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

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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