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REVIEW ARTICLE

Production of wood-based panel from recycled wood resource: a literature review

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Abstract
This article presents and discusses the available studies on utilization of waste wood (WW) resource for wood-based panel production. The cited literature indicated that the majority of WW research was from Europe and conducted mainly on recycled material from particleboard. In addition, particleboard was presented as the first option of wood-based panel product manufactured from waste wood. There was a lack of research on the recycling of plywood. Physical and chemical contaminants fluctuated strongly between low- and high-quality recycled wood mixes depending on their origins. Findings from studies also noticed that wood-based panels (e.g., particleboard) could be produced from 100% WW. However, the physical and mechanical properties of wood-based panel drop with the high proportion of WW content due to the decrease in slenderness ratio and increase in contaminants. Moreover, formaldehyde emission content of particleboard and Oriented Strand Board (OSB) manufactured from WW particles increases when the WW percentage increases. Contrary, the formaldehyde amount decreases with the increase in recycled fiber content in fiberboards. Notably, the properties and emission of recycled wood composite products could be improved by applying high-tech sorting technologies, appropriate chipping techniques, pretreatment steps and formaldehyde-free binders during waste wood handling and production process.

1 Introduction

Post-consumer waste wood is a valuable feedstock for energetic and material sector. Its volume has been increased together with the rapid urbanization and industrialization. Based on Eurostat data in 2014, Europe generates annually about 60 million tons of waste wood collected from different sectors. Germany is the country in Europe collecting the highest number of waste wood per year, accounting for about 6.6 million tons in 2016 (Purkus et al. 2019). Italy, UK and France generate roughly 4 million tons per year, whereas Belgium, Austria, Spain and Poland produce around 2 million tons in 2014 (Silvio 2018). In addition, Sweden, Norway and Denmark collect nearly 1.0 million tons per year (Sekundaerrohstoffe 2018). According to the United State Environmental Protection Agency (EPA), USA generated about 18.1 million short tons of waste wood in 2018 collected from municipal solid waste streams.

Waste wood originates from various resources. Therefore, it is not a homogeneous material due to its complexity of wood types, applications and sources (Bergeron 2014). In addition, waste wood is also considered as a highly sophisticated material in terms of chemical and physical composition (Edo et al. 2016). Various physical and chemical contaminants exist in the waste wood resources causing problems for recycling processes and influencing the properties of recycled products. Nowadays, mechanical processes (e.g. sieving, magnet or eddy current) can sort physical contaminants in waste wood such as plastic, metal, textile, etc. However, chemical contaminants that are coming from substances of wood preservatives, paints, glues, etc. are not easy to eliminate from waste wood mechanically. Thus, the management of these contaminants from inputs plays an important role in cascading and re-using this valuable resource effectively (Besserer et al. 2021). From this point of view, management using waste wood ordinances has been established and used in many countries. However, there is a lack of uniform waste wood ordinance among countries

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nowadays. Germany, Austria and Switzerland apply the same ordinance divided into four categories depending on the characteristics of the waste wood, namely AI, AII, AIII and AIV, whereas France, Belgium, Netherlands and Luxemburg classified their waste wood categories with A, B, C and D (Jan 2019). UK, Sweden, Estonia and Spain have their own waste wood ordinances. In addition, many countries have not established waste wood ordinance. In this sense, it is difficult to trade different collected waste wood assortments between European countries.

Despite the difference in waste wood management, the recycling rate of waste wood varies from country to country in material and energy uses. For instance, in European countries, for decades, energy utilization of waste wood exceeds material utilization, accounting for 60–95%. Sweden, Switzerland, Norway, Netherlands, and Finland are the top leading European countries, which share high waste wood portion for energy purpose, ranging from 85 to 95% (BAV e.V. 2021). In the sector of material use, Italy ranks in first position among European countries with a 42%, share of waste wood in panel production, followed by Austria with 33% (Silvio 2018).

As resources, fossil and renewables are limited in their availability, though for different reasons, the European Green Deal laid the political basis for a shift from linear to circular economy. Products entering the cycle must be designed in a way that supports circular utilization (Fig. 1). However, repeated utilization of resources through recycling requires a thorough cleaning process to prevent contaminants that may have entered the resources cycle decades ago from being carried over and accumulated. As the use of natural resources gains massive interest, their efficient use together with consumer protection is of high concern. Many authors have therefore been working on the characteristics of different waste wood resources and their utilizations. Some focused on the origins and contaminants of waste wood materials (Tables 1, 2). The others concentrated on the application

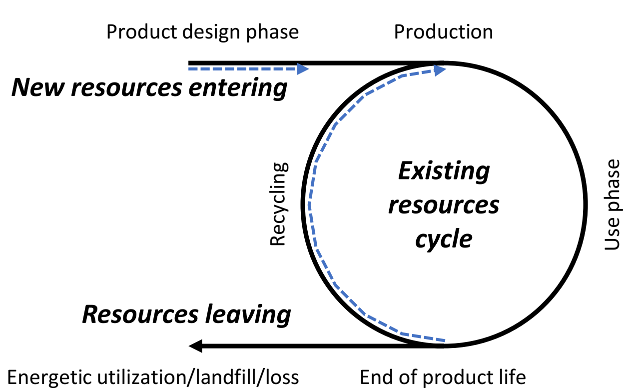

Fig. 1 Existing resources utilization pathways (solid line) and approaches towards a circular economy (dotted lines)

of waste wood to the production of wood-based panel as well as its effects on the physical and mechanical properties and formaldehyde emission of final products (Tables 3, 4). Due to the variety of materials and the effects of possible contaminations, this paper presents an overview of the conducted waste wood research with the goal to answer the following questions:

1. Where do the waste wood materials come from and what are the target composites?
2. What are the challenges that recyclers are facing during the conversion of waste wood?
3. What is the concentration of recycled wood material in the new composite products and its consequences?

2 Methods

The stated questions were addressed by collecting peer-reviewed articles, proceedings of conferences and reports of research projects relating to waste wood material and its utilization from the following scientific websites:

- ScienceDirect (https://www.sciencedirect.com/)
- Google Scholar (https://scholar.google.com/)
- WorldCat (https://www.worldcat.org/)
- SpringerLink (https://link.springer.com/)
- Taylor&Francis Online (https://www.tandfonline.com/)
- ACS Publications (https://pubs.acs.org/)
- Web of Science (https://www.webofscience.com)

The following keywords were used:

- Waste wood contaminants
- Waste wood composites
- Recycled wood, formaldehyde emission
- Secondary wood resources
- Wood residues utilization

The term waste wood mentioned in the searched articles is restricted to used/secondary or recycled wood. Research articles, dealing with by-products from sawmills or the like are not included in this article.

The collected publications for the review article were analyzed and categorized dealing with the research questions focusing on the recycling of waste wood materials from wood-based panel products to produce wood-based panel only. Therefore, wood plastic composite-based publications and the research papers that focused on waste wood materials from solid wood with and without CCA treated will not be discussed and shown up in the Supplementary information.

3 Results and discussion

3.1 Waste wood origin and target composite type

3.1.1 Waste wood origin

Table 1 includes twenty-eight research articles classified into two main categories namely origin and target composite type presenting the origin of waste wood materials conducted in the last twenty years. About half of the studies in Table 1 was conducted from 2015 to 2019. The results indicated that a large proportion of waste wood stream originates mainly from recycling center companies or combustion power plants. In this waste stream, construction and demolition (10 references) and furniture (9 references) dominate the origin uses of waste wood, followed by packaging (6 references), whereas municipal counts for only one interest (Lesar et al. 2018). This finding is also consistent with the research of Mantau and Doering (2018) and Van Benthem et al. (2007) about waste wood streams in Europe.

In the sector of waste wood type, most studies dealt with/focused on wood-based panel (17 references). It is surprising that particleboard was found more than fiberboard, plywood and OSB in waste wood type of wood-based panel industry. According to FAO (2018), plywood production accounted for the largest volume of wood-based panel globally, followed by fiberboard, particleboard and OSB. Therefore, it was expected that more secondary/recycled plywood would be found in the waste wood type rather than particleboard and fiberboard. However, the finding in this research is controversial to the

Table 1 Origin of waste wood materials

References	Origin										
	WW type					Original use				Contaminant analysis	
	PB	FB	OSB	Plywood	Solid wood	C & D	Municipal	Furniture	Packaging	Physical	Chemical
Schild et al. (2019)											
Faraca et al. (2019)	x	x	x	x		x		x	x	x	x
Azambuja et al. (2018a)	x	x		x	x	x					
Azambuja et al. (2018b)	x	x		x	x	x					
Hameed et al. (2018a)								x	x		
Laskowska and Maminski (2018)				x							
Hong et al. (2018)		x									
Lesar et al. (2018)	x	x	x	x	x	x	x	x	x	x	x
Robey et al. (2018)						x					x
Hameed et al. (2018b)								x	x		
Zamarian et al. (2017)	x	x		x	x			x			
Edo et al. (2016)		x						x		x	x
Roffael et al. (2016)		x									
Andrade et al. (2015)				x	x				x		
Costa et al. (2014)											
Martins et al. (2007)								x	x		
Nagalli et al. (2013)				x		x		x		x	
Lykidis and Grigoriou (2011)	x										
Mirski and Dorota (2011a)	x							x			
Mirski and Dorota (2011b)	x										
Suffian et al. (2010)	x										
Lykidis and Grigoriou (2008)	x										
Yang et al. (2007)						x					
Wang et al. (2007)						x					
Mantanis et al. (2004)		x									
Jermer et al. (2001)										x	x
Tolaymat et al. (2000)						x					x
Krzysik et al. (1997)						x					

Table 1 (continued)

References	Origin	Target composite type and research topic						
	Country	Wood based panel			Composition		Strength properties	FE
		PB	FB	OSB	Pure WW	Mix		
Schild et al. (2019)	Canada			x		x	x	
Faraca et al. (2019)	Denmark							
Azambuja et al. (2018a)	Brazil	x				x	x	
Azambuja et al. (2018b)	Brazil	x				x	x	
Hameed et al. (2018a)	Sweden	x			x		x	
Laskowska and Maminski (2018)	Poland	x				x	x	
Hong et al. (2018)	Korea		x			x	x	x
Lesar et al. (2018)	Germany, UK, Finland, Slovenia							
Robey et al. (2018)	USA							
Hameed et al. (2018b)	Sweden	x			x			x
Zamarian et al. (2017)	Brazil	x				x	x	
Edo et al. (2016)	Sweden							
Roffael et al. (2016)	Germany		x			x	x	x
Andrade et al. (2015)	Portugal	x				x	x	
Costa et al. (2014)	Portugal	x			x		x	x
Martins et al. (2007)	Portugal	x				x	x	x
Nagalli et al. (2013)	Brazil							
Lykidis and Grigoriou (2011)	Greece	x			x		x	x
Mirski and Dorota (2011a)	Poland			x		x	x	x
Mirski and Dorota (2011b)	Poland			x		x	x	
Suffian et al. (2010)	UK	x			x		x	
Lykidis and Grigoriou (2008)	Greece	x			x		x	x
Yang et al. (2007)	Taiwan	x			x		x	
Wang et al. (2007)	Taiwan	x			x		x	x
Mantanis et al. (2004)	Portugal		x			x	x	
Jermer et al. (2001)	Sweden, German, Netherlands							
Tolaymat et al. (2000)	USA							
Krzysik et al. (1997)	Poland		x			x	x	

FAO statistic about the production volume and recycling amount of plywood. On the other hand, more plywood and OSB were expected in waste wood research rather than particleboard and fiberboard as the waste wood stream came mostly from construction and demolition. Moreover, it could be that plywood and OSB are often used for exterior applications or as formwork. Therefore, they could be contaminated by preservatives and are usually not suitable for material utilization anymore.

The majority of the found research was conducted based on the waste wood materials collected in Europe (18 references) and South America (4 references). Only six articles were found in other countries such as Canada (Schild et al. 2019), Korea (Hong et al. 2018), USA (Robey et al. 2018; Tolaymat et al. 2000), Taiwan (Yang et al. 2007; Wang et al. 2007). This shows that Europe is more concerned with the waste wood recycling topic than other continents due to established recycling programs, policies and regulations (e.g., European Union Commission Decision 2009/894/EC; Zero Waste Europe 2014).

3.1.2 Target composite type

Relating to the target composite type, the possibilities of using different waste wood percentages to produce wood-based panels were investigated. Particleboard (14 references) is by far the most favorable product to be made from waste wood materials. The number of fiberboards (Hong et al. 2018; Roffael et al. 2016; Mantanis et al. 2004; Krzysik et al. 1997) and OSB (Schild et al. 2019; Mirski and Dorota 2011a, b) articles together account for seven references. There was no research found using waste wood materials for the production of plywood. The reason could be the impossibility of processing waste wood materials into veneers for plywood production. This can be done only from wood logs. On the other hand, there are more advantages in low cost, simple treatment process (mechanical e.g., chipping instead of chemical methods), and less technical barriers for waste wood during the conversion of wood-based panel (particleboard, fiberboard, OSB, plywood) into particles for particleboard production compared to conversion of old fiberboard into fiber or old OSB and plywood into strands. In general, recycled plywood can be processed into strands for the production of OSB when they are well collected and sorted. However, waste wood streams are normally a mixture of wood-based panel products together. The difficulty in the conversion process of inhomogeneous waste wood types into proper strand size and shapes hinders the usage of this resource in the three-layer OSB panel production compared to virgin wood.

3.2 Challenges in waste wood conversion and recycled composites products

3.2.1 Contaminants in waste wood and sorting technologies

3.2.1.1 Contaminants in waste wood Material flows during recycling must ensure that the products contain only non-hazardous contamination levels. The type and threshold of contaminations described in the national legal framework determines whether waste wood may be reused for material purposes or can only be thermally utilized. To use the waste wood efficiently by sorting out as little uncontaminated wood as possible is one of the most challenging steps during recycling. Physical contaminants or material impurities in WW are usually plastic, metal, glass, textiles, concrete or stone (Edo et al. 2015; Vaermeforsk 2012; Krook et al. 2006) that may originate from different material sources depending on the end-use of wood products or the waste wood collection plant/process. Chemical contaminants on the other hand may come from wood treatments, which were applied in order to improve wood products appearance (e.g., coating pigments, paints, oils), strengthen properties (e.g., gluing agents), prevent biological decay (e.g., wood preservatives) or fire resistance (e.g., flame-retardants) indicated by Johan et al. (2007).

Table 2 shows the research conducted in Europe and America on the analysis of physical and chemical contamination in waste wood. The waste wood materials were collected from different sources such as combustion plant, construction site and recycling companies. Physical and chemical impurities of waste wood fluctuate considerably from the findings. It can be seen in Table 2 that physical contaminants were found from 1 to 3% basic dry weight of total material content (Faraca et al. 2019; Lesar et al. 2018; Edo et al. 2016; Jermer et al. 2001). A higher proportion of non-wooden material was found in low quality mixed recycled wood (e.g., hazardous waste wood) rather than in high quality material (e.g., clean/non-hazardous waste wood) (Lesar et al. 2018). These fluctuations might be relevant to types, sources, fractions and seasons in year, collection and sorting process as well as management of waste wood at recycling facilities. Lesar et al. (2018) also indicated that companies with sophisticated sorting systems showed low content of non-wooden compounds in their waste wood materials. Nowadays, manual sorting, size, sink-float, gravity, magnetism, surface tension, and electric conductivity are the most popular sorting methods, which can help to sort out up to 96% of physical impurities in waste materials (Lahtela and Kaerki 2018).

The chemical elements in waste wood originate from various substances accumulated from preservatives, adhesives, pigments, paints, coatings or lacquers. Wood preservatives (e.g., Chromated Copper Arsenate CCA) can be found in many waste wood samples of the collected articles. The amount of Cr, Cu and As varies widely depending on various origins of incoming recycled wood. For example, the waste wood materials from Europe (Faraca et al. 2019; Lesar et al. 2018; Edo et al. 2016; Jermer et al. 2001) tend to contain less CCA than the ones from America (Robey et al. 2018; Tolaymat et al. 2000). It can be explained by the fact that the CCA has been banned in Europe since 2006 as wood preservative (EU Directive 2006/139/CE), whereas it is still allowed in USA. Therefore, these CCA values are lower than in USA. Moreover, Jermer et al. (2001) also found that the amount of arsenic, copper and chromium in German waste wood are lower than in Sweden. This may be a result of the German wood waste ordinance which limits strictly those chemical impurities at lower values compared to Sweden [e.g., As and Cd (2 mg/kg), Cu (20 mg/kg), Cr and Pb (30 mg/kg), Hg (0.4 mg/kg), Cl (600 mg/kg)].

In addition, the amount of Pb, Hg, Cd and Cl varied significantly depending on waste wood sources. Pb was found at high level (up to 2900 ppm) in waste wood from Sweden (Edo et al. 2016) whereas Cl was found (up to 1191 ppm) in waste wood mix of Sweden, Germany and Netherlands (Jermer et al. 2001). The reasons for these phenomena could be due to the difference in waste wood quality among countries depending on company size, collecting seasons and deliveries of waste wood. These elements are commonly used in pigments, paints, coatings, lacquers for wood floor and furniture treatment and were found more in Swedish waste wood (Fjelsted and Christensen 2007; Jermer et al. 2001). Furthermore, Pb and Cd also originated from heat stabilizers in PVC products (Mesch 2010; Krook et al. 2004). Another reason could be due to the waste wood fraction variations. Faraca et al. (2019) proved that the fractions of waste wood affected the amount of contaminants. For instance, the amount of Cl and Pb in waste wood increases

Table 2 Contaminants in waste wood

References	Country	Source	Contaminants analysis					
			Physical/material contaminants					
			%wt. dry basic of total material content (1)	Variation in (1)				
				Stone (%)	Plastic (%)	Metal (%)	Textile (%)	Other (%)
Faraca et al. (2019)	Denmark	Recycling center	1–2		1–8	92–99	0–1	
Lesar et al. (2018)	Germany, Slovenian, Finish, UK	Recycling companies	1–2.96					
Robey et al. (2018)	USA	Recycling Facilities						
Edo et al. (2016)	Sweden	Combustion power plant	1.1	19–44	14–25	14–22		
Nagalli et al. (2013)	Brazil	Construction site		28.8–75.7		48.3–69.2		2.9–11.1
Jermer et al. (2001)	Sweden, Germany, The Netherlands	Combustion plant	< 1					
Tolaymat et al. (2000)	USA	Recycling facilities						

References	Contaminants analysis									
	Chemicals/trace element									
	mg/kg dry wood (ppm)									
	Cr	Cu	As	Pb	Hg	Cd	Cl	PCP	PCB	PAH
Faraca et al. (2019)	0.5–150	1–500	0.03–7.0	0.1–120		0.01–0.5		10^{-5}–1.0	10^{-3}–10^{-1}	10^{-5}–10
Lesar et al. (2018)	3–59	1–25		1–116			97–802			
Robey et al. (2018)	7.0–94.6	3.7–348	2.0–150							
Edo et al. (2016)	1.5–313	3.6–3200	0.10–270	1.80–2900	0.5–1	0.5–1	0.07–0.13			
Nagalli et al. (2013)										
Jermer et al. (2001)	9–73	0–64	1–41	0–153	0.06–0.52	0.12–1.22	91–1191			
Tolaymat et al. (2000)	10–29,000	39–1600								

when the waste wood particles, which are lower than 4 mm (fine fraction) increases (Edo et al. 2016; Vaermeforsk 2012; Jermer et al. 2001). This is probably due to the crushing and chipping process resulting in more surface coating materials removed from the waste wood surface increasing the amount of heavy metal and Cl in the fine fraction after sieving. There are limited studies conducted on finding organic compounds of waste wood in the recycling process. Faraca et al. (2019) was the only reference found in analyzing PCP, PCB and PAH of waste wood materials. The finding showed that those substances are mainly coming from old furniture. In the past, PCB was used as plasticizers in the coating ingredients of paints and flame retardant (Butera et al. 2014; Jartun et al. 2009a, b). Nowadays, these substances are slowly replaced by other ingredients in paints and coating recipes applied to wood surface treatment. Therefore, high quality waste wood was found containing less of these components and complies with European standards for organic pollutants.

3.2.1.2 Sorting technologies Different sorting technologies have been developed to detect and eliminate chemical contaminants in waste wood particles such as atomic absorption spectroscopy (CV, GF, or HG-AAS), inductively coupled plasma spectrometry (ICP-OES, ICP-MS), energy dispersive X-ray fluorescence (ED-XRF) and near infrared (NIR) spectroscopy (Mauruschat et al. 2016; Fellin et al. 2014, 2011; Hasan et al. 2011a, b; Williams 1976). It is noticed that atomic absorption spectroscopy and inductively coupled plasma spectrometry are the methods used to detect the chemical contaminants of waste wood or biomass in the laboratory indicated by EU Commission decision 2009/894/EC. Other sorting techniques such as energy dispersive X-ray fluorescence (ED-XRF) and near infrared (NIR) spectroscopy have recently shown advantages in the sorting process of waste wood due to fast detection and high sorting efficiency. Plastics and wood preservatives can be detected and sorted by these techniques easily. For example, Hasan et al. (2011a, b) stated that the application of ED-XRF in online sorting could eliminate 92–96% of wood preservatives (CCA) and alkaline copper quaternary (ACQ) in recycled wood at recycling plants. This method also showed high efficiencies with certain limitations for the elemental analysis of six different groups (origin, type, material, visually detected pollution, pollutant macro category and pollutant specification) from wood residues in wood recycling plants (Fellin et al. 2014). On the other hand, Fellin et al. (2011) stated the positive results on the application of infrared spectroscopy for the detection of pollutants in wood residues. Moreover, Mauruschat et al. (2016) indicated that near infrared (NIR) spectroscopy and automatically pneumatic nozzles can distinguish four types of plastic granulate in WPC. In addition, this study also showed the possibility to distinguish between untreated and treated wood at different moisture contents containing inorganic and organic preservatives. However, these technologies need more investigations/improvements prior to being used on an industrial scale besides focusing on the development of new sorting techniques.

Principally, the detection and sorting of most contaminants in waste wood could be conducted by appropriate methods. However, the waste wood after sorting and processing could contain certain contaminants. Depending on types and contents, those physical and chemical contaminants in waste wood resources will be classified whether they are problematic for the later wood-based panel products.

3.2.2 Properties of wood-based panel produced from waste wood

Table 3 presents information about the properties of wood-based panels made from recycled wood. In this part, some factors influencing physical and mechanical properties of particleboard, fiberboard and OSB produced from recycled wood such as treatment process of waste wood (e.g., hydrothermal process), waste wood mixing ratio, and adhesives type will be addressed.

3.2.2.1 Particleboard Different investigations based on hydrothermal treatment processes were conducted at various schedules to separate waste wood into particles and use them for the production of particleboard (Andrade et al. 2015; Lykidis and Grigoriou 2011, 2008). The findings indicated that the particleboards manufactured from treated waste wood particles show stable dimensions. However, the mechanical properties (MOE, MOR and IB) and physical properties (thickness swelling and water absorption) of the panel decrease when the temperature increases. This finding is also consistent with the results of Michanickl (1996a) and Boehme and Michanickl (1998). It can be explained by the degradation of holocellulose and lignin in recycled wood resulting in reduction of the mechanical properties of boards due to the temperature increase (Yilgor et al. 2001). Moreover, these findings correspond to the research of Goldstein (1973) that the treatment temperature range should be between 110 and 170°C for recycled particles of particleboards. Additionally, Lykidis and Grigoriou (2011, 2008) concluded that the panel made from hydrothermally treated waste wood particles at around 150 °C shows better quality than others.

The effects of different waste wood ratio on the physical and mechanical properties of particleboard were investigated by Azambuja et al. (2018a, b), Laskowska and Mamiński (2018), Zamarian et al. (2017), Martins et al. (2007) and Suffian et al. (2010). The research results stated that it is possible to use 100% recycled wood particles in the production of panel products with UF as binder. In general, the higher the wood mix ratio applied, the lower the mechanical properties (MOE, MOR and IB) and the higher the hygroscopic properties (thickness swelling and water absorption) of panel achieved. The reasons could be due to the decrease in slenderness ratio of waste wood particles formed during the chipping process, which leads to the limitation of contact area between the particles (Arabi et al. 2011). In addition, the physical contaminants from surface coating materials (e.g., polypropylene, polyethylene, polyvinylchloride) of different waste wood-mix resources (e.g., construction and demolition, furniture, packaging) cause negative effects on glue bonding of panel production, resulting in the decline of strength properties of boards. Moreover, Czarnecki et al. (2003) confirmed that waste wood particles containing PF resin could hinder UF curing due to its alkaline character resulting in reducing MOE, MOR and IB of recycled particleboard. On the other hand, Azambuja et al. (2018b) proved that the strength properties of produced particleboard containing up to 50% of waste wood mix are comparable to the one made from fresh wood particles and their values meet the standard of panel type P2. In general, the properties of the particleboards can be controlled based on the waste wood ratio in wood mixture.

Adhesive types also strongly affect the properties of particleboards. Several investigations focused on PF, TF and PMDI adhesives instead of UF for the improvement of particleboard properties using 100% waste wood particles (Hameed et al. 2018a; Laskowska and Mamiński 2018; Yang et al. 2007; Wang et al. 2007). The key findings illustrated that the MOE, MOR, and IB increase and TS and WA decrease when the percentages of those glues in waste wood mixture increase. This may be due to the differences in bonding properties (e.g., impregnation/absorbing ability only on surface or deeply inside middle lamella of wood) of UF, PF, TF and PMDI adhesives with wood particles/fiber during the curing process affecting the physical and mechanical properties of produced panels. Better bonding

Table 3 Properties of wood-based panels made from waste wood

Target composite	References	WW type			Adhesives	WW ratio (%)	Density (kg/m^3)	Physical and mechanical properties				
		WBP	Solid wood	Unknown				Static bending		IB (MPa)	TS (%)	WA (%)
								MOE (GPa)	MOR (MPa)		24 h	24 h
Particleboard	Azambuja et al. (2018a)	x	x		UF	25; 100	750	0.49–1.30	4.6–7.2	0.18–0.76	15.2–26.7	44.4–79.4
	Azambuja et al. (2018b)	x	x		UF	25; 50	750	0.70–1.49	3.7–8.4	0.48–0.92	14.2–27.9	43.2–81.3
	Hameed et al. (2018a)			x	UF, TF, PMDI	100	640	2.10–2.12	10.1–11.0	0.40–0.42	8.9–16.2	26.9–51.5
	Laskowska and Mamiński (2018)	x			UF, PF	20; 40; 60; 80; 100	650	0.10–2.0	1.5–17.0	0.01–0.55	2.0–13.0	
	Zamarian et al. (2017)	x	x		UF	10; 25; 50; 75; 100	700	1.45–1.96	10.2–13.1	0.60–0.96	11.6–16.0	34.8–42.7
	Andrade et al. (2015)	x	x		UF	0; 25; 50; 75; 100	600	0.61–0.84	4.4–9.0	0.37–0.89	30.5	92.5
	Martins et al. (2007)			x	UF	50; 70; 100	612	0.52–1.00	3.4–8.9	0.16–0.42		
	Lykidis and Grigoriou (2011)	x			UF	100	680	1.78–2.69	9.2–14.2	0.38–0.54	19.4–24.0	79.8–86.3
	Suffian et al. (2010)	x			UF	100	650	2.56	13.8	0.61	35.7	63.6
	Lykidis and Grigoriou (2008)	x			UF	100	650	2.14–2.58	9.5–17.2	0.18–0.94	26.2–59.1	79.0–119.6
	Yang et al. (2007)			x	PF	100	700; 800	1.73–5.33	11.1–29.0	0.12–0.42	2.0–11.0	
	Wang et al. (2007)			x	PF, PMDI	100	800	2.08–3.45	11.4–27.9	0.56–0.73	7.0–18.1	
Fiberboard	Hong et al. (2018)	x			UF	10; 20; 30	700	1.60–2.30	10.0–18.0	0.08–0.22	18.2–53.0	23.2–92.8
	Roffael et al. (2016)	x			UF, PMDI	0; 33; 67; 100	730			0.40–0.54	14.7–19.6	49.7–75.3
	Mantanis et al. (2004)	x			UF	25	750		32.4–37.8	0.60–1.02	7.0–8.2	
	Krzysik et al. (1997)			x	PF	70	1000	3.38–4.18	11.7–37.7	0.41–0.59	7.1–12.5	13.2–25.5
OSB	Schild et al. (2019)			x	PF	0; 25; 50; 100	600	8.10–12.65	28.0–33.5	0.38–0.59	28.5–39.0	70.0–77.0
	Mirski and Dorota (2011a)	x			MUPF	0; 25; 50; 75; 100	600	1.55–6.75	9.9–36.9	0.32–0.64	26.9–33.6	
	Mirski and Dorota (2011b)	x			PMDI	0; 25; 50; 75; 100	600	1.40–7.15	10.2–44.1	0.49–0.88	21.6–32.9	

OSB Oriented Strand Board, *WW* waste wood, *WBP* wood-based panel, *UF* urea formaldehyde, *TF* tannin formaldehyde, *PF* phenol formaldehyde, *PMDI* polymeric methylene diphenyl isocyanate, *MUPF* melamine urea phenol formaldehyde, *MOE* modulus of elasticity, *MOR* modulus of rupture, *IB* internal bond, *TS* thickness swelling, *WA* water absorption ability will result in better board properties. Laskowska and Maminski (2018) and Yang et al. (2007) stated that boards made from PF showed better properties than UF boards, whereas Wang et al. (2007) indicated that panels produced from PMDI showed higher properties than PF ones. Furthermore, Hameed et al. (2018a) demonstrated that the combination of TF and PMDI at the ratio of 30%:70% and 40%:60% in particleboard manufactured from waste wood material complied with the standard values of type P2 strength.

3.2.2.2 Fiberboard In the sector of fiberboard produced from the mixture of waste wood fiber and virgin wood, Hong et al. (2018), Roffael et al. (2016), Mantanis et al. (2004) and Krzysik et al. (1997) found that the strength properties (MOE, MOR and IB) of the panel decrease tendentially with the increase in waste wood fiber content. It could be explained by the fact that the handling process (e.g., hammering, cooking, refining) of recycled fiberboard into fiber resulted in shortening the fiber length of recycled fiber leading to the reduction in mechanical properties. There was a controversial finding in hygroscopic properties of investigated fiberboard. Hong et al. (2018) and Krzysik et al. (1997) found that TS and WA of investigated fiberboard increased with the higher proportion of recycled fiber content, whereas Roffael et al. (2016) and Mantanis et al. (2004) stated that TS and WA were improved and decreased when more recycled fibers are used. However, the difference could be explained by the fact that the adhesive content in recycled fiberboard contributes to the increase in TS and WA. Moreover, the interaction of cross-linking of the lignocellulose fibers with existing UF-pre-polymers in UF resin could be a reason for this effect (Andrews et al. 1985). Another possibility may be the effects of contaminants from adhesives, coating layers or surface laminate types (e.g., polyethylene terephthalate) in recycled fiberboard. Therefore, the findings indicated that it is only feasible to substitute 20% (Hong et al. 2018) to 25% (Mantanis et al. 2004) of recycled fiber in the UF wood mixture to produce fiberboards, reaching mechanical and physical properties comparable to virgin wood fibers.

At industrial scale, fiberboard recycling is facing a major problem of effectively collecting, sorting and disintegrating the wood fibers. Recycled fiberboards from off-cuts, machining errors, and transport and storage losses contain different types of wood adhesives and coating surface materials. These cause difficulties in applying appropriate technologies (e.g. mechanical, thermo-hydrolytic and chemical) to disintegrating fiberboard waste wood into reclaimed fiber completely in a single step used for fiberboard production. Therefore, the combination of mechanical, thermal and chemical technologies is requested. However, this combination will lead to the quality reduction in recovered fibers (Irle et al. 2019; Buschalsky and Mai 2021).

In addition, most collected waste wood resources at recycling centers or companies are mixtures of different wood types such as particleboard, fiberboard, plywood and OSB. Fiberboard accounts for about 5–15% of the amount of these waste wood resources and normally is not easy to separate from the mixture by traditional sorting methods (Fechter 2021). This amount will generate challenges (e.g. dust during chipping process of waste wood into particles and higher consumption of adhesives at gluing stage) when using it for the manufacture of industrial particleboards. For the time being, sorting technologies are developed that can sort out most of the fines from the waste wood mixture. Great effort is made to increase the recovery of MDF by different technologies besides improved sorting such as steaming at high pressure, ohmic heating or microrelease.

3.2.2.3 OSB For the production of OSB from waste wood, Mirski and Dorota (2011a, b) stated that 75% of recycled wood particles could replace virgin ones in the core layer of OSB with MUPF and PMDI, complying with the mechanical and physical property values of standard EN 300. On the other hand, Schild et al. (2019) indicated that the substitution up to 100% of unsorted waste wood particles in the core layer of OSB with PF is possible and the MOE, MOR and IB of the boards comply with standard requirements, except for TS and WA. However, MOE and MOR decrease when the waste wood content increases, whereas IB, thickness swelling and water absorption increase with the increase in waste wood proportions. These effects could be due to the inhomogeneous distribution of strands and particles and particles contaminants (e.g., wood preservatives, resonated waste wood particles, paints) in the face and core layers of OSB resulting in high-density variations in core layer and the whole board.

3.2.3 Formaldehyde emission

Table 4 shows the summarized data of studies conducted on formaldehyde emission of wood-based panels (particleboard, OSB, fiberboard) produced with various waste wood ratio and adhesives types.

Tendentially, the amount of formaldehyde emission of particleboard and OSB produced from waste wood particles increases with higher proportion of waste wood mixture. Martins et al. (2007) indicated that particleboards produced from higher waste wood ratio (from 50 to 100%) and same UF content showed higher formaldehyde emission. Mirski and Dorota (2011a) found the same tendency in the production of OSB from recycled wood. The reason for this is probably due to the former concentration of formaldehyde included in the glue of recycled wood. In contrast, Hong et al. (2018) and Roffael et al. (2016) found that the amount of formaldehyde emission of fiberboards made from waste

Table 4 Formaldehyde emission of wood-based panel products produced from waste wood

Target composite	References	WW type			Adhesives (%)		WW ratio (%)	Density (kg/m^3)	Formaldehyde emission			
		PB	FB	Unknown	Type	%			Chamber (ppm or mg/m^3 air) (EN 717–1)	Perforator (mg/1000 g o.d) (EN 120)	Flask (mg/1000 g o.d) (EN 717–3)	Desiccator (mg/L)
Particleboard	Hameed et al. (2018b)			x	UF, TF, PMDI		100	640	0.06–0.59	3.10–13.30	5.30–145.4	
	Costa et al. (2014)			x	UF	7	100	650		2.90–8.50		
	Martins et al. (2007)			x	UF	7	50; 70; 100	612		2.20–6.96		
	Lykidis and Grigoriou (2011)	x			UF	8;12	100	680		3.68–14.40		
	Lykidis and Grigoriou (2008)	x			UF	7	100	650		1.61–10.26		
	Wang et al. (2007)			x	PF PMDI	6 4	100	800				0.03–0.89
OSB	Mirski and Dorota (2011a)	x			MUPF	5	0; 25; 50; 75; 100	600		4.87–6.21		
Fiberboard	Hong et al. (2018)		x		UF	12	10; 20; 30	700				0.80–1.50
	Roffael et al. (2016)		x		UF PMDI	10 0.5;1.0	0; 33; 67; 100	730		1.90–11.80	2.70–122.0	

UF urea formaldehyde, *PF* phenol formaldehyde, *TF* tannin formaldehyde, *PMDI* polymeric methylene diphenyl diisocyanate, *MUPF* melamine urea phenol formaldehyde wood fiber decreases with the increase in recycled fiber content. This formaldehyde reduction could be related to the amount of urea pre-polymers, urea and ammonia generated during the degradation of amino-plastic resin in recycled fiberboard reacting with formaldehyde as formaldehyde scavengers. Another explanation might be the release of melamine during hot-pressing acting as formaldehyde scavengers (Sugita et al. 1990; Martin et al. 1992). Furthermore, the findings of Costa et al. (2014), Martins et al. (2007) and Mirski, and Dorota (2011a) indicate that formaldehyde emission of particleboards and OSB (middle layer) produced from 100% recycled wood meets the standard values of EN 120 (< 8.0 mg/100 g o.d).

The type of adhesives affects the formaldehyde emission strongly. According to Hameed et al. (2018b), the particleboard produced from UF showed higher amount of formaldehyde content than TF/PMDI. Moreover, the amount of formaldehyde content reduced notably when the ratio of TF/PMDI increased. Wang et al. (2008) added that formaldehyde release of particleboards made from waste wood decreases linearly when the PMDI/PF ratio increases. The same tendency was found in the study of Roffael et al. (2016) with UF and PMDI for fiberboard production from secondary wood fibers.

On the other hand, the hydrothermal process of waste wood particles contributed to reduce the amount of formaldehyde emission. Moreover, the formaldehyde content of thermally treated wood particles is comparable or almost the same as the formaldehyde content of the virgin ones. Waste wood particles treated at 150 °C with 30% water retention/20 mins; 45% water retention/10 mins; and 60% water retention/8 mins (Lykidis and Grigoriou 2011) and 6 bar/156 °C/45 min (Lykidis and Grigoriou 2008) reduce considerably the formaldehyde content in the produced particleboards compared to control panel and comply with emission class E1. Roffael (1995), Michanickl (1996a, b) and Dix et al. (2001a, b) found the same. It can be explained by the fact that the increase in temperature during hydrothermal treatments speeds up the degradation of adhesives in waste wood particles and therefore, urea and other derivatives of hardened urea-formaldehyde will be activated as formaldehyde catchers (Roffael and Kraft 2005).

It can be noticed that the formaldehyde emission of wood-based panels manufactured from waste wood could be reduced using thermal hydrolysis process to handle waste wood particles or formaldehyde-free adhesives.

4 Conclusion

Over the last two decades, many efforts have been put into studying the properties of waste wood resource and its application on material use. Evidently, waste wood is not a homogeneous material. Therefore, there are still some limitations that need to be overcome before waste wood can be used as raw material for wood composites production. Considering the research questions put forward in this review of waste wood utilization, the following conclusions can be drawn:

- It is not surprising that most of previous investigations focused on recycled wood of construction and demolition, furniture and packaging since they are the most popular waste wood stream resources. The potential municipal waste resource was missing in the research.
- There are not enough published data and results available based on research with material derived from plywood and OSB as compared to particleboard and fiberboard even though most of the wood-based panel products in the world are plywood. It is controversial between production volume, usage and recycling.
- Due to the rather strict national and/or Europe-wide regulations controlling recycling topics, European institutions and European research institutes are currently the forerunners in waste wood studies. However, the European member states are lacking a common legislation scheme about the recycling of wood regarding classification and thresholds. Waste wood resources in other continents such as Asia, Africa and Australia would be of high research interest in the future. In addition, more studies about waste wood ordinances should be conducted especially for countries outside Europe.
- The advantages in technical and mechanical treatment process of waste wood into particles indicated that particleboard was the primary option for the production of wood-based panel compared to fiberboard and OSB. The present literature analysis has confirmed that currently, there appears to be hardly any research on the use of waste wood materials in the production of plywood.
- Physical and mechanical contaminants of waste wood resources would not be a problem for wood composites recycling if they were well managed. This management can be done beforehand at recycling companies or facilities via steps of collection, separation and sorting into certain grades. In general, every contaminant could be detected and eliminated by appropriate sorting techniques. On the other hand, the focus on improvement of sorting methods will bring the future perspective values for cleaning waste wood mix. Moreover, changing ingredients of coating pigments, paints, preservatives etc., which contain less harmful substances contributing to reduce contaminants in recycled wood, would be an option as well.
- Particleboard and the core layer of OSB panel products could be substituted up to 100% by waste wood particles. However, the contaminants and the low slenderness ratio

of recycled wood particles will result in the reduction of physical and mechanical properties of the panel products. Those disadvantages could be overcome by applying modern sorting techniques to eliminate contaminants and appropriate chipping techniques in order to increase the slenderness ratio of recycled wood particles. Further investigations are needed at the moment for the improvement of fiberboard properties made from 100% recycled fibers since only up to 25% of waste wood fiber can be utilized in the fiberboard wood mixture achieving comparable physical and mechanical properties with fiberboard from virgin wood.

- Using waste wood for the production of wood-based panel increases the risk of formaldehyde emission in products of particleboard and OSB, except for fiberboard. However, this risk can be addressed by applying pre-treatment steps to reduce formaldehyde emission (e.g., hydrothermal process) or using formaldehyde-free adhesives (e.g., PMDI)

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Andrade PI, Araújo SO, Neiva DM, Vital BR, Oliveira C, Angélica C, Gominho J, Pereira H (2015) Strength properties and dimensional stability of particleboards with different proportions of thermally treated recycled pine particles. Holzforschung 70(5):467–474. https://doi.org/10.1515/hf-2015-0090

Andrews K, Reinhard R, Frick JG, Bertoniere R (1985) Cellulose reaction with formaldehyde and its amid derivates in formaldehyde release from wood products. In: Proceedings of the ACS symposium series No. 316. (**ISBN 0-8412-0982-0**

Arabi M, Faezipour M, Layeghi M, Enayati AA (2011) Interaction analysis between slenderness ratio and resin content on mechanical properties of particleboard. J for Res 22(3):461–464. https://doi.org/10.1007/s11676-011-0188-2

Azambuja RR, Castro VG, Trianoski R, Iwakiri S (2018a) Recycling wood waste from construction and demolition to produce particleboards. Maderas Ciencia y Tecnologia 20(4):681–690. https://doi.org/10.4067/S0718-221X2018005041401

Azambuja RR, Castro VG, Trianoski R, Iwakiri S (2018b) Utilization of construction and demolition waste for particleboard production. J Build Eng 20:488–492. https://doi.org/10.1016/j.jobe.2018.07.019

Bergeron FC (2014) Assessment of the coherence or the Swiss waste wood management. Resour Conserv Recycl 91:62–70

Besserer A, Troilo S, Girods P, Rogaume Y, Brosse N (2021) Cascading recycling of waste wood: a review. Polymers 13(11):1752. https://doi.org/10.3390/polym13111752

Boehme C, Michanickl A (1998) Process for recovering chips and fibers from residues of timber-derived materials, old pieces of furniture, production residues, waste and other timber containing materials. Patent No. US5804035, EP 0697941

Bundesverband der Altholzaufbereiter und -Verwerter (BAV e.V.) (2021) Waste wood markets in Europe, Kategorie Europa. https://altholzverband.de/2021/09/27/waste-wood-markets-in-europe/. (German waste wood association (2021) Waste wood markets in Europa, Category Europe). Accessed on 12.10.2021

Buschalsky FY, Mai C (2021) Repeated thermo-hydrolytic disintegration of medium density fiberboards (MDF) for the production of new MDF. Eur J Wood Prod 79:1451–1459. https://doi.org/10.1007/s00107-021-01739-6

Butera S, Christensen TH, Astrup TF (2014) Composition and leaching of construction and demolition waste: inorganic elements and organic compounds. J Hazard Mater 276:302–311. https://doi.org/10.1016/j.jhazmat.2014.05.033

Costa NA, Pereira J, Ferra J, Cruz P, Martins J, Magalhães FD (2014) Formaldehyde emission in wood-based panels: effect of curing reactions. Int Wood Prod J 5(3):146–150. https://doi.org/10.1179/2042645314Y.0000000070

Czarnecki R, Dziurka D, Łęcka J (2003) The use of recycled boards as the substitute for particles in the center layer of particleboards. Electron J Pol Agric Univ Wood Technol 6(2):#01. http://www.ejpau.media.pl/volume6/issue2/wood/art-01.html. Accessed 22 Dec 2019

Dix B, Schafer M, Roffael E (2001a) Using fibers from waste fiberboards pulped by a thermo-chemical process to produce medium density fiberboard (MDF). Holz Roh Werkst 59(4):276

Dix B, Schafer M, Roffael E (2001b) Using fibers from waste particleboard and fiberboards pulped by a chemo-thermo-mechanical process to produce medium density fiberboard (MDF). Holz Roh Werkst 59(4):299–300

Edo MB, Persson E, Jansson PE (2015) Assessment of chemical and material contamination in waste wood fuels—a case study ranging over nine years. Waste Manage 49:311–319. https://doi.org/10.1016/j.wasman.2015.11.048

Edo M, Bjoern E, Per-Erik P, Jansson S (2016) Assessment of chemical and material contamination in waste wood fuels—a case study ranging over nine years. Waste Manag (new York, NY) 49:311–319. https://doi.org/10.1016/j.wasman.2015.11.048

European Union Commission Decision 2009/894/EC (2009) On establishing the ecological criteria for the award of the community eco-label for wooden furniture (notified under document C (2009) 9522) OJ L 320, 5.12.2009:23–32. http://extwprlegs1.fao.org/docs/pdf/eur91599.pdf. Accessed on 13.01.2022

FAO (2018) Global forest products. Fact and figures. 6–8. https://www.fao.org/3/ca7415en/ca7415en.pdf. Accessed on 17.08.2021

Faraca G, Alessio B, Thomas A (2019) Resource quality of wood waste: the importance of physical and chemical impurities in wood waste for recycling. Waste Manag 87:135–147. https://doi.org/10.1016/j.wasman.2019.02.005

Fechter JO (2021) Von der Vision zur Umsetzung—IKEAS Recyclingziele für Altholz, IKEA of Sweden. BAV-Altholztag, Koeln, Germany. (Fechter JO (2021) From vision to implementation—IKEAS recycling targets for waste wood, IKEA of Sweden. BAV Waste Wood Day, Cologne, Germany)

Fellin M, Negri M, Zanuttini R (2011) Monitoring pollutants on wood residues using FT-IR-ATR technology, ISCHP 11-Virginia Tech, Blacksburg, VA, USA 16–18 October 2011, pp 187–195. (**ISBN 978-0-9837700-0-8**)

Fellin M, Negri M, Zanuttini R (2014) Multi-elemental analysis of wood waste using energy dispersive X-ray fluorescence (ED-XRF) analyzer. Eur J Wood Prod 72(2):199–211. https://doi.org/10.1007/s00107-013-0766-4

Fjelsted L, Christensen TH (2007) Household hazardous waste: composition of polluted waste. Waste Manag Res 25:502-S09. https://doi.org/10.1177/0734242X07082956

Goldstein I (1973) Degradation and protection of wood from thermal attack. In: Ddd V (ed) Wood deterioration and its prevention by preservative treatments, Volume I: degradation and protection of wood. Syracuse wood science series, vol 5. Syracuse University Press, New York

Hameed M, Roennols E, Bramryd T (2018a) Particleboard based on wood waste material and bonded by hybrid resin of TF and PMDI. Part 1: the mechanical and physical properties of particleboards. Holztechnologie 59(4):24–32

Hameed M, Roennols E, Bramryd T (2018b) Particleboard based on wood waste material and bonded by hybrid resin of TF and PMDI. Part 2: the extractable formaldehyde content and formaldehyde release. Holztechnologie 59(5):32–38 (**ISSN: 0018-3881**)

Hasan RA, Schindler J, Solo-Gabriele HM, Townsend TG (2011a) Part I: online sorting of recovered wood waste by automated XRF-technology. Detection of preservative-treated wood waste. Waste Manag (new York, NY) 31(4):688–694. https://doi.org/10.1016/j.wasman.2010.11.010

Hasan RA, Solo-Gabriele H, Townsend TG (2011b) Part II: online sorting of recovered wood waste by automated XRF-technology—sorting efficiencies. Waste Manag (new York, NY) 31(4):695–704. https://doi.org/10.1016/j.wasman.2010.10.024

Hong MK, Lubis MAR, Park B, Sohn CH, Roh J (2018) Effects of surface laminate type and recycled fiber content on properties of three-layer medium density fiberboard. Wood Mat Sci Eng 15(3):163–171. https://doi.org/10.1080/17480272.2018.1528479

Irle M, Privat F, Couret L, Belloncle C, Deroubaix G, Bonni E, Cathala B (2019) Advanced recycling of post-consumer solid wood and MDF. Wood Mater Sci Eng 14(1):19–23. https://doi.org/10.1080/17480272.2018.1427144

Jan VM (2019) Überblick über den Europäischen Markt, SUEZ trading. BAV-Altholztag, München, Deutschland (Jan VM (2019) European Market Overview, SUEZ Trading. German waste wood association—Waste wood day, Munich, Germany)

Jartun M, Ottesen RT, Steinnes EVT (2009a) Painted surfaces „ important source of polychlorinated biphenyl (PCBs) contamination to the urban and marine environment. Environ Pollut 157:295–302

Jartun M, Ottesen RT, Tl V, Kvist Q (2009b) Local sources of polychlorinated biphenyls (PCB) in Russian and Norwegian settlements on Spitsbergen Island, Norway. J Toxicol Environ Health Part A Curr Lssues 72:284–294. https://doi.org/10.1080/15287390802539426

Jermer J, Annika E, Claes T (2001) Analysis of contaminants in waste wood. In: Annual meeting paper, the international research group on wood preservation. IRG/WP 01-50179

Johan S, Maria Z, Ron Z (2007) Combined thermal treatment of CCA-wood waste and municipal sewage sludge for arsenic emissions control. Report 2007-1. Faculty of Technology. Abo Akademi University. http://users.abo.fi/rzevenho/CCAreportVT2007-1.pdf. Accessed on 15.10.2021

Krook J, Mirtensson A, Eklund M (2004) Metal contamination in recovered waste wood used as energy source in Sweden. Resour Conserv Recycl 41:1–14. https://doi.org/10.1016/50921-3449(03)00100-9

Krook J, Mirtensson A, Eklund M (2006) Sources of heavy metal contamination in Swedish wood waste used for combustion. Waste Manag 26:158–166. https://doi.org/10.1016/j.wasman.2005.07.017

Krzysik JMA, Youngquist AJ, Bowers H (1997) Medium density fiberboard panels from waste wood and paper. Mater Sci (**Corpus ID: 18005113**)

Lahtela V, Kaerki T (2018) Mechanical sorting processing of waste material before composite manufacturing—a review. JESTR 11(6):35–46. https://doi.org/10.25103/jestr.116.06

Laskowska A, Mamiński M (2018) Properties of particleboard produced from post-industrial UF- and PF-bonded plywood. Eur J Wood Prod 76(2):427–435. https://doi.org/10.1007/s00107-017-1266-8

Lesar B, Humar M, Hora G (2018) Quality assessment of recycled wood with and without non-wooden materials from selected recycling companies in Europe. Waste Manag (new York, NY) 79:362–373. https://doi.org/10.1016/j.wasman.2018.08.002

Lykidis C, Grigoriou A (2008) Hydrothermal recycling of waste and performance of the recycled wooden particleboards. Waste Manag (new York, NY) 28(1):57–63. https://doi.org/10.1016/j.wasman.2006.11.016

Lykidis C, Grigoriou A (2011) Quality characteristics of hydrothermally recycled particleboards using various wood recovery parameters. Int Wood Prod J 2(1):38–43. https://doi.org/10.1179/2042645311Y.0000000002

Mantanis G, Eleftheria A, Panagiotis N, Aires C (2004) A new process for recycling waste fiberboards. In: 38th international wood composites symposium, pp 119–122

Mantau U, Doering P (2018) Rohstoffmonitoring Holz. Altholz im Entsorgungsmarkt—Herkunft und Aufbereitung, INFRO Teilbericht. http://infro.eu/downloads/studien/10_ATH_2016_Zusatz_Teilbericht_FINAL_20180904.pdf. Accessed on 08.09.2021

Martin RE, Hizo CB, Ong AM, Alba OM, Ishiwata H (1992) Release of formaldehyde and melamine from melamine tableware manufactured in the Philippines. J Food Prot 55(8):632–635

Martins J, João P, Brígida P, Cristina C, Luisa C (2007) Effect of recycled wood on formaldehyde release of particleboard. In: COST action E49 conference "Measurement and Control of VOC Emission from Wood Based Panels", Braunschweig, Germany

Mauruschat D, Plinke B, Aderhold J, Gunschera J, Meinlschmidt P, Salthammer T (2016) Application of near-infrared spectroscopy for the fast detection and sorting of wood–plastic composites and waste wood treated with wood preservatives. Wood Sci Technol 50(2):313–331. https://doi.org/10.1007/s00226-015-0785-x

Mesch K (2010) Heat stabilizers. In: Encyclopedies of polymer science and technology. Wiley Online Library. https://doi.org/10.1002/0471440264.pst153

Michanickl A (1996a) The material utilization of products made from wood-based panels. In: Proceedings of the third Eurowood symposium, Braunschweig, Germany, pp 1–5

Michanickl A (1996b) Recovery of fibers and particles from wood-based products. In: Proceedings no 7286: the use of recycled wood and paper in building applications. Forest Products Society, pp 115–119

Mirski R, Dorota D (2011a) The utilization of chips from comminuted wood waste as a substitute for flakes in the oriented strand board core. For Prod J 61(6):473–477. https://doi.org/10.13073/0015-7473-61.6.473

Mirski R, Dorota D (2011b) Applicability of strand substitution in the core of OSB. In: BioResources 6(3):3080–3086

Nagalli A, Fernada PL, Piera MP, Rafaela MH, Ronaldo LSI (2013) Analysis of wood waste contamination used in construction sites. EJGE 18(Bund. S):3999–4009

Purkus A, Luedtke J, Becher G, Jochem D, Polley H, Rueter S, Weimar H, Maack C (2019) Charta fuer Holz 2.0—Kennzahlenbericht 2019 Forst & Holz. Guelzow-Pruezen: Fachagentur Nachwachsende Rohstoffe e.V. (FNR). 45 S (Purkus A, Luedtke J, Becher G, Jochem D, Polley H, Rueter S, Weimar H, Maack C (2019) Charter for wood 2.0—key figures report 2019 forest and wood. Guelzow-Pruezen: Agency for Renewable Resources e.V. (FNR). 45S)

Robey NM, Solo-Gabriele HM, Jones AS, Marini J, Townsend TG (2018) Metal's content of recycled construction and demolition wood before and after implementation of best management practices. Environ Pollut (barking, Essex: 1987) 242(Pt B):1198–1205. https://doi.org/10.1016/j.envpol.2018.07.134

Roffael E, Franke R (1995) On recycling of wood-based panels. In: Proc. IUFRO XX World Congress. Tampere, Finland, August 1995. http://www.metla.fi/iufro/iufro95abs/d5pap69.htm

Roffael E, Kraft R (2005) Zur quantitativen Bestimmung von Harnstoff mittels Indophenolmethode (Berthelot-Reaktion). (On the quantitative estimation of urea using the Indophenol method). Holz Roh Werkst 63:309–310

Roffael E, Behn C, Schneider T, Krug D (2016) Bonding of recycled fibers with urea-formaldehyde resins. Int Wood Prod J 7(1):36–45. https://doi.org/10.1080/20426445.2015.1131918

Schild A, Cool J, Barbu MC, Smith GD (2019) Feasibility of substituting core layer strands in randomly OSB with contaminated waste wood particles. Wood Mater Sci Eng 52(5):1–8. https://doi.org/10.1080/17480272.2019.1652682

Sekundaerrohstoffe A (2018) Aufkommen, Verwendung, Maerkte und Trends. EU-Recycling 11:30–32

Silvio M (2018) Panel production trends: will the role of waste wood change? Poeyry group. In: 11th European wood-based panel symposium, pp 10–12 October 2018, Hamburg, Germany

Suffian M, Ormondroyd GA, Hale MD (2010) Comparisons of particleboard produced from Acacia hybrid and a UK commercial particleboard furnish from recycled wood. J Trop for Sci 2010:227–236

Sugita T, Ishiwata H, Yoshihira K (1990) Release of formaldehyde and melamine from tableware made of melamine–formaldehyde resin. Food Addit Contam 7(1):21–27

Tolaymat TM, Timothy GT, Helena SG (2000) Chromated copper arsenate-treated wood in recovered wood. Environ Eng Sci. https://doi.org/10.1089/ees.2000.17.19

United State Environmental Protection Agency (2018) Facts and figures about materials, waste and recycling. Wood: Material-Specific Data. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/wood-material-specific-data. Accessed on 10.01.2022

Vaermeforsk (2012) Report 1234 Braenslehandboken (The fuel handbook), p 442 (**ISSN 1653-1248**)

Van Benthem M, Leek N, Mantau U, Weimar H (2007) Markets for recovered wood in Europe: case studies for the Netherlands and Germany based on the Bioxchange project, pp 1–12. http://www.probos.nl/images/pdf/artikelen/PaperProbosforCOST-E31.pdf. Accessed on 09.01.2022

Wang SY, Yang T, Lin L, Lin C, Tsai M (2007) Properties of low-formaldehyde-emission particleboard made from recycled wood-waste chips sprayed with PMDI/PF resin. Build Environ 42(7):S.2472-S.2479. https://doi.org/10.1016/j.buildenv.2006.06.009

Williams C (1976) The rapid determination of trace elements in soils and plants by X-ray fluorescence analysis. J Sci Food Agric 27:561–570

Yang TH, Lin C, Wang S, Tsai M (2007) Characteristics of particleboard made from recycled wood-waste chips impregnated with phenol formaldehyde resin. Build Environ 42(1):189–195. https://doi.org/10.1016/j.buildenv.2005.08.028

Yilgor N, Unsal O, Kartal S (2001) Physical, mechanical and chemical properties of steamed beech wood. For Prod J 51(11–12):89–93

Zamarian EHC, Iwakiri S, Trianoski R, Albuquerque CECA (2017) Production of particleboard from discarded furniture. Rev Árvore 41(4):333. https://doi.org/10.1590/1806-90882017000400007

Zero Waste Europe (2014) Press release: Eurostat data for 2014 confirms need for European residual waste target. Published in 23.03.2016. https://zerowasteeurope.eu/press-release/press-release-eurostat-data-for-2014-confirms-need-for-european-residual-waste-target/. Accessed on 13.01.2022