011; Elliott, 2006). Many existing materials rely on fossil fuels with a prospectively limited availability, which leads to
an increasing competition for the scarce resources (Birol, 2012). Therefore, an alternative raw material base and a more efficient production are required. As an alternative to materials which are based on fossil fuels, those materials made from renewable re-sources are promising. They help to ensure future resource allo-cation due to their renewable character. When comparing traditional, fossil fuel based materials with materials made from renewable resources, the latter show various environmental ad-vantages. An increased usage of renewable resources can at least partially encounter diverse environmental problems humanity is faced with, e.g. climate change and biodiversity threats (Lenzen et al., 2012).

Nevertheless, efficient and sustainable resource utilisation is also required for renewable resources as a competition between

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different forms of land usage has emerged in recent years, e.g. cultivation of food crops, bioenergy crops or crops for technical applications (Godfray et al., 2010). When considering the realisation of (multiple) material usage of raw materials including their by-products, the principle of cascading utilisation becomes crucial. Developing materials based on by-products is promising, as by-products are often directly converted into energy nowadays (Carus et al., 2008).The strategy of efficient and sustainable resource utilisation is also pursued by green chemistry, an industrial sector that aims at optimising raw material utilisation by minimising waste creation (Ashori, 2008). Dealing with waste is an important issue. Waste disposal laws, for example, force the wood processing industry to find applications for by-products and wastes (Migneault et al., 2014).

Wood polymer composites (WPCs) are a group of hybrid materials mainly consisting of renewable resources. They help to realise a more responsible and efficient method of resource utilisation as they contain wood waste materials and by-products and like this are in line with the principle of cascading utilisation and resource efficiency. WPC is a merger of different components including synthetic ones (e.g. plastics). Therefore it has to be considered that the natural and synthetic components together affect the environmental impact of WPC. Little research has been done yet to investigate how the conflictive combination affects WPC eco friendliness. Nonetheless, this question is crucial for evaluating WPC in light of environmental issues which are increasingly gaining in importance in political discourses, corporate policies and customer requirements. Therefore, the purpose of the present article is to review the possible contribution of WPC to cascading utilisation and to identify factors influencing its eco friendliness.

2. General composition and fields of application

Wood plastic composites are a group of materials mainly consisting of wood, thermoplastic polymers and, to a small amount, additives. The wood content of the material may vary up to more than 80% (Klyosov, 2007). Depending on the region of manufacture and on the availability, softwoods as well as hardwoods in the form of fibres, particles, or fine flour serve as raw material. The term wood fibre thereby generally corresponds to spindle-shaped wood cells with an aspect ratio (length to diameter ratio) of 10:1 to 25:1 (Klyosov, 2007) which are separated by different pulping methods. Wood particles are fibre bundles or, as in the case of fine flour, cell wall fragments with an aspect ratio of 1:1 to 5:1 (Clemons, 2008). The constitution of the wood component influences the physical and mechanical properties of the WPC (Clemons, 2008). While fibres, having a greater aspect ratio (length/width ratio), enhance the tensile strength (Chen et al., 2006; Klyosov, 2007; Stark, 1999), particles are easier to dose to the production process and easier to disperse in the polymeric matrix and therefore result in more homogeneous materials (Shahi et al., 2012; Yam et al., 1990). In addition, the properties mentioned beforehand as well as visual properties of the WPC depend on the intrinsic properties of the wood species used (Clemons, 2008).

As a thermoplastic matrix material polyvinyl chloride (PVC), polyethylene (PE), and polypropylene (PP) are commonly used for most applications (Ashori, 2008; Carus et al., 2014). WPC combines the differing properties of wood and polymer. Wood is strongly hydrophilic and therefore prone to high moisture absorption and swelling rates resulting in decay and dimensional instability, which is disadvantageous especially for outdoor applications. By incorporating the wood into a hydrophobic polymer matrix, the moisture absorption and sensitivity to fungal decay and insect attack is reduced. Simultaneously, the wood enhances the stiffness, thermal stability and creep behaviour of the polymer (Michaud et al., 2009; Shahi et al., 2012). The properties of WPC strongly depend on the compatibility and interfacial adhesion between wood and polymer, which represents one of the main limitations as wood is strongly polar and most matrix polymers are nonpolar (Michaud et al., 2009). To overcome this drawback, particle/fibre surface modifications can be applied (Ashori, 2008; Vieira de Carvalho Neto et al., 2014) and additives like compatibilisers and coupling agents are used (Adhikary et al., 2008; Kuo et al., 2009). Other additives to tailor the WPC's properties to its destined application comprise, among others, blowing agents for the production of foamed WPC, biocides, pigments to dye the WPC, UV stabilizers, flame retardants, and lubricants as processing aid (Ashori, 2008; Satov, 2008).

WPCs show a thermoplastic behaviour enabling processing on the same machines and with the same equipment as their unfilled matrix. The main processing methods for the production of WPC products are extrusion and injection moulding, which are both highly productive and economically advantageous (Sykacek et al., 2009), as well as compression moulding and thermoforming. In 2012 the production of WPC amounted to 1,100,000 t in North America and 900,000 t in China. In the EU 260,000 t of WPC were produced, 67% of it in the field of deckings and 24% in the automotive industry, followed by siding and fencing, technical applications, furniture, and consumer goods (Table 1) (Carus et al., 2014). The application in automotive industry comprises trim parts e e.g. door panels, dashboard, and cabin linings e as well as thermo-acoustic insulations (Ashori, 2008). The production of WPC in the EU is expected to grow by approximately 10% per year, especially in the fields of furniture, technical parts, and consumer goods (Carus et al., 2014).

Initially, wood fibres or particles have been used as cheap fillers for polymers to reduce production costs (Selke and Wichman, 2004). Nowadays, in the light of continuously rising polymer prices and growing ecological awareness of consumers, WPCs with their good and adjustable properties offer an alternative to traditional materials in many fields of application (Carus et al., 2008). Comprising two different materials, namely wood and polymer, WPC opens up possibilities to contribute to a sustainable use of raw materials and an enhanced cascading utilisation.

3. Contribution to cascading utilisation

3.1. Wood component

As a variety of types of wood particles or fibres can serve as raw material for WPC (Table 2), this material offers an opportunity to enhance the sustainability of the wood processing industry in the form of added value by optimizing the material use and minimizing and recycling wood wastes (Eshun et al., 2012; Migneault et al., 2014). Wood waste can be divided into post-industrial and post-consumer wood waste. While post-consumer wood waste may comprise sources like old newspapers, wood pallets, and building and construction residues, post-industrial wood waste includes sawdust, shavings, chips, milling

Table 1
Production of WPC in the European Union 2012 in tonnes (Carus et al., 2014).

Wood-plastic composites	260,000
Decking	174,000
Automotive	60,000
Siding and Fencing	16,000
Technical Applications	5000
Furniture	2500
Consumer	2500

Table 2
Overview of exemplary alternative raw materials for the production of WPC.

Wood component		Polymer component	
Wood industry	Agriculture	Recycled polymer	Biopolymer
Old newspaper	Cereal straw	Grocery bags	TPS (thermoplastic starch)
Wood pallet	Corn stalks	Pallet wrap	PLA (polylactic acid)
Building/construction residues	Corn cob	PE bottles	
Sawdust, shavings, chips, offcuts	Rice straw	Food packaging	
Milling residue	Rice husks	Agricultural films	
Trees, branches, bark	Sugarcane bagasse		
reaction wood flour	Betel nut husks		
Wood based panel residues	Soy stalk		
Pulping sludge			

residue, offcuts, trees, branches, and bark (Daian and Ozarska, 2009; Eshun et al., 2012; Winandy et al., 2004). Buyuksari et al. (2012), for example, successfully used compression wood flour from black pine to reinforce plastics, a type of wood which is preferably not used for commercial timber or pulp and paper due to unsuitable properties. Solid wood offcuts are predominantly free of contaminations whereas wood wastes from the production of derived timber products often contain adhesives, resins, coatings, etc., which might involve subsequent treatments or process adaptions before the introduction to WPC production (Daian and Ozarska, 2009).

Recycling and reprocessing residues from medium density fibre board (MDF) production produces a high amount of fine particles. Due to the increased fibre/particle surface more resins are needed to bond the fibres/particles. This makes them unsuitable for the production of boards (Daian and Ozarska, 2009). However, for the production of WPC they turned out to be suitable as sawn MDF residues containing cured urea-formaldehyde resin applied to reinforce plastics resulted in WPC with a higher hydrophobicity and dimensional stability than control specimens made from virgin MDF fibres (Migneault et al., 2014).

Migneault et al. (2014) tested different wood wastes regarding their suitability to serve as a filler for WPC, namely sawmill sawdust, bark, sawdust from oriented strand boards (OSB) containing methylene diphenyl diisocyanate (MDI) adhesives, laminated veneer lumber (LVL) with phenol formaldehyde (PF) adhesives, deinking sludge, thermomechanical pulp (TMP) (raw material for MDF board production) sludge, and Kraft sludge from pulp and paper industry. They found out that the properties of the resulting WPCs differed significantly depending on the type of fibre used but they differed even more depending on the proportion of fibres. The modulus of elasticity (MOE) was higher for WPCs made from clean wood fibres than for those made from residues. In addition, the MOE rose with increasing wood or cellulose content. Kraft sludge turned out to be well suitable for the production of WPC as it led to partly better properties than birch and spruce wood flour, whereas bark from aspen and spruce and TMP sludge should be avoided. Deinking sludge led to promising results, as well. The authors concluded that contrary to the application of waste materials in other wood derived products, for WPC the contamination and ash content of the raw materials is not a limiting factor (Migneault et al., 2014). Although bark is a residue that occurs in high quantities in wood industry, its suitability for the production of WPC is questionable. Apart from Migneault et al. (2014), several other studies found the properties of bark filled polymer to be inferior to those of wood filled polymer, e.g. lower tensile and flexural properties (Safdari et al., 2011; Sewda and Maiti, 2007; Yemele et al., 2010), lower crystallinity and Izod impact strength (Sewda and Maiti, 2007), higher susceptibility to white and brown rot fungi (Moya-Villablanca et al., 2014). In addition, the bark seems to limit the performance of coupling agents like MAPP, when coupling agents are used to improve water uptake and thickness swelling (Najafi et al., 2008).

Soucy et al. (2014) also examined the use of sludge from pulping processes e namely TMP, chemithermomechanical pulp (CTMP), and Kraft e for WPC applications. They differentiated between primary sludge (fine particles mechanically removed from waste water mainly containing cellulose, hemicelluloses, lignin, bark, and fillers from paper production) and secondary sludge (remaining solids in waste water after bacterial digestion) and tested the influence of different compositions of the sludge content on the properties of the WPC. Tensile and flexural MOE and strength increased with increasing sludge content, while maximum strain and rupture energy decreased. In consistency to the behaviour of traditional wood flour filled WPC, the stiffness, water swelling and water absorption increased and impact energy and elongation at break decreased with rising sludge content. Increasing the ratio of secondary sludge reduced the tensile strength and flexural properties. The authors draw the conclusion that the use of any pulping sludge will result in competitive properties of the WPC as long as the content of secondary sludge is below 10%. As before, Kraft sludge delivered the best properties from all three types of pulping processes and therefore has a high potential for industrial application in WPC production (Soucy et al., 2014).

Not only wastes from wood processing industry can serve as a filler for WPC but also agricultural residues and by-products like cereal straw, corn stalks, rice straw, rice husks and sugarcane bagasse (Ashori, 2008; Ashori and Nourbakhsh, 2009). The further use of such agro-wastes offers a great potential to enhance the economy of cultivation especially in developing countries (Sinha, 1982). Vieira de Carvalho Neto et al. (2014), filled recycled PE with sugarcane bagasse fibres resulting in an increased tensile and flexural modulus of the material compared to the neat polymer. After acetylation of the fibres, the properties were even enhanced due to better surface compatibility (Vieira de Carvalho Neto et al., 2014). Table 3 gives more examples of recent research on agro-waste reinforced polymers in developed and developing countries.

3.2. Polymers

Apart from substituting the lignocellulosic component of WPC with waste and by-products from forest and agricultural industries, also the polymeric side offers possibilities to contribute to enhanced resource efficiency and sustainability. As plastics comprise one of the major parts of municipal solid waste, a reduction of polymer use with respect to environmental issues is desirable (Nourbakhsh and Ashori, 2009). On the one hand, recycled polymers can fully or partially substitute virgin polymers in WPC. On the other hand, the use of biopolymers, especially bio-

Table 3
Research related to reinforcing polymers with agricultural by-products.

Agricultural by-product	Reference
Wheat straw	Ahankari et al., 2011; Ashori and Nourbakhsh, 2009; Le Digabel et al., 2004; Nyambo et al., 2010; Panthapulakkal and Sain, 2007
Corn stalk, corn cob	Flandez et al., 2012; Nourbakhsh and Ashori, 2010; Nyambo et al., 2010; Ogah and Afiukwa, 2014; Panthapulakkal and Sain, 2007
Rice straw, rice husks	Ashori and Nourbakhsh, 2009; Bourne and Bajwa, 2007; Hassan et al., 2011; Ismail et al., 2011; Ogah and Afiukwa, 2014; Petchwattana et al., 2012b; Wang et al., 2007; Zhao et al., 2012
Sugarcane bagasse	Vieira de Carvalho Neto et al., 2014
Betel nut husk	Yusriah et al., 2014
Soy stalk	Nyambo et al., 2010

based polymers, instead of traditional fossil based polymers provides the means of decreasing the environmental impact of WPC (Michaud et al., 2009).

3.2.1. Recycled polymers

Several WPC manufacturers already use recycled polymers which they obtain, for example, from grocery bags and pallet wrap, sometimes even in combination with recycled wood-based materials (Winandy et al., 2004). Scientific research is engaged in investigating how the use of recycled polymers influences the properties of WPC. Nourbakhsh and Ashori (2009) showed that WPC made from poplar fibres and recycled high density PE (HDPE) meets the minimum property requirements to compete with traditional WPC in some applications. Selke and Wichman (2004) produced WPC from virgin HDPE and once used milk bottles made from the same material. The properties of the resulting compounds did not differ statistically. When adding 25% post-consumer polymer (including labels) to the recycled polymeric part of WPC, the composite still had good tensile properties. During recycling of post-consumer plastic bottles a strict separation of HDPE and PP cannot be assured. In WPC, a contamination of HDPE with PP does not influence the material properties markedly (Selke and Wichman, 2004). Ares et al. (2010) found out that adding equal amounts of recycled and virgin PP to PP-based WPC improved the tensile strength compared to WPC with only virgin PP while maintaining the melting and crystallization behaviour. The rheological properties changed only slightly so that processing via extrusion under the same conditions was still possible (Ares et al., 2010). Leu et al. (2012) tried to develop an optimized material composition regarding mechanical and physical properties for WPC made from recycled PP and recycled wood flour. They studied the influence of wood particle size, wood content, coupling agent concentration, and lubricant concentration.

When processing recycled plastics, not only mechanical and physical properties of the resulting products play a role. Also chemical requirements and safety certifications must be met. Especially when post-consumer plastics from food packaging are used for the production of WPC, the odour of the resulting material may limit the applicability. For low density PE (LDPE) and PE/EVA (ethylene vinyl acetate) films used beforehand in agricultural and industrial application, the emission of volatile compounds was greater for the reprocessed materials than for the virgin materials (Félix et al., 2013). These increased emissions result from thermo-oxidative degradation during repeated recycling. WPC exhibits a characteristic odour profile not only from the degradation of the polymer component but also from the lignocellulosic components. It is possible to (partially) mask unpleasant odours by adding additives or aromas (Félix et al., 2013).

3.2.2. Biopolymers

Biopolymers, either biobased and/or biodegradable, are an answer to decreasing fossil resources and to increasing amounts of plastic waste. Yet, the production costs for biobased polymers are higher than for fossil derived ones, but in the light of rising prices for fossil resources, the market for biopolymers is rapidly growing (Endres and Siebert-Raths, 2009). Especially in the field of short-lived consumer goods, the share of biopolymers increases as the use of durable polymers for those applications is less and less accepted (Agnantopoulou et al., 2012). Combining biopolymers with lignocellulosic fillers brings about several advantages. As wood is a natural, fully biodegradable polymer, manufacturing of WPCs with biodegradable polymers results in likewise biodegradable compounds. For polymers certified as compostable with respect to the withdrawn DIN 54900 (1997) standard, adding up to 49% of lignocellulosic material does not abate compostability (Sykacek et al., 2009). The incorporation of wood and other natural fibres can help to balance some property and processing limitations of biopolymers. Wood fibres increase the tensile strength of biopolymers, adding wood flour reduces shrink marks and warpages of products manufactured by injection moulding (Sykacek et al., 2009). Starch-based polymers exhibit an affinity to water absorption and poor mechanical properties resulting in a limited long-term stability. By adding wood flour to thermoplastic starch (TPS), Agnantopoulou et al. (2012) succeeded in increasing the tensile strength and MOE and decreasing the elongation at break. The improvement of mechanical properties results from the strong interfacial bonds which wood and TPS form due to their chemical similarity, making coupling agents unnecessary. With increasing wood content the moisture absorption of the composite decreases which enhances the long-term stability. As a result, TPS and wood form a WPC that is well suitable for application in non-humid environments, e.g. indoor applications, and at the same time reduces the environmental impact after disposal (Agnantopoulou et al., 2012).

3.3. Recycling of WPC

A “green composite” exhibits not only the possibilities of biodegradation and utilisation of recycled materials as raw material, e.g. wood and plastic wastes. A green composite also offers the possibility of being recycled itself (Shahi et al., 2012). WPC for recycling may originate either from post-consumer sources or from waste produced in-house during manufacturing. In-house recycling benefits the saving of resources and the reduction of production costs. Petchwattana et al. (2012a) evaluated the influence of multiple processing by extrusion on the properties of WPC made with PVC. As recycling material they used WPC scrap from the start-up process and profiles that did not pass the quality control. From testing different mixing ratios of recycled and virgin WPC they found a ratio of 30:70 recycled:virgin as most suitable regarding flexural properties, impact performance and reduction of material costs. Even after reprocessing seven times the mechanical properties stayed relatively unchanged, confirming that in-house recycling of WPC is an opportunity (Petchwattana et al., 2012a). Shahi et al. (2012) investigated the mechanical and physical properties of HDPE filled with 60% wood flour after re-extrusion. The recycled

WPC showed a higher flexural modulus but a lower flexural strength compared to the virgin WPC. The crystallinity did not change significantly. The melting temperature differed only marginally, making adaptions of process conditions unnecessary. The density of recycled WPC decreased compared to virgin WPC while the water absorption increased noticeably, although a reduction of water absorption was expected due to changes in wood particle size and wood composition (decomposition of hydrophilic components through high temperature) and a better dispersion of particles inside the matrix after processing twice (Shahi et al., 2012).

Beg and Pickering (2008a, 2008b) found different results for WPC made from 50% Radiata pine kraft fibres. After two recycling steps tensile strength increased due to better fibre dispersion inside the matrix but during further processing tensile strength decreased again caused by fibre damage. As a general result, tensile and flexural strength and modulus, fibre length, and melt temperature decreased while failure strain, hardness, interfacial bonding density, crystallinity, and thermal stability increase with up to eight recycling steps (Beg and Pickering, 2008a). Equilibrium moisture content, diffusion coefficient and thickness swelling decreased as well (Beg and Pickering, 2008b).

Up to now, the recyclability of WPC is insufficiently researched and only few publications are available. One constraint in recycling WPC is the wood component which starts to degrade and emit volatiles on repeated processing at temperatures around 220 °C (Shahi et al., 2012). Another constraint is the degradation of the polymer. Reprocessing induces thermal and oxidative degradation, i.e. chain scission and decrease of molecular weight (Beg and Pickering, 2008a; Englund and Villechevrolle, 2011; Petchwattana et al., 2012a). A thereof resulting change of the viscous behaviour may require modifications of further manufacturing processes.

Englund and Villechevrolle (2011) investigated the influence of polymer blends on the mechanical and physical properties of WPC, showing that the properties rather depend on the composition of the blend than on the fact of using a blend. Nevertheless, the influence of WPC composition, e.g. wood/fibre type, polymer type, mixing ratio of wood, polymer and WPC types, on the recyclability of WPC is not sufficiently investigated yet. The great variability of WPC compositions in the waste stream, especially of post-consumer WPC, complicates recycling and necessitates the development of collection and in-line monitoring systems on the part of recyclers and manufacturers (Winandy et al., 2004). The composition of the recycled WPC e predominantly in-grade or as a mixture containing different types of polymers, wood, etc. e will determine if it is suitable as a base for high quality products or applications requiring only lower qualities.

4. Environmental impact

When evaluating the environmental impact of a composite material, it has to compete with at least one of its pure constituents. In the case of WPC and depending on the application, solid wood and neat plastics are the competitors. For the decking market a growth of WPC deckings over solid wood deckings was predicted in consequence of customers perceiving WPC as being more durable and of low maintenance, and of a restricted use of timber treated with chromated copper arsenate (CCA) (Winandy et al., 2004). To substitute CCA, an alkaline copper quaternary treatment (ACQ) is used. Bolin and Smith (2011) conducted a life cycle assessment (LCA) to quantify and compare the environmental impact of decking made from ACQ treated timber and from WPC. The WPC was made from 50% recycled wood fibre and recycled and virgin HDPE (25% each). Although WPC producers market their products as environmentally friendlier than treated timber (Winandy et al., 2004), the LCA showed that the use of WPC has a higher environmental impact, for example three times more greenhouse gas emissions and 8.5 times higher total energy use (Bolin and Smith, 2011).

Bergman et al. (2013) compared the environmental impact of California redwood (Sequoia sempervirens) deckings to deckings made from foamed PVC and WPC made from either virgin or recycled PE. This study, as well, attributed the lowest environmental burden to solid wood, while foamed PVC exhibits the highest environmental burden. However, the study indicated that producing WPC from recycled polymer has strong environmental benefits compared to using virgin polymers (Bergman et al., 2013). Mahalle et al. (2014) undertook an LCA on the laboratory scale production of WPC made from the biobased polymer polylactic acid (PLA) and MDF fibres compared to neat PP. Except for the eutrophication potential, the WPC achieved better results concerning the environmental impact compared to PP, especially with respect to energy use. On the part of the biocomposite, PLA transport represented the greatest share in environmental impact. When blending PLA with locally available TPS, the environmental burden of the biocomposite was even reduced (Mahalle et al., 2014). To the best of our knowledge, no studies are available on how the origin of the wood component influences the environmental impact of WPC. Derreza-Greeven et al. (2013) conducted an LCA that compares deckings made of WPC with deckings made of solid wood from different origins, i.e. hard and soft wood from Germany, tropical wood from Southeast Asia (from illegal clear-cutting and sustainable forestry), and with deckings made from non-certified WPC pellets imported from China. The results indicate that the origin of the wood plays an important role in defining the environmental impact, especially when transport and land use are considered. Therefore a detailed study on the environmental impact of WPC depending on the origin of its wood component, including recycled wood and wood wastes, would be desirable (Derreza-Greeven et al., 2013).

Kim and Song (2014) state that wood products made from wood wastes possess greater carbon storage capabilities than the amount of carbon discharged during their production. They evaluated the global warming potential of using wood waste either for the production of particle boards or the energy recovery via combined heat and power generation. The particle board production turned out to be environmentally more beneficial with regard to temporary carbon storage. From their findings the authors suggest to use wood waste of good quality for the production of particle boards while wood waste of low quality should be used for energy recovery (Kim and Song, 2014). Using low quality wood waste for producing WPC might also be an option and should be evaluated with respect to the environmental impact.

5. Discussion

The aim of cascading utilisation is to enhance the multiple material use of resources and by-products from production processes before finally converting them to energy. The recovery of wood wastes and by-products from wood industry provides a great secondary resource for producing new materials (Eshun et al., 2012). Reusing wood industry waste is not only advantageous for the industry by supplying a new fibre source and reducing production costs. It also benefits the environment by reducing the accumulation and discarding of wood waste and by recycling an industrial waste to high value products (Chavooshi et al., 2014; Soucy et al., 2014).

Considering the variety of wood wastes and by-products mentioned in Chapter 3.1 utilised to produce WPC, WPC can be valued as a suitable intermediate step in the utilisation cascade of wood and agricultural industry. Nevertheless, it should be mentioned that the use of alternative raw materials for the production of WPC is not always without problems. Deinking sludge, for example, was presented as a possible resource for WPC. Deinking sludge typically contains heavy metals which might impose limitations on the industrial scale processing and the application of the final product with respect to environmental and health aspects. Other lignocellulosic sources might need special treatment to meet property requirements of the WPC. Especially in the case of enhancing compatibility of filler and matrix, chemical modification and grafting have to be evaluated regarding the environmental impact (Michaud et al., 2009). The environmental impact of using additives to tailor WPC properties has been excluded from this overview but should be included when it comes to evaluating the environmental profile of WPC. WPC can be fully eco-friendly only if all of its single components are eco-friendly.

In comparison to solid wood, WPC will loose with respect to environmental burden in many applications as wood itself has a neutral CO_2 balance and the CO_2 impact of processing wood is lower than of processing WPC (Bergman et al., 2013; Kim and Song, 2014; Mahalle et al., 2014). But in comparison to neat plastics WPC represents an eco-friendly alternative especially if recycling materials and biopolymers are used (Bergman et al., 2013; Mahalle et al., 2014). To produce fully biodegradable WPC is possible, if it is feasible for the specific application. However, it should be mentioned that the eco friendliness of biopolymers currently is subject to great controversy. Yates and Barlow (2013) reviewed several LCAs concerning the environmental impact of biopolymers. They report that most LCAs concentrate on global warming potential (GWP) and non-renewable energy use (NREU) as impact categories and attest biopolymers to have a lower impact compared to petrochemical polymers. Some LCAs also include other categories like acidification potential (AP) and eutrophication potential (EP). Biopolymers show a higher impact in those categories due to the intensive agricultural land use (Yates and Barlow, 2013). Hottle et al. (2013) confirm those findings with their review of sustainability assessments of bio-based polymers. Another point of discussion are the discrepancies in data bases available for novel materials like biopolymers which make the reliability of LCAs questionable (Hermann et al., 2010; Hottle et al., 2013; Yates and Barlow, 2013).

As mentioned above, “green composites” are not only biodegradable and suitable for the manufacture from recycled products. Even more, they can be recycled themselves. The cited literature attests that from a material side of view WPC offers the possibility of recycling. Up to date, the amount of WPC waste is still low, though it is expected to be growing in future. But so far, there has been no economic incentive to realize recycling of post-consumer WPC. Furthermore, the factors influencing the resulting material properties are not yet understood. As there are multiple types of WPC on the market, research has to be conducted on how material properties of recycled WPC are affected by waste stream contaminations like mixed filler type or polymer type. Being a composite of natural and synthetic materials, WPC itself is not covered as a separate material by waste disposal or recycling regulations. The German Waste Wood Ordinance (Altholzverordnung, Stand 24.2.2012), for example, treats WPC as “waste wood” only if it contains more than 50% by mass of wood. Injection moulded parts mostly containing less than 50% of wood are not covered. Therefore it has to be checked how a nationwide collection system could be designed and implemented and if classification systems depending for example on filler type or polymer type are necessary.

In contrast, in-house recycling on-site of the WPC production plants definitely is an option already performed by several producers as waste streams are easy to monitor. It reduces production costs and helps to enhance a sustainable resource utilisation.

6. Conclusion

Due to a continuously growing resource demand sustainable and efficient utilisation of resources comes into focus in many sectors. In the wood and agricultural industry the goal is to increase material recycling of wastes and by-products before feeding them to energy recovery systems. The present review illustrated the role WPC could possibly play in the utilisation cascade of wood industry under consideration of environmental issues. The cited literature on current research showed that a variety of wood wastes and by-products could serve as raw materials for WPC. Also on the polymer component side a utilisation of recycled materials as well as biopolymers is feasible. When using biodegradable polymers, the production of a fully biodegradable composite is possible.

From a material point of view, WPC offers the opportunity of being recycled itself but nationwide recycling systems are still missing. Although it cannot compete with solid wood in terms of environmental impact, WPC represents an eco-friendly alternative to neat plastics by enhancing efficient resource utilisation.

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