Wood-Plastic Composites—Performance and Environmental Impacts

Matthew John Schwarzkopf and Michael David Burnard

Abstract This chapter reviews and discusses the performance and environmental impacts of wood-plastic composites (WPCs) used in a variety of applications ranging from construction and automotive sectors to consumer goods. Performance is considered in terms of fitness for use, manufacturing methods, material components of WPCs, and user perceptions of the material. Recent research related to matrix components and their relation to mechanical properties are covered in detail, especially regarding effects of the wood component. Manufacturing processes are also significant contributors to the suitability of WPCs for a given use, and the impact of various aspects of manufacturing are discussed as well. The environmental impacts of WPCs are reviewed and contain comparisons to solid wood alternatives, different matrix components, and future considerations for performing environmental impact assessments of WPCs. Finally, critical aspects of further innovation and future research are covered that are necessary to improve WPCs use as suitable replacements for solid plastic products and materials.

Keywords Applications · Fibres · Manufacturing · Matrix components · Renewable composites · User perceptions · Wood-plastic composites

1 Introduction

Wood-plastic composites (WPCs) are a product class that has been developing over the last 40 years resulting in increased applications and expanded market share. More specifically, WPCs are composites containing a wood component in particle form (wood particles/wood flour) and a polymer matrix. They are used in a variety

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A. Kutnar and S.S. Muthu (eds.), *Environmental Impacts of Traditional and Innovative Forest-based Bioproducts*, Environmental Footprints and Eco-design of Products and Processes, DOI 10.1007/978-981-10-0655-5_2

of structural and non-structural applications ranging from component and product prototyping to outdoor decking. However, construction and automotive applications are the most common worldwide (La Mantia and Morreale 2011; Eder and Carus 2013). WPCs can be used outdoors as well as indoors, and some common applications include construction materials, garden and yard products, automotive applications (interior and engine), household items, packaging and consumer goods.

The decision to use a WPC product in place of another, generally speaking, should be predicated on achieving greater performance, reduced price, or reduced environmental impact. Using exterior decking as an example of improved performance, a homeowner may choose to use WPC decking instead of pressure-treated timber because of the ease of maintenance and improved durability (i.e. coatings do not need to be applied), or aesthetic reasons (e.g. lack of knots and splits likely to be found in solid wood).

The benefits are not always clear though, as there are many trade-offs to consider when choosing WPCs—especially when replacing responsibly sourced renewable materials. Including any non-renewable materials in the product can significantly increase its environmental impact. However, the case for WPCs may be clearer when the competing product is made entirely of non-renewable polymers, as the wood fraction of many WPCs can approach 50 % of the product volume, and therefore reduce the resource pressure on non-renewable materials (e.g. polymers derived from fossil sources). The environmental impact of WPCs is directly affected by the ratio of renewable to non-renewable materials in the product. Not only do WPCs have lower environmental impacts than unfilled plastics (but higher than solid wood or most other wood composites), use of sustainably harvested and recovered wood products in long-life products sequesters atmospheric carbon and can produce a positive environmental impact (Hill et al. 2015).

Wood is often used in plastics as a means to reduce price compared to a solid plastic product. Wood used in WPCs often comes from side streams such as sawdust produced while manufacturing lumber or recovered wood products, and is much cheaper to produce than the plastic that it replaces in many products. This often helps to reduce prices for consumers.

Promising progress and research into bioplastics [i.e. plastics made from biopolymers such as Polylactic acid (PLA)] reinforced with natural fibres (including wood) indicate the potential for these renewable materials to eventually enter the WPC market (Mukherjee and Kao 2011). However, these composites still have significant environmental impact due to processing and production, and steps to reduce the energy demands and water use should be taken (Qiang et al. 2014).

WPCs already have a significant market share (260,000 t in Europe in 2012) and the trend is increasing (Eder and Carus 2013). The current reliance on plastics, especially those derived from fossil sources, means that this demand is likely to continue increasing especially as developing economies continue to grow. However, to meet industrial, consumer, and environmental demand's research must continue to improve the processes for making WPCS, the component materials, and final product functionality.

This chapter will give an overview of the material properties, manufacturing processes, applications, and current developments related to WPCs.

2 Components of WPCs

WPCs are a group of composite materials and products comprised of two primary and distinct phases. One of these phases is the matrix which holds the different components together, binding them and providing load transfer between them. The matrix in WPCs is either a thermoset or more commonly a thermoplastic polymer. The other primary phase is the wood component. The wood component can be of any shape or size and acts as a filler and/or reinforcement to the composite. Making up a relatively small proportion of the total composite are additives which are added to aid in processing and affect a variety properties of the final product.

2.1 Matrix Component

2.1.1 Thermosets

Thermosets are a class of polymers that upon curing cannot be remelted or reprocessed for the same type of usage. From a liquid state these polymers are cured into rigid solids that are chemically cross-linked. The mechanical properties of these polymers come from initial molecular units and the density of cross-links formed during curing (Hull and Clyne 1996). The wood adhesives industry often uses thermosets to take advantage of this cross-linked form which provides a solid and durable bond. When used with wood, the liquid polymer penetrates the wood microstructure to varying degrees and is then cured, forming a three dimensionally dispersed interphase region. Common thermosets being used are urea–formaldehyde, phenol–formaldehyde, epoxy, and polyamides. One of the first WPCs using a thermosetting polymer was a phenol–formaldehyde—wood composite which is branded Bakelite by Rolls Royce in 1916, used for the shifting knob in their vehicles (Clemons 2002).

2.1.2 Thermoplastics

Thermoplastics are a class of polymers that can be heated and softened, cooled and hardened, and then resoftened while maintaining their characteristic properties from their first usage. Thermoplastics are used for a variety of everyday products like plastic soda bottles, single use shopping bags, milk jugs, etc. Unlike thermosets, these polymers are not cross-linked and rely on the properties of their monomer units, large molecular weights, and polymer chain entanglement for their mechanical performance (Hull and Clyne 1996). When heated, these polymer chains disentangle and allow them to slide past each other, allowing for reprocessing. High density polyethylene (HDPE), polypropylene (PP) and polyvinyl chloride (PVC) are the most common thermoplastic polymers used in WPCs (Klyosov 2007). HDPE accounts for the majority of the thermoplastics used in WPCs at 83 %, followed by PP at 9 % and PVC making up 7 % of the total WPC thermoplastic volume (Caulfield et al. 2005). Due to the thermal stability of wood, thermoplastics are used because they can be processed at relatively low temperatures below wood's thermal degradation temperature (180–200 °C). These polymers are also attractive for WPCs because they can be cut, screwed, and nailed with tools already used for wood construction.

2.2 Wood Component

Polymer manufacturers have historically used minerals and synthetic materials like talc, calcium carbonate, mica, glass fibres, and carbon fibres as extenders and reinforcing materials (Eckert 2000). Wood as a filler or reinforcing material has been used in composite materials for thousands of years (Bodig and Jayne 1982) and the introduction of a natural filler like wood particles in polymers was appealing to polymer manufacturers. Wood has many advantages to traditional fillers like lower cost, relatively high strength to weight ratio, low density, is relatively soft and easily integrated into existing plastic production lines, can offset the amount of polymer used, and is a renewable resource (Wolcott and Englund 1999; Clemons 2002; Farsi 2012). English et al. (1996) found that wood flour used in PP composites offers similar performance to that of talc and other mineral fillers but with a lower specific gravity providing for lighter composites.

In its own right, wood is a naturally occurring composite utilising polymers in a highly structured cellular construction. A thorough treatment of wood and its constituents related to composite materials can be found in Bodig and Jayne (1982). The wood material used in WPCs can be from a virgin source or is often a post-industrial co-product like trimmings from sawmills, breakdown of urban and demolition wood, or logging trimmings/slash. These materials are then chipped and ground into their final form as wood particles. Typical methods for the comminution of wood into wood particles are through the use of hammer and attrition mills. Unlike clear (free of defects) and undamaged wood, the wood particles often used in WPCs have been heavily altered. Using this type of mechanical breakdown, the finished product (Fig. 1) is heavily damaged and its properties are far from those of defect free, clear wood.

Particles are typically less than 1 mm in length and have a wide distribution of aspect ratios (Wang 2007). These particles are comprised of bundles of short fibres rather than long individual wood fibres. The complex morphology of the particle cellular structure, its irregular geometry, and the damage caused through processing should be acknowledged when designing and manufacturing WPCs (Teuber et al.

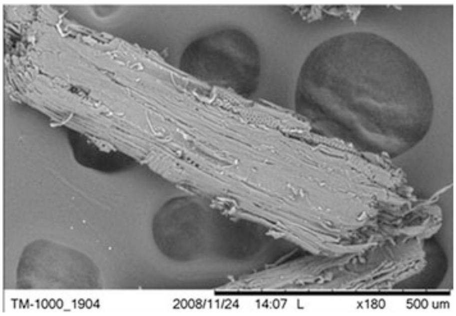


Fig. 1 SEM image of a wood particle used in WPCs (Schwarzkopf 2014)

2015). WPC properties are significantly influenced by the wood species and particle size characteristics of the wood particles being used (Stark and Rowlands 2003).

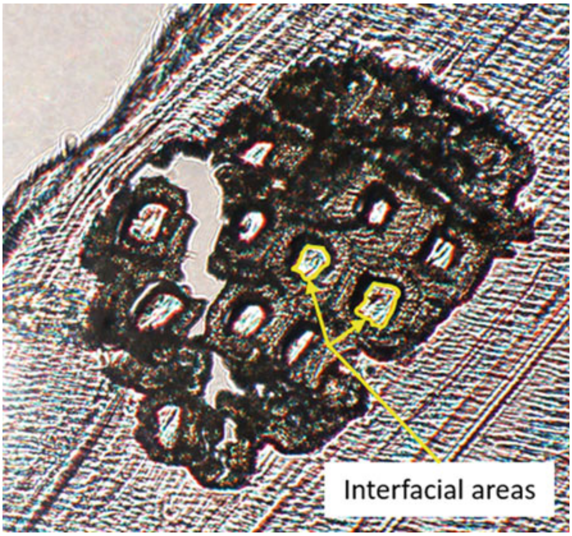
2.2.1 Wood Species

The wood species used in WPCs is typically determined by geographical location, availability, and price. The wood species used affects important aspects of WPC production like chemical compatibility and mechanical contributions to the composite. Common wood species used are pine, maple, and oak. Berger and Stark (1997) tested a variety of wood species in injected-moulded WPCs. They found that hardwood species provide improved tensile properties and heat deflection when compared with softwoods, and that ponderosa pine wood flour provided the optimum blend of mechanical property enhancements. These results are by no means the answer for all situations but show that wood species selection is an important factor to consider.

One aspect dependent on the wood species selection is the microstructure of the wood itself. The effective surface area for interaction with the polymer and the degree of polymer penetration into the wood structure both affect the composite properties. Escobar and Wolcott (2008) investigated the influence of different species on WPCs. Part of this study looked at the effect that different anatomical features of wood had on the polymer penetration through the wood structure. For example, Fig. 2 shows a cross-sectional view of a wood specimen with cell lumens filled with HDPE.

Gacitua and Wolcott (2009) found that wood species with higher interfacial areas (Fig. 2) may increase the amount of mechanical interlocking of the polymer with the wood structure. Circled in yellow are examples of the interfacial areas where the wood and polymer interact. This area also includes the entire perimeter of the wood particle. Depending on which wood species is used, the microstructure may be much different and increase or decrease this interaction area. It is also important to note that the degree of polymer penetration within the wood structure is also affected by the polymer's composition with respect to molecular weights. Low molecular weight components can more easily penetrate the wood structure, but contribute less to mechanical properties and an optimum balance must be found.

Fig. 2 Wood particle embedded in PE showing cell lumen penetration and highlighting areas making up the entire wood–polymer interaction area. *Photo credit* Muszyński, L



2.2.2 Wood Particle Size

The size and geometry of the wood particles being used in WPCs affect the flow/handling characteristics and mechanical properties. Wood particles obtained on an industrial scale often have a large-size distribution (Fig. 3) making it more difficult to design for certain properties. However, the more milling and screening that are done to make the particles smaller or narrow this distribution increase the cost

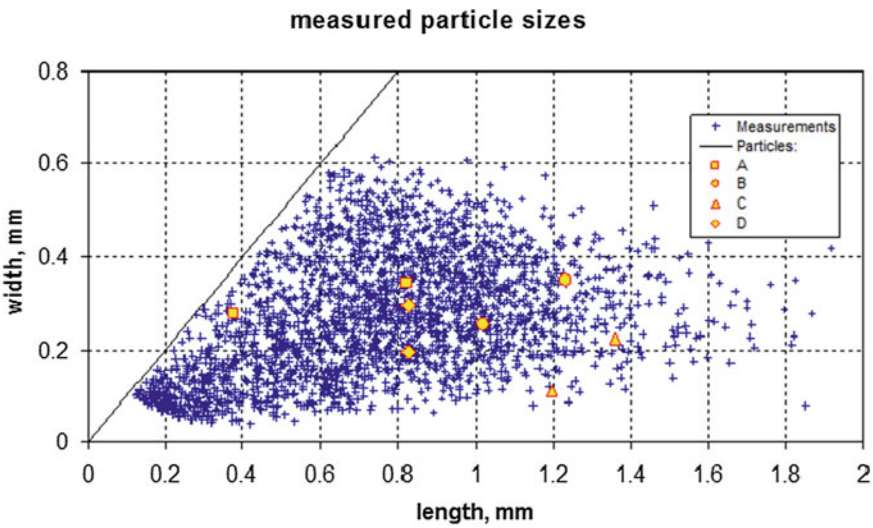


Fig. 3 Particle size distribution scatter plot from a 40-mesh sample (Wang 2007)

significantly. Particle size is characterised by the size of spaces in a mesh screen the particles pass through. Mesh size refers to how many openings there are in a screen within 2.54 cm^2. For example, a 100-mesh screen has 100 openings in 2.54 cm^2. The higher the mesh number, the smaller the particles. Mesh sizes of particles used in WPCs will vary depending upon the desired product properties and finish, and are most commonly from 10 to 80 mesh (Patterson 2001; Clemons 2002).

Stark and Rowlands (2003) investigated the effect of particle size on the mechanical properties of wood/PP composites. They manufactured WPC test specimens using particle mesh sizes 35–235 and performed a variety of mechanical tests. They found WPCs with larger particle sizes contained more stress concentrations which affected the impact energy of the product. They also found that even more important than particle size was the aspect ratio of the particles which is the length divided by the width of the largest minor axis of the particles. Generally, when there are particles with a larger aspect ratio, there is the potential for more effective load transfer between the matrix and the particles leading to better mechanical properties (Schwarzkopf and Muszynski 2015). Based on a 40-mesh sample of commercially obtained wood particles, Wang (2007) investigated the distribution of particle sizes. Using optical measurements of micrographs, Wang found that the median aspect ratio was 2.8. Using fillers with greater aspect ratios like wood fibre (10–20) can improve mechanical properties of the WPC, but difficulties in processing occur when feeding and metering the fibres into extruders (Patterson 2001).

3 Manufacturing Methods

WPCs started being produced by the plastics industry which had prior expertise in processing and manufacturing of plastic products (Clemons 2002). This industry had used filler materials in the past and when wood became a viable option, it was integrated into their existing production lines. While other wood-based composites are typically made in a panel or beam like geometry. WPCs starting in a molten state can be formed into highly detailed, linear profiles using extrusion processes or can be formed into complicated shapes via injection moulding. In any thermoplastic composite, the components must first be blended together and then later formed into the desired product.

3.1 Compounding

Mixing or compounding is the act of combining the wood and polymer components together. During the compounding procedure it is critical to evenly disperse the wood particles throughout the molten polymer. This dispersion is especially important with highly filled WPCs (Schirp and Stender 2009). It is also important in this step to wet or encapsulate the wood particles with the polymer. Proper dispersion and wetting allow uniform and more effective load transfer to occur throughout the composite. If not compounded properly, the composite will have reduced mechanical properties compared with an optimally compounded blend and increases the risk of durability issues. After compounding, the material can go directly to shape formation of the final product or can be chipped into pellets for later use.

3.2 Extrusion

The majority of WPCs are extruded into long linear profiles to use as decking planks, siding, fences, etc. Extruders serve the two main purposes of compounding the wood and filler, and then forming the shape of the extruded profile.

The wood and polymer components are metered and fed into the extruder and mixed using single or twin-screw configurations. The screws act to mix and move the material forward. Throughout the barrel of the extruder, the mix is heated through friction between the barrel, screw, and wood–polymer mix as well as by heated zones along the length. At the end of the extruder is a die through which the material is fed, forming the desired profile. Twin screw extruders are sometimes used as compounding units for producing pre-blended pellets. Manufacturers using a single screw extruder or injection moulding process often purchase these pre-blended pellets which are more easily fed into the machine and do not require an extra compounding step.

3.3 Injection Moulding

Injection moulding is used much less for WPCs, but can be used to make more complex shapes for a variety of products. The first steps in injection moulding are similar to extrusion, but instead of being forced through a die, the mixed material is injected into a mould. The wood-plastic mixture fills the mould, is cooled, and is then ejected in the preparation for the next piece to be formed.

3.4 Wet Processes for Sheet Formation

Sheets of WPC, which are often used in the automotive industry (e.g. doors or shelving applications), are either extruded or formed by a wet process. In wet process fabrication, a slurry of water and wood is created and mixed with chemical additives before being hot pressed into sheets (Pritchard 2004). These sheets may use a plastic scrim to help holding the board together (Pritchard 2004).

3.4.1 3D Modelling with WPCs

3D modelling (or additive manufacturing) is a manufacturing technique that allows for complex shapes to be created by depositing or removing materials (such as WPCs and other plastics, but a variety of materials can be used) in a customisable pattern to make three-dimensional objects. For most of these processes object models are created in a 3D modelling environment (such as computed-aided drafting (CAD) software), then processed in software that splits the 3D object into a collection of layered elements which can be created by the modelling technique.

3D modelling is most frequently used as a rapid prototyping method. Prototyping allows the users to create and test variations of product designs. Commercial applications for 3D modelling are expanding in a range of fields, however. Furthermore, the affordability of non-commercial 3D printers (particularly Fused Deposition Modelling (FDM) systems) has allowed researchers, hobbyists, and small scale component manufacturers to explore a variety of materials, methods, and products. WPCs are used in 3D modelling to reduce material costs and reduce the environmental impact using fossil-based plastics. As in other WPC applications, waxes, photostabilisers, lubricants, and other additives are used in the material matrix to alter the properties of the final product and aid in the manufacturing process.

FDM is a leading 3D modelling method in many manufacturing areas (Nikzad et al. 2011). The WPC used in this method is a filament that is fed into a nozzle that heats and deposits the WPC according to the product design. The WPC must be heated to a pliable state without exceeding the thermal degradation temperature of the wood fibre in the filament, which can limit the types of plastics used in these applications.

Selective laser sintering (SLS) is another 3D modelling technique which is in developmental stages for use with WPCs (Guo et al. 2011). SLS utilises powders which melt at different temperatures and that are fused together by laser radiation and form solids as the temperature of the combined material decreases. The methods for preparing WPCs for SLS are underdevelopment, but the wood component must be treated (alkalised) and mixed with a thermoplastic adhesive powder.

3.5 Reinforcement of Plastic Matrices with Renewable Materials

The primary purpose of using renewable fibre reinforcement in plastics is to reduce material cost, which has a secondary effect of reducing ecological impacts, especially when replacing non-renewable reinforcement (e.g. metals and glass) (Corbière-Nicollier et al. 2001). However, reinforcing plastics with particulates and fibres impacts material properties (strength, durability, appearance, etc.) as well as their ecological impact (Corbière-Nicollier et al. 2001; Zhong et al. 2001; Bouafif et al. 2009; Westman et al. 2010; Mukherjee and Kao 2011). Using renewable fibres and particulates alter the properties of the composite material in a variety of ways based on the geometry of the reinforcement, the type and components of the matrix the renewable components are part of, and the type of fibre or particle embedded in the matrix (Mukherjee and Kao 2011). Materials such as wood, reeds, kenaf, grasses (like bamboo), cotton, carbon fibres, rayon, nylons, and many other renewables allow reduced demand on fossil and other non-renewable (e.g. metals and glass) matrix components.

4 Physical Characteristics

Composite materials are often optimised by selecting components for their strength, stiffness, flexibility, and durability. When compared with individual materials, composites may also offer more consistent performance, lower production costs, and create an avenue for the utilisation of renewable resources. WPCs are no different and are formulated to meet the needs of the consumer by finding the right balance of these properties. Mechanical properties and durability are among the most important to WPCs.

4.1 Mechanical Properties

With WPC decking making up the largest share of the WPC market (Clemons 2002), we can look at mechanical properties important to this market. WPC deck boards are subjected to bending when they span a gap between supports and are being dynamically loaded when walked on and supporting the static loads (e.g. furniture and grills). Both the ultimate tensile stress (UTS) and modulus of elasticity (MOE) are important properties to consider. UTS is the maximum stress that a material can be subjected to before breaking. MOE refers to a material's ability to resist deformation and in a general sense is the stiffness of the material. For decking, this is important for limiting deflection of the product. It should be mentioned that a true elastic response in plastic composites is debatable, and the response of the material is highly dependent on the testing rate, temperature, previous history of the specimen, etc. Comparing values between different profiles, WPC formulations and specimens from different testing facilities is difficult, but for research and development purposes determining these values as a comparison is helpful. A study done by Karas (2010), assessed a variety of mechanical properties including MOE and UTS for wood-HDPE composites. Commercial pine flour was used as a filler as well as a variety of wood fillers from "low-grade" sources including: whole-tree juniper (WJ) (including bark), forest thinning material (FT), and urban wood from demolition (UW).

In the left plot in Fig. 4, UTS is plotted against the filler loading ratio. There is a horizontal line at 20 MPa which represents the UTS value for the HDPE used in this experiment that contains no filler. The other lines represent composites made from HDPE and the various filler types mentioned above. When increasing the wood filler loading ratio there is a slight increase in UTS, but with higher loading levels near 60 % wood, the UTS decreases. This behaviour is expected because when more and more of the composite is wood, the particles are often not entirely encapsulated by the polymer and optimal load transfer is not possible. The right plot in Fig. 4 is showing the MOE plotted against the loading ratio of wood fillers. As the filler ratio increases from 0 to 60 %, the MOE increases for all of the samples. This stiffening behaviour is also present in composites using fillers other than wood. Filling WPCs above 60 % requires care in particle dispersion and increases the likelihood of problems with not fully encapsulated particles, water absorption, crack formation, and biological attack.

WPCs have found success in a variety of markets including outdoor decking, railings, fences and landscaping timbers, but the number of applications for WPCs is limited to service not requiring high-mechanical performance (Clemons 2002). Hull and Clyne (1996) stated that understanding load transfer is the key to understanding the composite's mechanical behaviour. In WPCs, commonly used thermoplastic polymers like PP are hydrophobic (water-hating) while the constituent polymers of wood, like cellulose, are hydrophilic (water loving) in nature and have reactive hydroxyl groups along the length of their chains (Sjöström 1993). This results in an incompatibility between the polar wood component and the non-polar thermoplastic materials resulting in poor adhesion between the two (Lu et al. 2000) and lower mechanical properties than properly bonded components.

Attempts to improve the quality of these bonds have been made in the past by experimenting with additives known as coupling agents. Coupling agents are defined by Pritchard (1998) as "substances that are used in small quantities to treat a surface so that bonding occurs between it and other surfaces, e.g., wood and thermoplastics." The effects of coupling agents on the mechanical properties of WPCs have been studied extensively (Woodhams et al. 1984; Maldas and Kokta

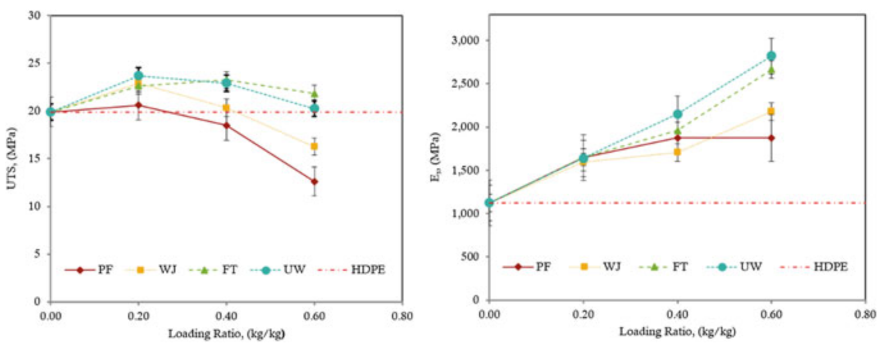


Fig. 4 *Left* Ultimate tensile stress versus wood filler loading ratio. *Right* Secant modulus of elasticity versus wood filler loading ratio; *PF* pine flour, *WJ* whole-tree juniper, *FT* forest thinning, *UW* urban wood, *HDPE* reference specimen with no filler (Karas 2010)

1991; Raj and Kokta 1991; Stark and Rowlands 2003) and have shown that coupling agents increase the strength and stiffness of the bulk composite. This approach has been the topic of much research and a detailed review of coupling agents used in WPCs has been compiled by Lu et al. (2000). One commonly used coupling agent is maleic anhydride-grafted polypropylene (MAPP). This type of coupling agent reacts with the wood component on one end, and on the other end entangles a modified PP with the bulk PP polymer. Stark and Rowlands (Stark and Rowlands 2003) study showed that the addition of MAPP had the greatest effect on the properties of wood fibre composites containing wood particles with greater aspect ratios (≈16). As they pointed out, wood particles commonly used in WPCs have low aspect ratios (3–5). This being the case, coupling agents can only assist in interfacial bonding to a limited extent. While one would expect better performance from fibres with larger aspect ratios, this method adds cost and complexity to the manufacture and processing of WPCs. Whether or not a WPC manufacturer decides to use a coupling agent, the interaction between the polymer matrix and the embedded particle still requires attention. Unlike measuring mechanical properties of WPCs like creep or bending strength at a macroscale, understanding the interaction between the particle and matrix requires a look at the microscale. In the past, a variety of methods have been used to explain and predict the interactions between the wood and polymer phases using idealised analytical and numerical techniques (Clyne 1989). These methods held some common assumptions including: the embedded particles which are homogenous and isotropic, impermeable, cylindrical in shape, have a large aspect ratio, have a perfect bonding interface with the matrix, and have no transfer of load on their ends. Such assumptions can hardly be applied to irregular, porous bio-based particles like wood (Raisanen et al. 1997). These methods provided approximations of load transferred with an embedded inclusion in a thermoplastic matrix but lacked the complexity of the actual system to be satisfactory. Recently, Schwarzkopf and Muszynski (2015) investigated these interactions using optical measurement techniques based on the digital image correlation (DIC) principle. This study aimed to develop a methodology for the efficient measurement of strain distribution patterns in the matrix material surrounding embedded wood particles. Wood particles and reference wire particles were embedded in a HDPE matrix. The specimens were pulled in tension and imaged throughout the test. By comparing successive images to one another, the displacements and strains on the surface of the specimen could be determined. The results from their study showed that there is a good agreement between theoretical (Clyne 1989) and observed strain distribution patterns (Fig. 5). However, a quantitative analysis of the load transfer between the two needs to happen using morphologically informed predictive modelling tools. This approach has been used for analysing load transfer in adhesively bonded specimens by Kamke et al. (2014) and gives a unique look at the internal stress transfer in wood-based composites.

Observed
Principle Strain

Theoretical

Observed
Shear Strain

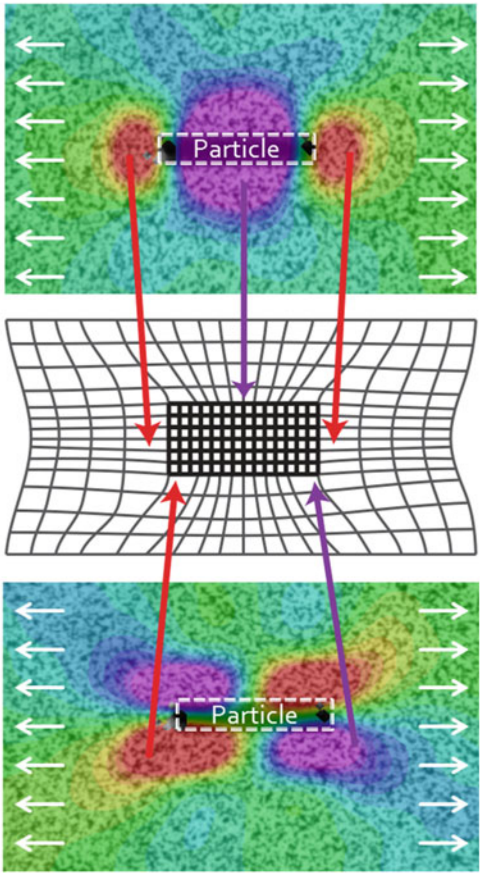


Fig. 5 Comparison of observed strains (obtained from DIC) and a theoretical representation of the interaction between an embedded particle and a polymer matrix. Theoretical model adapted from Clyne (1989)

4.2 Durability

When compared with solid wood materials, WPCs have lower mechanical properties in strength, stiffness, and creep resistance. On the other hand, WPCs are less susceptible to moisture absorption and absorb at a slower rate, providing for better resistance to fungal attack and dimensional changes (Caulfield et al. 2005). This being the case, it is important to remember that the wood particles within the WPC are still a nutrient source for microbial decay and have the potential to become degraded. While in theory the encapsulation of wood particles by a polymer should provide some level of protection from biological decay and moisture intake, external forces may compromise this protective layer.

WPCs are often marketed as highly durable, low maintenance, and a good alternative to solid wood as an exterior product. One area under investigation for using WPCs in exterior applications is in highway signs and markers. There are many types of roadway markers, signs, and fixtures that exist along every kilometre of the roadway.

Based on only two of these markers, tubular markers and inroad reflectors (Fig. 6), Thompson et al. (2010) estimated that approximately 870 t of plastic is being used annually in eight western states of the US. By introducing any amount of wood filler into these products, a substantial volume of plastic could be displaced by a renewable resource. While highway markers do not generally demand high-structural performance, they are subjected to harsh environmental conditions, mechanical abrasion, and ground contact throughout their entire service life. Rain will soak the materials, temperatures will drop below and well above freezing temperatures, vehicle tyres will drive over inroad markers, and the sun will expose them to UV rays. Karas (2010) investigated the use of WPCs in highway applications and assessed their durability. In this study, durability was assessed by measuring selected mechanical properties of WPCs before and after accelerated weathering treatments as well as weight loss due to ground contact tests. To simulate the effects of environmental conditions that WPCs used in highway applications encounter, an accelerated weathering unit was used that applied UV light, heat, and moisture. A soil contact test was also used to assess the durability of the WPCs with respect to mass loss from biological decay.

As expected, WPC specimens that had been exposed to accelerated weathering experienced lower mechanical performance than those that were unweathered. Specimens that had higher loading levels of wood filler experienced more mass loss and in specimens that were exposed to accelerated weathering, the mass loss was almost double that of unweathered specimens. This was believed to be due to the degradation of the polymer at the surface of the specimens. While the HDPE was not substantially degraded due to biological decay in the soil contact tests, it may have been degraded when exposed to UV in the weathering treatments. By degrading the surface matrix material and allowing cracks and pathways to form throughout the structure, more wood particles were exposed to biological attack. This breakdown of the surface polymer encapsulating the wood fillers can also occur during freeze thaw cycles and due to physical wear by car and truck tyres abrading the surface of roadway markers. While WPCs used in decking materials will not need to protect against vehicles driving over them, the same durability concerns exist.

Fig. 6 Some examples of in-road markers found along the roadway. *Photo Credit* Karas, M

Schirp et al. (2008) provides a state of the art summary of the biological degradation of WPCs and provides some strategies for improving the durability of WPCs. One of these strategies is to limit the loading ratio of wood filler to under 50 % unless using an antimicrobial treatment such as zinc borate which is effective against wood-decay fungi and insects. This again touches on the incomplete encapsulation of wood particles at higher loading ratios. Essentially, any cracks or openings in the WPC or between the polymer and the wood provide a pathway for moisture and biological decay to enter, as well as for crack propagation. Another method used to improve the durability is to apply a cap stock layer. Most of the durability issues in WPCs start at the surface and work inwards. Instead of distributing expensive additives like antimicrobial, colourants, and anti-UV agents throughout the volume of the WPC, a thin layer of harder plastic with these protective additives is added to the outside (Hanawalt 2012). While effective, the cost of making the production process more complicated must be assessed.

5 WPC Applications and Use

In Europe, WPCs account for nearly 11 % (260,000 t) of composite products production, which includes product categories ranging from construction to consumer goods (Carus et al. 2015). Table 1 lists common products, their product categories, and the associated manufacturing processes typically used to create them. Outdoor decking and automotive components account for the greatest share of WPC production in Europe (67 and 24 %, respectively), while other uses including siding and fencing, furniture, consumer goods, and technical applications account for the remainder (Carus et al. 2015). WPCs are considered a growth market, with increases in major markets like North America and Europe estimated to be around 10 % while in China growth is estimated to reach 25 % in 2015 (Eder and Carus 2013).

Table 1 Some common WPC products, their product categories, and associated manufacturing products

Product examples	Product category	Manufacturing process
Decking boards and tiles, siding, and window frames	Construction, outdoors	Extrusion and injection moulding
Garden furniture and fencing	Garden/yard and outdoors	Extrusion
Automotive interior trims and engine components (exposed to temperatures less than 110 °C)	Automotive	Extrusion, injection moulding and sheet forming
Furniture parts and furniture	Housing and interior	Extrusion and injection moulding
Packaging (e.g. corner protectors), components for: games, household electronics and other devices	Consumer goods, interior and outdoor	Extrusion and injection moulding, FDM

Table adapted from Eder and Carus (2013)

5.1 Construction

WPCs are often used in the built environment, both indoors and outdoors. Although exterior decking is the most common application worldwide, other construction-related products are also important. These include railing system components, stairs, window and door applications, flooring, exterior siding, fencing and landscape materials, interior moulding and trim work (Clemons 2002; Klyosov 2007; Eder and Carus 2013; Carus et al. 2015). WPCs for construction purposes are typically extruded and made to function and look like their solid wood counterparts. These WPCs support conventional fasteners like screws, nails, brackets, and others which allow them to be used without significant adjustment to typical building practices (Pritchard 2004). The appearance of WPCs depend on the material contents and finishing measures which include imprinting "wood-like" properties such as grain structure and coatings, as in Fig. 7.

5.2 Automotive

The automotive industry uses WPC and other renewable-based fibre composites in increasing quantities both to offset costs, reduce weight, and, in Europe, in an effort to meet the demands for high recyclability contents of vehicles. Wood fibres in fibre–plastic composites used in the automotive industry account for only about 38 % of the total renewable fibre usage (Carus et al. 2015). Other fibres in common use are cotton, flax, kenaf and hemp. The primary use of WPC's in automobiles is for storage (trims in trunks, shelves for spare tyres, etc.) and interior door trims, while other renewable fibre-based composites are used for higher value interior

Fig. 7 WPC coloured and formed to imitate the appearance of wood

trims including in dashboards and doors (Carus et al. 2015). In contrast to other fields, WPCs in the automotive field are often used to replace metal or fibreglass components, as opposed to wood or plastics.

European regulations stipulate that by 2015 reuse and recovery of all end-of-life vehicles in the European Union must reach a minimum of 95 % by average vehicle weight, and reuse and recycling of materials from end-of-life vehicles must reach a minimum of 85 % by average vehicle weight (The European Parliament and the Council of the European Union 2000). The use of renewable fibre-based composites significantly reduces the weight of many vehicle components, and also increases the recyclability. These factors, along with the existing technological capabilities of vehicle manufacturers, provide for strong future growth in the automotive sector, particularly in Europe where renewable fibre use could increase from 60,000 to 300,000 t each year (Carus et al. 2015).

5.3 Furniture, Highway Materials, Consumer Goods, and Other WPC Applications

WPCs are already in use by major furniture producers, such as IKEA (2015a, b). Applications in packaging and consumer products, including instruments, toys, tableware are not yet mainstream, but are areas of likely growth (Haider and Eder 2010).

Highway construction in the United States utilises several materials which are suitable for substitution by WPCs (e.g. treated wood and pure plastics), and may become a growth sector in the future if certain barriers are overcome (Thompson et al. 2010).

5.4 Perceptions of WPCs

User perceptions, knowledge, and preferences regarding materials have a large impact on the overall utilisation of a product and vary in importance and impact based on the needs and expectations of the user (Clemons 2002; Thompson et al. 2010). Material specifiers, manufacturers, and product users (both builders and building occupants) all interact with materials and form opinions from their experiences, which ultimately impact later material specification decisions.

Manufacturers of products, especially of products that are exposed to public view like furniture, interior trim work, exterior decking, etc., may perceive WPCs as ‘fake’ and undesirable despite their workability and potential to imitate the appearance of wood (Pritchard 2004). If manufacturers do not approve of the material and refuse to use it (or do so begrudgingly), WPCs are unlikely to gain traction in this subsector of the wood products market. However, manufacturers who typically deal with plastics are more likely to view the material in positive terms because it reduces material costs compared to solid plastics and can be considered to improve appearances, and reduce environmental impacts (Pritchard 2004; Bismarck et al. 2006; Klyosov 2007).

In the highway construction sector in the western U.S., WPCs were perceived favourably by highway contractors compared to other more frequently used materials despite low utilisation and relatively low familiarity (Thompson et al. 2010). Given the favourable perception of these products, the authors conclude that once other challenges related to product certification are met, WPCs are well placed to enter a potentially lucrative and sizeable market (Thompson et al. 2010).

In contrast to manufacturers and builders, lay persons often have different needs and expectations from materials, especially related to aesthetics and maintainability. For example, day-to-day building users have both active and passive responses to their built environment. In both cases, the materials, design, and perceived qualities of the environment impact user's subjective and biological responses to the environment (Burnard and Kutnar 2015). In the case of subjective reactions users may decide that they dislike a building's (or products) design and in some cases may choose not to use it which has direct economic impacts. In the case of biological responses, human well-being can be impacted by the user's reaction to their environment, especially over long periods of time. Material selection is a critical part of designing buildings for human well-being (Burnard and Kutnar 2015). In new building design paradigms that emphasise providing positive human health impacts, including nature and natural elements in the built environment is important because positive health impacts have been demonstrated repeatedly in outdoor environments with greater degrees of naturalness (less apparent human intervention). User perceptions of material naturalness are then a key to determine which materials should be used in buildings designed to produce positive health impacts for occupants (Burnard et al. 2015). A study comparing user perceptions of building material naturalness conducted in three countries (Finland, Norway, and Slovenia) demonstrated that users were quickly able to identify WPCs with imitated wood-like features as significantly less natural than wood products that had undergone varying degrees of transformation (solid wood, wood-based composites, stone, metal, ceramics, and textiles were included in the study) (Burnard et al. 2015). However, the WPC in the study was one of the few materials where differences in perceptions of naturalness between countries were apparent, indicating that participants from two of the countries (Finland, Norway) were able to distinguish between the natural and imitated materials more readily than their counterparts (Slovenia). In addition to less favourable ratings of naturalness, the study found that users in Finland and Norway view the material as natural in a binary decision task about half as often as Slovenians (25 and 50 %, respectively) (Burnard et al. 2015). Compared to other materials in the study only seven materials were viewed as not natural by more respondents overall (Fig. 8). In these cases, the difference in perceptions may be related to the more prevalent use of wood materials in the built environment in Finland and Norway than in Slovenia (Burnard et al. 2015).

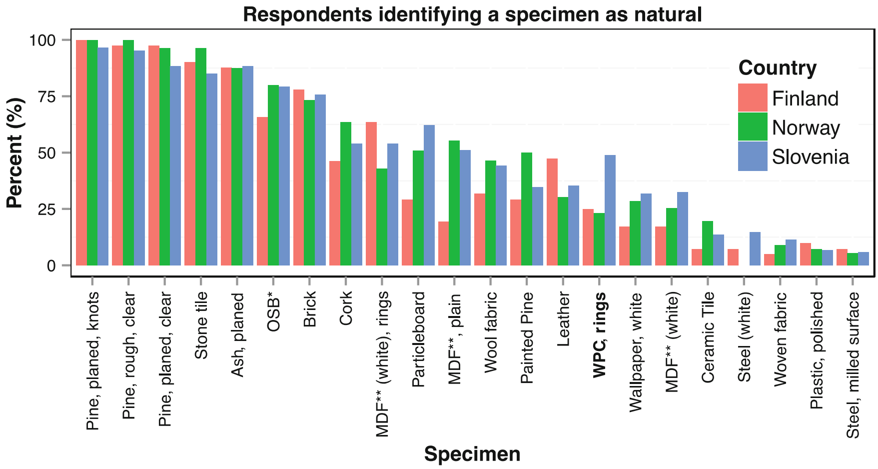


Fig. 8 Percent of respondents stating the listed specimen was natural in a binary decision assessment (Adapted from Burnard et al. 2015). **OSB* Oriented Strand Board; ***MDF* Medium Density Fibreboard

6 Environmental Impacts of WPCs

Environmental impacts of processes and products have become an increasingly publicised and are used by scientists, marketers, material selectors, and the public to gain insight into how different technologies and products affect our environment. Life cycle assessment (LCA) is means of estimating the environmental impact of a product and the process used to create it. LCAs examine inputs and outputs of a system used to create a product over a specified portion of its life. For example, a cradle-to-grave LCA would use detailed information about the production and extraction of raw materials, transportation, manufacturing, throughout the product's useful life, and finally disposal (with wood products final disposal includes significant energy recovery through combustion). Cradle-to-gate is another common assessment period, which begins with raw material production but ends when the product leaves the producers facility and does not include the use phase or disposal. However, with the increased focus on recycling and reuse accounting for the environmental impact of products from cradle-to-cradle is increasingly important, especially in Europe where recycling and environmental targets are quite aggressive (Gärtner et al. 2012; Höglmeier et al. 2013). In cradle-to-cradle scenarios for renewables, materials are "cascaded" and reused after each life cycle, preferably with minimal transformation in sequential uses, until finally the materials are burned for energy reclamation (Gärtner et al. 2012; Höglmeier et al. 2013). WPCs fit well into the wood cascade as repeat processing continually produces material side streams which are suitable for use in WPCs, and reduction in material quality and size (from solid timber to particles and fibres) after each life cycle will eventually produce materials suitable for use in WPCs. Recycled plastics are also used in WPCs which can significantly reduce their environmental impact (Vidal et al. 2009; Oneil et al. 2013). Not only does wood use offset the quantity of non-renewable material in WPCs, using wood in long-life products also sequesters atmospheric carbon and mitigates the climate change potential connected to the energy use of material extraction and processing (Hill et al. 2015).

The environmental impact of WPC matrix components varies greatly based on the type of matrix used. Commonly used petroleum-based polymers (HDPE, PP, PVC) produce negative environmental impacts throughout their life cycle, largely because they rely on non-renewable raw materials (Rajendran et al. 2012; Qiang et al. 2014). Using alternative, renewable-based, biodegradable polymers such as PLA may produce smaller environmental impacts once improved manufacturing techniques are developed that reduce water and energy utilisation (Qiang et al. 2014).

Studies directly comparing solid timber decking products against alternative WPCs conclude that solid wood produces a significantly lower environmental impacts than in both cradle-to-gate and cradle-to-grave scenarios (Bolin and Smith 2011; Oneil et al. 2013). Bolin and Smith (2011), following ISO 14040 and ISO 14044 standards (ISO/IEC 2006a, b), compared treated lumber used for decking (alkaline copper quaternary (ACQ) lumber, an unspecified southern pine from the US) to a WPC composed of 50 % recycled wood with a matrix mixture of virgin and recycled HDPE (25 % of the total each). Comparing a theoretical deck of approximately 30 m^2, the ACQ-treated lumber deck used 14 times less fossil fuels and nearly 3 times less water, produced 4 times less acid rain, 3 times less greenhouse gas emissions, half of the smog and ecological toxicity, and nearly equal eutrophication (Bolin and Smith 2011). The authors note that using biomass or renewable energy sources for WPC production could significantly reduce the striking difference in fossil fuel consumption between the ACQ-treated lumber and the WPC (Bolin and Smith 2011). Assuming production in regions where renewable energy sources are more common (Europe, or the west coast of the US) could significantly alter the outcomes of this type of comparison.

Another study comparing 9.3 m^2 of decking made from virgin PVC, virgin WPC, recycled WPC, and redwood lumber found that recycled virgin WPC produced less global warming potential and ozone depletion than PVC, more smog, acidification, eutrophication and respiratory effects using the US Environmental Protection Agency's TRACI methodology (Oneil et al. 2013). Recycled WPC produced reduced impacts in comparison to virgin WPC in all categories except ozone depletion, in which it produced similar effects. Compared to PVC, recycled WPC produced significantly reduced impacts except eutrophication which was greater for recycled WPC and smog impacts, which were approximately equal for both (Oneil et al. 2013). In all categories, redwood lumber produced significantly lower impacts between 10 and 30 % of the most significant impacts of the compared products, except for global warming potential that produced a negative effect (approximately 140 % reduced impact compared to PVC) (Oneil et al. 2013).

6.1 Product Category Rules and Environmental Product Declarations

Product category rules (PCR) are defined methods for creating environmental product declarations (EPD) for product groups such as "wood materials". EPDs are standardised statements of products environmental impacts that are meant to be comparable to other similarly produced products that have EPDs following the same PCR. The international standard for producing PCRs is ISO 14025, which defines the necessary elements of PCRs, and, in effect, of EPDs (ISO/IEC 2006c). Though no specific PCR or EPD could be found for a WPC product of any kind at the time of this writing, a PCR for general wood materials can be used to produce a WPC EPD. The PCR for wood materials developed by the firm Institut Bauen und Umwelt e.V., specifies that their PCR can be used for a variety of wood composites, including special wood materials which could include WPCs (Institut Bauen und Umwelt e.V. 2009). Going forward using actual products for comparison, using LCAs or EPDs-produced following a published PCR will provide more comparable results. However, these tools are still developing and authors of LCAs and EPDs should utilise the latest standards and versions of PCRs to conduct their comparisons.

7 Summary

WPCs are a product category with many existing and emerging applications. The vast majority of WPCs are used for exterior decking and other exterior board applications. This market continues to grow in North America, is beginning to grow in Europe, and rapid growth is expected in China. Automotive applications continue to grow as well, however, competition in this subsector from other fibre sources poses a risk for WPCs. In both these primary uses, wood is used to reduce the cost and weight of plastic products as well as to improve material properties such as strength.

An added benefit of using wood as a filler product in plastics is the reduced environmental impact that can be achieved by offsetting the amount of non-renewable materials used in a product with renewably sourced wood. Often, the wood used in WPCs can come from primary production side streams, forest slash, or recovered wood products, which reduces the strain on raw forest resources. However, competition for these products from energy producers, as well as fibreboard and particleboard producers, has an impact on material costs for WPC manufacturers which may steer them towards other renewable sources instead of wood.

Current development is focused on improving material qualities ranging from strength to durability, as well as improving the compatibility of matrix components for longer lasting products. Other current work is focused on examining the environmental and performance impacts of using WPCs as substitution products in various new applications, using renewable-based plastics with wood reinforcement, and examining new manufacturing methods for WPCs.

Future research and innovation must overcome challenges related to matrix compatibility, rising costs related to increased demand for forest resources as a fuel source, product shortcomings such as exterior durability, impact strength, as well as knowledge gaps and negative perceptions amongst manufacturers in some sectors and consumers. Other areas for innovation and development are rapid manufacturing with WPCs either for prototyping or bespoke product manufacturing. In each case new innovations and developments must consider the environmental impacts associated with the raw materials, manufacturing process, product utilisation, recycling, and end-of-life scenarios. Improved data collection and quality amongst manufacturers and consumers will help to improve the quality of LCAs conducted on WPCs. Furthermore, using PCRs to produce comparable EPDs may alleviate negative consumer and manufacturers perceptions about the suitability and environmental impact of WPCs in a variety of product categories.

Acknowledgments The authors are pleased to acknowledge the support of WoodWisdom-Net+ and the Slovenian Ministry of Education, Science, and Sport of the Republic of Slovenia for their support of the What We Would believe and cascading recovered wood projects; European Commission for funding the project InnoRenew CoE under the Horizon2020 Widespread-2015 program, and infrastructure program IP-0035.

References

Berger MJ, Stark NM (1997) Investigations of species effects in an injection-molding-grade, wood-filled polypropylene. In: Fourth international conference on woodfiber–plastic composites, Madison, WI, pp 19–25

Bismarck A, Baltazar-Y-Jimenez A, Sarikakis K (2006) Green composites as panacea? Socio-economic aspects of green materials. Environ Dev 8:445–463. doi:10.1007/s10668-005-8506-5

Bodig J, Jayne B (1982) Mechanics of wood and wood composites. Van Nostrand Reinhold, New York

Bolin C, Smith S (2011) Life cycle assessment of ACQ-treated lumber with comparison to wood plastic composite decking. J Clean Prod 19:620–629. doi:10.1016/j.jclepro.2010.12.004

Bouafif H, Koubaa A, Perré P, Cloutier A (2009) Effects of fiber characteristics on the physical and mechanical properties of wood plastic composites. Compos Part A Appl Sci Manuf 40:1975–1981. doi:10.1016/j.compositesa.2009.06.003

Burnard MD, Kutnar A (2015) Wood and human stress in the built indoor environment: a review. Wood Sci Technol 49:969–986. doi:10.1007/s00226-015-0747-3

Burnard MD, Nyrud AQ, Bysheim K, Kutnar A, Vahtikari K, Hughes M (2015) Building material naturalness: perceptions from Finland, Norway and Slovenia. Indoor Built Environ 0:1–16. doi:10.1177/1420326X15605162

Carus M, Eder A, Dammer L, Korte H, Scholz L, Essel R, Breitmayer E, Barth M (2015) Wood-plastic composites (WPC) and natural fibre composites (NFC): European and global markets 2012 and future trends in automotive and construction

Caulfield DF, Clemons C, Jacobson RE, Rowell RM (2005) Wood thermoplastic composites. In: Rowell RM (ed) Handbook of wood chemistry and wood composites. CRC Press, Boca Raton, pp 365–378

Clemons C (2002) Wood-plastic composites in the United States: the interfacing of two industries. For Prod J 52:10–18

Clyne TW (1989) A simple development of the shear lag theory appropriate for composites with a relatively small modulus mismatch. Mater Sci Eng A122:183–192

Corbière-Nicollier T, Gfeller Laban B, Lundquist L, Leterrier Y, Månson J-A, Jolliet O (2001) Life cycle assessment of biofibres replacing glass fibres as reinforcement in plastics. Resour Conserv Recycl 33:267–287. doi:10.1016/S0921-3449(01)00089-1

Eckert C (2000) Opportunities for natural fibers in plastic composites. In: Progress in woodfibre–plastic composites. University of Toronto

Eder A, Carus M (2013) Global trends in composites (WPC). Bioplastics Mag 8:16–17

English B, Stark N, Clemons C (1996) Wood and mineral fillers for injection molding grade polypropylene, Madison, WI

Escobar WG, Wolcott MP (2008) Influence of wood species on properties of wood/HDPE composites. Washington State University

Farsi M (2012) Thermoplastic matrix reinforced with natural fibers: a study on interfacial behavior. In: Wang J (ed) Some critical issues for injection molding. InTech, pp 225–250

Gacitua W, Wolcott MP (2009) Morphology of wood species affecting wood-thermoplastic interaction: microstucture and mechanical adhesion. Maderas-Ciencia y Technol 11:217–231

Gärtner SO, Hienz G, Keller H, Paulsch D (2012) Ökobilanz der kaskadierten Nutzung nachwachsender Rohstoffe am Beispiel Holz– eine Einordnung = “LCA of cascading use of renewable resources on the example of wood - a classification”. uwf. UmweltWirtschaftsForum 20:155–164. doi:10.1007/s00550-012-0259-7

Guo Y, Zeng W, Jiang K (2011) Preparation and selective laser sintering of wood–plastic composite powers and post processing. Dig J Nanomater Biostruct 6:1435–1444

Haider A, Eder A (2010) Markets, applications, and processes for wood polymer composites (WPC) in Europe. In: Teischinger A, Barbu MC, Dunky M, Harper D, Jungmeier G, Militz H, Musso M, Petutschnigg A, Pizzi A, Wieland S, Young TM (eds) Processing technologies for the forest and biobased product industries, pp 146–151

Hanawalt K (2012) Wood-pastics composites done right. Plast Technol 32–34

Hill C, Norton A, Kutnar A (2015) Environmental impacts of wood composites and legislative obligations. In: Wood composites, pp 309–332

Höglmeier K, Weber-Blaschke G, Richter K (2013) Potentials for cascading of recovered wood from building deconstruction—a case study for south-east Germany. Resour Conserv Recycl 78:81–91. doi:10.1016/j.resconrec.2013.07.004

Hull D, Clyne TW (1996) An introduction to composite materials, 2nd edn. Cambridge University Press, Cambridge

IKEA (2015a) Democratic design—IKEA

IKEA (2015b) IKEA PS 2012 Chair with armrests—IKEA

Institut Bauen und Umwelt e.V. (2009) PCR Wood Materials. Königswinter

ISO/IEC (2006a) ISO/IEC 14040:2006 environmental management—life cycle assessment—principles and framework

ISO/IEC (2006b) ISO/IEC 14044:2006 environmental management—life cycle assessment—requirements and guidelines

ISO/IEC (2006c) ISO/IEC 14025:2006 environmental labels and declarations—type III environmental declarations—principles and procedures

Kamke FA, Nairn JA, Muszynski L, Paris JL, Schwarzkopf M, Xiao X (2014) Methodology for micromechanical analysis of wood adhesive bonds using x-ray computed tomography and numerical modeling. Wood Fiber Sci 46:15–28

Karas M (2010) Sustainable bio-composites for west coast highways. MS thesis, Oregon State University

Klyosov A (2007) Wood-Plastic composites. Wiley, Hoboken

La Mantia F, Morreale M (2011) Green composites: a brief review. Compos Part A Appl Sci Manuf 42:579–588. doi:10.1016/j.compositesa.2011.01.017

Lu JZ, Wu Q, McNabb HS Jr (2000) Chemical coupling in wood fiber and polymer composites: a review of coupling agents and treatments. Wood Fiber Sci 32:88–104
Maldas D, Kokta BV (1991) Influence of maleic anhydride as a coupling agent on the performance of wood fiber—polystyrene composites. Polym Eng Sci 31:1351–1357
Mukherjee T, Kao N (2011) PLA based biopolymer reinforced with natural fibre: a review. J Polym Environ 19:714–725. doi:10.1007/s10924-011-0320-6
Nikzad M, Masood SH, Sbarski I (2011) Thermo-mechanical properties of a highly filled polymeric composites for fused deposition modeling. Mater Des 32:3448–3456. doi:10.1016/j.matdes.2011.01.056
Oneil E, Bergman R, Han H, Eastin I (2013) Comparative life-cycle assessment of California redwood decking
Patterson J (2001) New opportunities with wood-flour-foamed PVC. J Vinyl Addit Technol 7:138–141. doi:10.1002/vnl.10281
Pritchard G (1998) Plastics additives: an A–Z reference. Springer Science and Business Media, Berlin
Pritchard G (2004) Two technologies merge: wood plastic composites Geoff Pritchard describes how wood and resin are being. Plast Addit Compd 48:18–21. doi:10.1016/S0034-3617(04)00339-X
Qiang T, Yu D, Zhang A, Gao H, Li Z, Liu Z, Chen W, Han Z (2014) Life cycle assessment on polylactide-based wood plastic composites toughened with polyhydroxyalkanoates. J Clean Prod 66:139–145. doi:10.1016/j.jclepro.2013.11.074
Raisanen VI, Alava MJ, Niskanen KJ, Nieminen RM (1997) Does the shear-lag model apply to random fiber networks? J Mater Res 12:2725–2732
Raj RG, Kokta BV (1991) Reinforcing high density polyethylene with cellulosic fibers. I: The effect of additives on fiber dispersion and mechanical properties. Polym Eng Sci 31:1358–1362
Rajendran S, Hodzic A, Soutis C, MariamAl-Maadeed A (2012) Review of life cycle assessment on polyolefins and related materials. Plast Rubber Compos 41:159–168. doi:10.1179/1743289811Y.0000000051
Schirp A, Stender J (2009) Properties of extruded wood-plastic composites based on refiner wood fibres (TMP fibres) and hemp fibres. Eur J Wood Prod 68:219–231. doi:10.1007/s00107-009-0372-7
Schirp A, Ibach RE, Pendleton DE, Wolcott MP (2008) Biological degradation of wood-plastic composites (WPC) and strategies for improving the resistance of WPC against biological decay. ACS Symp Ser 982:480–507. doi:10.1021/bk-2008-0982.ch029
Schwarzkopf MJ (2014) Characterization of load transfer in wood-based composites. PhD Dissertation, Oregon State University
Schwarzkopf M, Muszyński L (2015) Strain distribution and load transfer in the polymer-wood particle bond in wood plastic composites. Holzforschung 69:53–60. doi:10.1515/hf-2013-0243
Sjöström E (1993) Wood chemistry: fundamentals and applications. Academic Press, San Diego
Stark NM, Rowlands RE (2003) Effects of wood fiber characteristics on mechanical properties of wood/polypropylene composites. Wood Fiber Sci 35:167–174
Teuber L, Militz H, Krause A (2015) Processing of wood plastic composites: the influence of feeding method and polymer melt flow rate on particle degradation. J Appl Polym Sci 43231. doi:10.1002/app.43231
The European Parliament and the Council of the European Union (2000) Directive 2000/53/EC—end-of-life vehicles
Thompson DW, Hansen EN, Knowles C, Muszynski L (2010) Opportunities for wood plastic composite products in the U.S. highway construction sector. Bio Resour 5:1336–1352
Vidal R, Martínez P, Garraín D (2009) Life cycle assessment of composite materials made of recycled thermoplastics combined with rice husks and cotton linters. Int J Life Cycle Assess 14:73–82. doi:10.1007/s11367-008-0043-7
Wang Y (2007) Morphological characterization of wood plastic composite (WPC) with advanced imaging tools: developing methodologies for reliable phase and internal damage characterization. Oregon State University

Westman MP, Fifield LS, Simmons KL, Laddha SG, Kafentzis TA (2010) Natural fiber composites: a review. Pacific Northwest National Laboratory, Report PNNL—19220

Wolcott MP, Englund K (1999) A technology review of wood-plastic composites. In: 33rd international particleboard materials symposium, pp 103–111

Woodhams RT, Thomas G, Rodgers DK (1984) Wood fibers as reinforcing fillers for polyolefins. Polym Eng Sci 24:1166–1171. doi:10.1002/pen.760241504

Zhong W, Li F, Zhang Z, Song L, Li Z (2001) Short fiber reinforced composites for fused deposition modeling. Mater Sci Eng A 301:125–130. doi:10.1016/S0921-5093(00)01810-4

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Environmental Impacts of Traditional and Innovative Forest-based Bioproducts
Kutnar, A.; Muthu, S.S. (Eds.)
2016, VII, 248 p. 51 illus. in color., Hardcover
ISBN: 978-981-10-0653-1