Recycling of Wood-Polymer Composites in Relation to Substrates and Finished Products

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Recycling of Wood-Polymer Composites in Relation to Substrates and Finished Products

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Abstract. Nowadays, the aim is to minimize the impact of a product or service on the environment in all phases of its life cycle. In particular, this applies to those in which the impact is greatest. One of the techniques that allow comprehensive assessment of the environmental impact of manufactured products is Life Cycle Assessment (LCA). With this method, an environmental declaration is made for the products obtained. WPC composites can be made in a sustainable way, without wasting any material and without altering. WPC composites can be made in a sustainable way, without wasting any material and without altering. Composites with wood fillers may be competitive to materials with inorganic fillers. Wood-polymer composites can be produced from original natural raw materials. They can also be obtained as a result of recycling, where either wood or polymers come from the recyclate. It is also possible to use both components from recovery. Another way is to use WPC as a future raw material. Research on the utilization of waste from such materials is also conducted in a number of research centres, taking material recycling as the basic direction, and technical products are manufactured from the obtained recyclate.

1. Introduction

The products or goods that are manufactured as well as the services rendered all have an impact on the environment. The magnitude of this impact depends on many factors, such as the length of use of the products, the means of production (e.g. energy or water) or the materials used (raw materials). Nowadays, the aim is to minimise the impact of a product or service on the environment in the all phases of its 'life cycle'. This is particularly true of those where the impact is greatest. At every stage of the product development process, parameters such as technical, ergonomic, economic, health and environmental properties are essential for the development of the final product [1,2]. Such an approach generates environmental benefits and may lead to a reduction in the costs of manufacturing, use and disposal of the products. These actions might improve the competitiveness of a company or a product. One of the techniques allowing for a comprehensive assessment of the environmental impact of manufactured products is the LCA (Life Cycle Assessment). It has its advantages and disadvantages. The advantages include flexibility, interdisciplinary and comprehensiveness. The disadvantages on the other hand include the fact that they are time-consuming and costly, the lack of time and space differentiation and the complexity of the analyses [3]. Life cycle assessment can be treated as a decision support tool which helps to choose the most advantageous way to design new products or technologies, as well as to develop the existing ones [4]. Despite the disadvantages, the use of the

LCA to evaluate products and manufacturing processes is of great importance. The LCA analysis should be a part of the development of the concept of 'extended manufacturer responsibility' [3]. The LCA analysis is an important tool that helps ensure proper sustainable development by assessing the environmental burdens associated with the product development [5]. This method allows for the selection of 'clean' production processes, avoidance of hazardous and toxic materials, maximisation of energy efficiency with regard to the production itself and the utilisation of the product, as well as the waste management design and, most importantly, material recycling [6]. Thanks to this method, an environmental declaration is made for the products obtained. Table 1 shows some of the environmental parameters assessed in accordance with the LCA for two different wood-based composites. The first of the composites consists of fibres of coniferous wood, PE (HD) and PP. The second product contains sawdust and HDPE. The total lifespan includes all stages from the production to the end of life.

Table 1. Environmental factors from LCA analysis for sample composites [7].

Composite	Total whole life cycle						
	Life time references [years]	**CO_2 [kg]**	**Air pollution [m^3]**	**Water pollution [m^3]**	**E_r [1] [MJ]**	**E_{nr} [2] [MJ]**	**Waste disposal [kg]**
composite boards h.34mm	20	63.5	5170	326	192	1250	2.44
composite wood cladding h.30 mm	40	45.1	4960	232	211	1080	2.01

[1] Total use of renewable primary energy resources. [2] Total use of non-renewable primary energy resources

The life cycle of polymer-wood composites has been shown in Figure 1. Their life cycle starts with wood cultivation or, in the recycling variant, with the recovery of wood or wood-based materials. Natural fibre polymer composites (73 MJ total energy) consume 45% less energy compared with ABS copolymer (132 MJ total energy). As a result, it causes lower emissions [8]. At the same time, the second component is produced from monomers or can be recovered by recycling. WPC composites can be produced in a sustainable manner, without wasting any material and without any alterations by means of a twin-screw extruder or injection moulding. Once the composite has ceased to serve its purpose, WPC can be re-extruded or the components can be separately collected and recycled. It has been shown [9] that wood-polymer composites made of newsprint paper can be recycled many times without visible loss of mechanical properties. For example, the author [10] found that the reinforcement of polypropylene with wood fibre recycled from hardwood and softwood pallets provides better flexural and tensile strength as compared with the use of wood flour. This is in line with the Cradle and Cradle® concept, i.e. 'from cradle to cradle' [11], which is sometimes referred to as a 'closed-circuit economy'. The product life cycle is based on the use of the waste in the next production process. The used raw materials are always in circulation, which reduces the use of natural resources and thus the amount of waste. C2C goes beyond the basic principles of sustainable development. Products are designed in such manner as to be treated a resource at the end of their life cycle and not just waste.

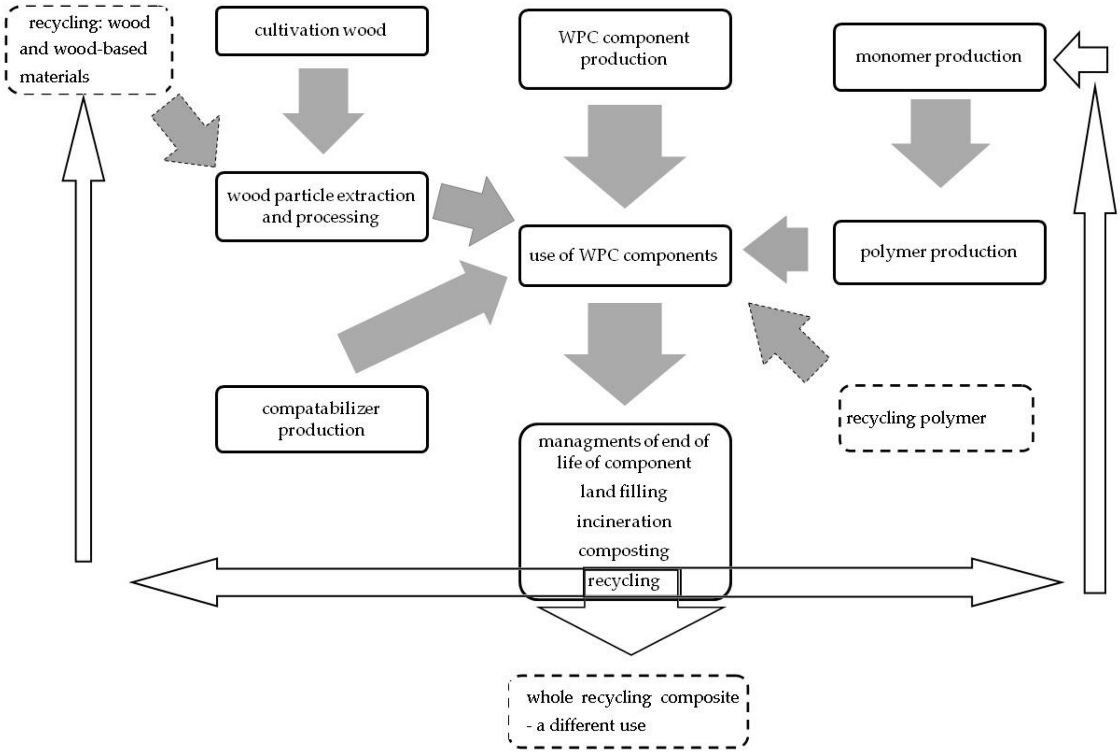

Figure 1. Life cycle of WPC composites (virgin and recycled)

2. Wood – polymer composite

A composite is a material consisting of at least two components that form separate phases and do not mix with each other. One of the components is the matrix and the other is the reinforcement. The matrix (warp) integrates the reinforcement and gives the products the right shape. Its task is also to provide the physical and chemical properties. The reinforcement, on the other hand, additionally improves selected properties of the material. The resultant composite obtains better or new properties in relation to the properties of the initial components.

Polymer-wood composites are known in the Polish and world literature under the following names: *wood polymer composites* and *wood plastic composites*, abbreviated to WPC. They are also referred to as wood materials or wood-polymer materials. In addition to the names mentioned above, the literature also mentions the name ‘artificial wood’[12].

Composites with wood fillers can be competitive with inorganic filler materials. Wood is a renewable raw material and ‘environmentally friendly’ in comparison with other materials [13,14]. Wood is a much less energy-intensive material than most of its alternatives, such as steel, aluminium, cement or bricks.

In such composites, wood or wood-based additives may be present as:

- the reinforcement;
- the filling.

The reinforcement can only be made of wood, e.g. in the form of fibres or grains, i.e. wood flour [15,16]. Usually small fibres are used, which are characterized by a high shape factor. The small dimensions allow for an even distribution of the fibres in the matrix and also provide a larger specific surface area and better adhesion [17]. Then they act as the reinforcement. On the other hand, lignocellulosic plastics in the form of particles act as the filling when their dimensions are approximately equal in all directions, and they can also have any shape [18]. In both of the cases described, the morphology of the wood components is not constant. It is susceptible to changes due to shear forces and high temperatures occurring during WPC processing [19]. Wood fibres provide a reinforcement characterised by high mechanical strength and a favourable shape factor. However, they pose some difficulties in processing with thermoplastics. Wood fibres are also considerably more expensive than wood flour which is therefore more frequently used. The use of wood flour as the reinforcement in WPC implies difficulties in obtaining repeatability of the composites. This is related to the lack of standardisation in the production of this filler, which causes its variable purity and composition.

Wood filler [20] is a reinforcement characterized by availability which determines the low price of this material. This filler is environmentally friendly due to the absence of toxic substances and its recyclability and biological degradation. Owing to its renewability, this product can compete with inorganic fillers. Wood fillers are lightweight materials, which means that the composites obtained with them are characterised by a lower density than that of corresponding composites with inorganic fibres. They are also robust and abrasion resistant. The main disadvantages of wood fillers include their flammability and the anisotropy of its mechanical properties. These are also materials that are not resistant to moisture. They are also characterised by varying quality depending on the source of origin.

Depending on the type of polymer used for wood bonding, WPC may or may not be desirable for the environment. Thermosetting polymers are not widely used in WPC, which, in combination with its recyclability, makes the thermoplastic material more environmentally promising, especially that the second phase, which is wood, is also recyclable [21]. However, a certain amount of duroplastics is used. Mixing wood with thermoplastic material required application of heat to ensure that the wood is thermally wetted with plastic to increase adhesion. The thermal mixing process has criteria that are strongly recommended, the melting or softening point of the plastic used must not exceed the degradation temperature of wood. The following polymers are used as the matrix for wood-polymer composites:

- thermoplastics, i.e. polyolefins or PVC (polyvinyl chloride); less frequently PS (polystyrene), ABS (acrylonitrile butadiene styrene terpolymer);
- biodegradable polymers.

The other polymers cannot be used for the preparation of WPC composites due to their melting point exceeding 190-200°C. The temperature is determined by the decomposition of some wood components, e.g. lignin or hemicellulose [22].

Mineral fillers such as glass fibres, talcum powder and carbon fibres are also used for polymer composites. Mineral fillers can improve many properties of polymer-wood composites, such as moisture resistance, fire resistance or mechanical properties [23]. In order to obtain appropriate properties of polymer-wood composites, various auxiliary and modifying agents have to be used. These include antioxidants, lubricants, dyes, flame retardants and compatibilisers (adhesives) [20, 24]. The use of antioxidants and stabilizers in the production of WPC serves to increase their resistance to aging and prevent degradation of polymers, e.g. under the influence of UV. Lubricants have a positive effect on the reduction of internal friction of polymers, which makes it easier to form finished products from them. Additives in the form of pigments and dyes allow to obtain polymer-wood composites with specific visual and aesthetic features. Compatibilisers, on the other hand, contribute to the increase of interfacial adhesion, which has a significant influence on the increase in the degree of homogenisation of composite components [25]. The use of a proper adhesive (compatibiliser) results in a combination of hydrophilic wood reinforcement with hydrophobic polymer matrix. Modification of fibres by acetylation, alkalisation, esterification and application of pro-adhesive agents is effective. However, not all of these methods are cost-effective [26].

3. Wood-polymer composite - components from recycling

Wood-polymer composites can be obtained from new raw materials. For such materials total life cycle is determined. The parameters that are determined include those presented in Table 1. However, it is also worthwhile to give consideration to production of such composites from secondary raw materials including recycled materials available in the market. Either a recycled matrix or a reinforcement/fill can be used [15]. Another option is that both components used are recycled. The recyclability of polymer, wood, wood-based plastics and polymer composites is shown in Figure 2.

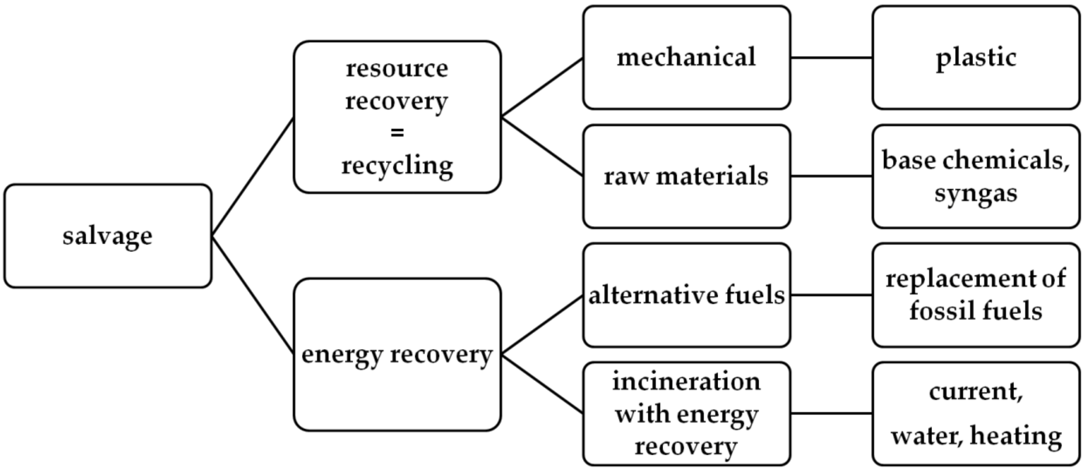

Figure 2. Methods for recovering polymer and wood materials as well as polymer composites

Mechanical recycling implies mechanical shredding of used waste in the form of quality raw material (recyclate) ready for further processing [27]. This method is used when the recovered waste is clean and homogeneous. Before the waste is reprocessed, it needs to be pre-identified, sorted and separated. These are important steps leading towards recycling. Polymer, wood and other mixtures of different compositions have unfavourable physical properties and limited usability. Therefore, it is necessary to select from solid waste fractions of materials with strictly defined properties [28,29]. Raw material recovery, i.e. chemical or thermal recycling, involves decomposition of waste, either temperature-induced or resulting from a chemical reaction, to the basic components from which the material was made. Raw material recycling uses many methods and technologies based on, inter alia, pyrolysis, gasification, depolymerisation or reduction melting in metallurgical furnaces or in other melting processes [30]. It does not require preliminary segregation of waste, washing or removing other organic substances. Energy recovery means burning waste and generating energy at the same time. It is particularly suitable for mixed and/or contaminated waste fractions. This is a response for fast developing countries concerning the problem of storage and the lack of waste management methods [31]. Secondary solid fuels obtained from waste are a new type of fuel for the production of which solid waste is used can be a valuable component in obtaining alternative fuels due to their high calorific value. These fuels are becoming more and more commonly used in the industry [30].

Recyclate can be obtained during the production of plastic parts or after they have been used up. It can be characterised by slightly worse properties than pure polymers, which is greatly affected by the fact that it is a more or less complex mixture of these chemicals. The lack of homogeneity in recyclate composition significantly contributes to the difficulties with quality control of the composite produced [32]. Therefore, pure polymer matrices are used to produce WPC of significant importance or intended for research.

At the end of the first life cycle or after repeated use, products made of plastics can be recycled to obtain new materials or polymer products. As recycled plastics can be obtained from different sources because they were subjected to different storage and reprocessing conditions, they can therefore exhibit different properties depending on their degree of degradation. Post-consumer plastic waste can contain many grades, colours and contaminants, leading to different results when these plastics are combined with wood flour / fillers. Plastic degradation is a problem that often occurs when a polymer is subjected to a process or service. The properties of waste plastics are different with regard to some important factors which are important for the production of WPC because the properties of WPC are a function of the plastic properties [33].

The woodworking industry and the waste generated as a result of its operation can be managed thanks to the dynamic development of production of energy from renewable sources. In fact, wood is a useful biomass for energy purposes – thanks to it, many wood processing plants have the possibility to use it effectively for energy purposes using thermal methods of burning scrap wood [34]. Wood products can be easily recycled and contribute to lower greenhouse gas emissions than non-renewable steel and concrete.

Due to the excessive amount of waste being produced, many wood industry plants apply practices related to the process of energy recovery, i.e. they use the resulting waste to obtain useful material, substances or energy. Basic recovery processes include thermal treatment of waste where heat plays an important role in the physical or chemical transformation of the waste [35]. The growing amount of wood waste is implies the necessity to find ways of managing it. This management should take into account the environmental aspects and, consequently, the principles and hierarchy of sustainable waste management. Unfortunately, a significant proportion of them, especially of post-use and wood-based origin, are sent to landfill sites. It seems necessary to find ways of using the waste being produced. One of them is to use it as reinforcement in polymer-wood composites.

In the production of wood-based composites it is possible to use wood fuel (biomass) as combustion energy [2]. Such fuel normally consists of wood residues (wood and bark) from the production of wood. In the production of OSB sheets 82% of the required heat energy is generated on site by burning wood fuel (biomass). And this energy represents approx. 38% of the total energy from the cradle to the end of the OSB sheet [36]. For coniferous plywood, this energy accounts for about 59% or 56% of the total energy from cradle to cradle [36, 37]. The use of wood as a fuel and energy source plays an important role and has a beneficial effect on the environment. Emissions of biogenic CO_2 due to wood combustion are often referred to as creating a neutral effect on global warming [38]. However, the use of petroleum-based adhesives (amino resins) for the production of wood-based composites is considered to be the main source of environmental impact [39].

Pure wood waste can be utilised in one way or another. The biggest problem is wood-based plastics which in addition to wood also contain adhesives or other chemical additives. In their case, it is not possible to thermally transform waste and obtain wood fuel as combustion will generate pollution. Therefore, these materials should be used for the production of polymer-wood composites.

The paper [15] investigates the cost-effectiveness of replacing glass fibres with wood fillers. For this purpose, the authors carried out a life-cycle analysis of car door panels. The panels were made from a polypropylene matrix and a filler with a mass share of 40%. The use of organic filler reduced the adverse impact of the component on the environment. At the same time, the wood filler was characterized by a lower cost, higher availability and lower density than glass fibres. An additional advantage of wood fibre composites was their easy recycling and smaller amount of waste products left after combustion.

Mineral fillers are usually primary, i.e. new, materials. Some recycled materials are suitable for use as mineral fillers in polymer-wood composites, for example recycled mineral wool [40]. Mineral wool is commonly used as a building insulation material accounting for about 60% of the total market of insulation products [41]. It is therefore a material fraction commonly found in the waste stream and is often considered difficult to recycle and therefore mainly sent to landfill.

Polymer-wood composites can first of all replace solid wood products, i.e. exterior and interior wall cladding in the construction industry. Secondly, pure plastic products, i.e. decorative linings in the automotive sector. The common view is that [42] WPC cannot compete with solid wood in terms of low environmental impact. It provides, however, an environmentally friendly alternative to pure plastics. It is possible [43] that WPC is an intermediate step in the cascade use of biomass before recovering energy from biomass.

The environmental assessment of products and services is carried out based on quantitative data in accordance with the Life Cycle Assessment (LCA) methodology. The history of the use of WPC from secondary or cascade resources dates back to the early 1990s according to, inter alia, [44, 45, 46]. The studies mentioned above present the views of the best experts in the field who state that there is a lack an ecological analysis based on quantitative data. There are studies on WPC [47,48] produced from virgin raw materials on a laboratory scale where LCA was performed ex ante. They focus on different alternative materials [49] or on the integration of WPC sustainability issues into the LCA [50].

In another publication, the authors [51] concluded that recycled plastic WPC is better for the environment than virgin plastic WPC but worse than solid wood planks.
Another publication compares the properties of a wood-polymer composite produced from new raw materials and recycled [52,53]. The data are presented in Table 2.

Table 2. Changes in the properties of polymer-wood composites depending on the applied 256 reinforcement (virgin, recycled).

Materials	**30% wood share**		**60% wood share**	
	Virgin	**Recycling**	**Virgin**	**Recycling**
Waste wood (category A II)	-	29%	-	58%
HDPE	-	68%	-	39%
Norway spruce	29%	-	58%	-
HDPE	68%	-	39%	-
MAPE (compatibilizers)	3%	3%	3%	3%
Physical properties				
Density [g/cm3	1.05	1.05	1.17	1.16
Stiffness				
Flexural E [GPa]	1.55	1.58	2.77	2.62
Tensile MoE [GPa]	1.74	1.65	2,87	2.74
Strength				
Flexural strength [MPa]	33.6	31.4	42.3	31.6
Tensile strength [MPa]	18.5	15.7	21.6	16.0

4. Wood-polymer composite - components from recycling

These composites are manufactured from recycled intermediates. They are used for products for the automotive, construction and road industries, e.g. outdoor deck floors, railings, fences, landscaping timbers, cladding and siding, park benches, moulding and trim, window and door frames, and indoor furniture as well as for agriculture or the packaging industry [54]. They are used both in indoor and outdoor applications. Wood-polymer composites are sold as recyclable products. Unfortunately, there is currently no detailed classification of waste legislation for WPC. Landfills are facing increasing amounts of WPC which cannot be assigned to a specific area.

Recycling is divided into two variants:

- internal recycling – production residues (relatively undamaged material) are reused during the production process;
- end-of-life recycling – objects are materially or energetically recycled after a certain period of use.

In practice, many WPC manufacturers already carry out ‘internal recycling’ where the cost is one of the reasons [55]. Methods of recovering polymer composites have been presented in Figure 3.

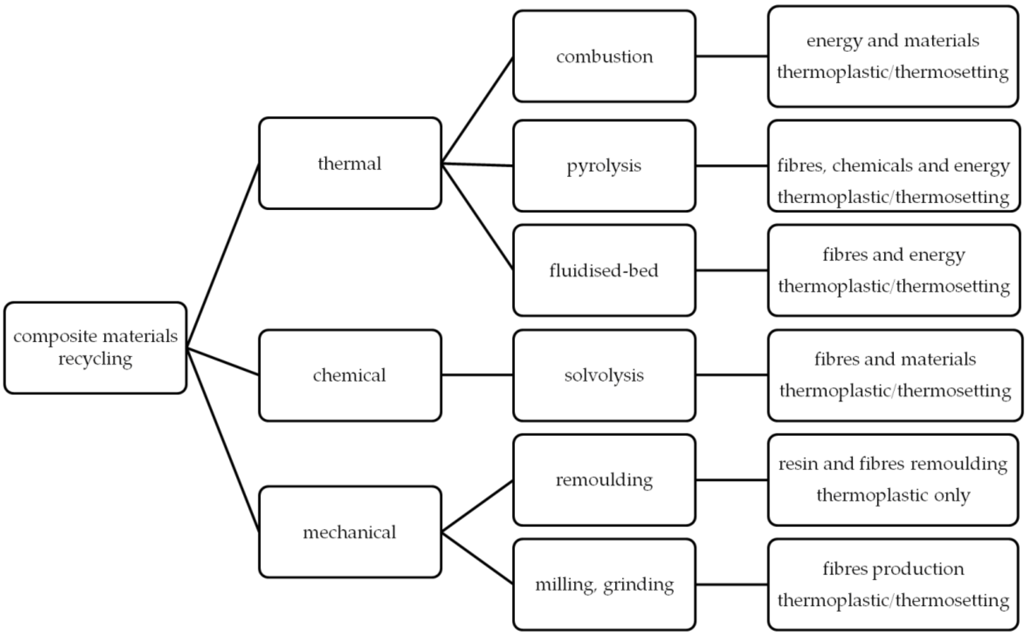

Figure 3. Methods for recovery of polymer composites based on thermoplastics and thermoset polymers.

Polymer-wood composites are probably the last step in the cascade chain of primary and secondary materials. The wood that would be used as the first to produce new materials from solid or modified wood is enriched with plastics and additives in the WPC product. In the final stage of its lifetime, WPC must be treated as bulky or hazardous waste. Therefore, is should be incinerated. This leads to environmental problems and the loss of precious materials. Recycling of composite materials would be an environmentally preferred route but the recovered WPC content is a sensitive issue. Composite incineration is the dominant end-of-life route due to the recycling directives and the lack of secondary markets for the WPC material [52]. Although production volumes are increasing, recycling rates are relatively low because of reduced material properties due to macromolecular decomposition during use.

There are several studies described in the literature in which the authors determined the environmental impact of various composite panels made of natural fibres using life cycle analysis [56,57,58,59]. The conclusion form this literature study is that composite panels made of polymers based on natural reinforcements show favourable results in terms of environmental impact and energy consumption compared to petroleum-based panels. However, epoxy resins were used for both types of composite panels. Their presence was the main contribution to the environmental impact (over 85%) [57]. However, the use of wood fibres as the reinforcement in composite panels shows an ecological advantage in comparison with polypropylene fibres [60]. Chemical recycling, i.e. raw material recycling [61,62], is also attempted. Non-catalytic and catalytic WPC pyrolysis has been studied by many researchers, also with the use of zeolites.

Until now, WPC recycling has not been sufficiently researched and only a few publications are available. One limitation of WPC recycling is the wood component, which begins to degrade and emit volatile substances during repeated processing at temperatures of about 220 °C [63]. Another limitation is the degradation of the polymer. Recycling causes thermal and oxidative degradation, i.e. chain fission and molecular weight reduction [64, 65]. The resulting change in viscosity may require modification of further production processes. After two stages of recycling of polymer-wood composites, such as with 50% of Radiata pine kraft fibres, the strength increased, but after two successive decreases in strength. In general, parameters such as tensile and bending strength and modulus, fibre length and alloy temperature may change. However, strain at break, hardness, interfacial bond density, crystallinity and thermal stability may increase. It depends on how many recycling cycles the composite data has been recycled [63]. In addition to the parameters mentioned above, equilibrium humidity, diffusion coefficient and swelling of thickness may also decrease [66]. Może być i tak, że nawet po siedmiokrotnym przetworzeniu właściwości mechaniczne pozostaną kompozytu względnie niezmienione. Pozwala to na pewne sformułowanie, że recykling wewnętrzny WPC jest szansą dla tych materiału [65]. Przez jakiś czas odciągnie się w czasie koniec ich życia.

The problem with the quality of recyclates can be solved if the recovery process is treated as a process of creating a new material [67].

Research on the disposal of waste from such materials is also conducted in a number of research centres, taking material recycling as the basic line of development, and technical products are manufactured from the recyclate obtained.

5. Results

The increasing quantity of both wood and polymer waste is associated with the need to find ways of managing it. The environmental aspects should be taken into account as well as the principles and hierarchy of sustainable waste management. However, a significant portion, mainly of post-use and wood-based origin, is sent to landfill sites. Wood is seen as one of the foundations of sustainable economic growth, while the use of thermoplastics from fossil hydrocarbon sources and WPC additives has the potential to have a significant environmental impact throughout the life cycle. A good way is to use the resulting waste, in particular wood-based waste, for the production of polymer-wood composites. In many cases they are renewable, relatively cheap, fully or partially recyclable and biodegradable.

A potential solution to the problem of resource scarcity is the cascade use of biomass and more efficient use of by-products in the sector of wood-based and polymer products. Products should be designed so as to be treated as a resource at the end of their life cycle, not just as waste..

The cascading principle is to some extent reflected in the national legislation of the European Member States in the implementation of the European Waste Framework Directive 2008/98/EC [68]. It prioritises alternative methods of decommissioning (EoL), calling for a so-called waste management hierarchy. This includes:

- (1) prevention;
- (2) preparation for re-use;
- (3) recycling (without any incineration);
- (4) other recovery (energy recovery);
- (5) safe disposal.

In addition to cascading, various other strategies and concepts have been developed, such as a closed-loop economy at the European level [59,69] and ProgRess at the German level, recycling and resource-efficient material circulation [52].

The construction industry faces a challenge to meet the sustainability goals set by the UN for energy, climate change and the depletion of natural resources. Buildings account for about 40% of energy consumption and 36% of CO_2 emissions in the EU [70]. Energy efficiency in buildings is necessary to achieve a higher level of sustainability in this sector. One way to reduce the energy consumption of buildings is to develop lightweight materials with low thermal conductivity. They will help to reduce energy loss inside buildings. In this context, it can be noted that wood-polymer composites are compatible with the C2C concept and are a potential material for sustainable development. "Green: composite, material", sustainable composite shows several elements. Demonstrates the possibility of biodegradation and the use of recyclable materials as a raw material, e.g. wood and plastic waste. It also offers the possibility of recycling the finished composite. WPC for recycling can come from post-consumer sources or from own waste generated during production. On-site recycling helps save resources and reduces production costs. Therefore, it seems that such material may belong to the group of sustainable building materials.

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