Resource quality of wood waste: The importance of physical and chemical impurities in wood waste for recycling

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Abstract

Recycling of post-consumer wood waste into particleboard may be hindered by the presence of physical and chemical impurities in the waste stream, therefore calling for increased attention on the quality of wood waste. However, wood waste comprises several uses/types of wood, along with different levels of contamination. This study provides the detailed sampling and characterisation of wood waste according to its source, type and resource quality grade. Eight tonnes of wood waste, intended for recycling and collected at three Danish recycling centres, were subdivided into 34 individual material fractions and characterised with respect to the presence of three classes of physical impurities (misplacements, interfering materials and low-quality wood waste) as well as chemical concentrations of more than hundred chemical elements and persistent organic pollutants (POPs). The results demonstrated that contaminant and concentration levels vary significantly according to wood waste type and source, thus emphasising that wood waste should not be viewed as a single material flow but rather be understood and managed according to the presence of individual fractions. Including only clean wood waste fractions at the three recycling centres, 41-87% of the collected wood waste per weight could be recycled – the rest being physical impurities. The results showed that chemical contamination was significantly higher for low-quality wood waste, thus clearly indicating that improvements in separate collection, sorting and handling of wood waste may improve the resource quality of wood waste and potentially achieve cleaner recycling practices.

Keywords: sampling; contaminant; chemical analysis; waste collection; heavy metals; POPs.

Abbreviations

BaP: Benzo(a)pyrene; BDL: below detection limit; CCA: chromated copper arsenate; C&D: construction and demolition; EoL: End-of-Life; EPF: European Panel Federation; EU: European Union; MDF: medium density fibreboard; OSB: oriented strand board; PAHs: polycyclic aromatic hydrocarbons; PCBs: polychlorinated biphenyls; PCP: pentachlorophenol; POPs: persistent organic pollutants; RC: recycling centres; UNECE: United Nations Economic Commission for Europe; WW: wood waste.

1 Introduction

Wood represents a natural resource with specific physical and chemical properties useful for a wide range of applications, for example construction, furniture, packaging and energy (Parham and Gray, 1984). In 2015, the total consumption of industrial roundwood in the United Nations Economic Commission for Europe (UNECE) region was 1.28 billion m³, of which approximately 16% was used for fuel (FAO/UNECE, 2016). At end-of-life, wood waste (WW) is considered a valuable material, due to its potential for both recycling and energy recovery (Jungmeier et al., 2002a; 2002b; Sathre and Gustavsson, 2006). Historically, the main end-of-life option for wood waste has been incineration, due to its relatively high calorific value. However, wood waste may equally well be suited for a range of recycling options, potentially cascading from direct reuse (utilising the inherent material properties) to subsequent recycling in applications with lower quality standards (Reichel et al., 2016). In Europe, about 33.7 thousand m³ wood products became wood waste in 2010 (EPRS, 2015; Mantau et al., 2010), 46% of which was recycled and 51% incinerated (EPRS, 2015). With increasing focus on recycling and circular economy in Europe (EC, 2018), wood waste represents an important source for secondary raw materials. The wide variety of different wood types, applications and sources makes WW a very heterogeneous material from a recycling perspective (Bergeron, 2014). As the composition and level of contamination affect recycling options, detailed information about wood waste composition is required (Vis et al., 2016). While wood waste from industry may be relatively well defined, and thus easier to recycle and utilise, wood waste generated by households and collected through municipal collection systems may be more challenging. So far, only a few attempts have been made to evaluate the quality of wood waste generated by households (see Table A.1 in the Supplementary data file for the definition of the term “quality” in this study).

The most prominent recycling option for wood waste is particleboard (a type of engineered wood-based panel), with a European production of 34.8 million m³ in 2015 (FAO/UNECE, 2016). Amounts of recycled wood waste in particleboards vary regionally: percentages range from 0% in Switzerland, to 15-30% in France, Spain and Germany, to 50-60% in the UK, Belgium and Denmark, and up to 100% in Italy (Humbert and Courot, 2016; Vis et al., 2016). Moreover, the share of wood waste usage varies also within countries based on the choice of the companies manufacturing the products. Depending

on the wood quality standards, additional recycling options include: wood chips, pellets, refuse-derived fuel, composting, use as mulch (horticultural, surfacing and soil improving mulch), animal bedding (high and standard quality) and pulping into paper products (see e.g. Dodoo et al., 2014; Trada, 2005; Vick et al., 1996). Applications that have gained increasing focus are recycling into other wood-based panels (e.g. oriented strand board, OSB, and medium density fibreboard, MDF), wood composites (e.g. wood-cement and wood-plastic composites) and bio-based chemicals, albeit the development of these options is somewhat limited, due to technical barriers arising from low-quality wood waste (Czarnecki et al., 2005; IRCOW, 2014; Winder and Bobar, 2016). Overall, recycling wood waste into particleboard is expected to remain the primary option in the near future, also given its low price (Vis et al., 2016). The quality of wood waste, however, is essential for all recycling applications in terms of not only the stability and longevity of the final product (Helsen et al., 1998; Vis et al., 2016), but also with respect to general concerns about product quality and safety associated with recycled products (Bergeron, 2014; Vis et al., 2016). Therefore, detailed information about material and chemical impurities in WW is essential to ensure a high-quality, clean and safe recycling loop.

To ensure recyclability, WW should contain minimum levels of impurities, which may be defined either as physical or chemical impurities (see Table A.1 for definitions). In the case of WW, physical impurities are present in the form of foreign materials such as plastics, metals, glass, textiles, soil, and inert (concrete, bricks, tiles, stones) (Edo et al., 2015; Krook et al., 2006; Värmeforsk, 2012), mostly reported as material impurities in wood waste for combustion. Chemical impurities may originate primarily from treatments aimed at improving product aesthetics (finishes, paints, oils, anti-stains), mechanical properties (binders, adhesives, gluing agents), resistance to biological decay (preservatives such as chromated copper arsenate, CCA, pentachlorophenol, PCP and creosote) and resistance to fire (phosphorous and brominated flame retardants) (Trada, 2005). Some of these chemicals are considered hazardous only when exceeding specific limit values (e.g. heavy metals), whereas other chemicals have been banned completely (e.g. CCA, PCP and creosote), with associated waste being classified as ‘hazardous’ (European Commission 1998, 2001, 2003, 2006). Concerns have been raised that when impregnated WW is not handled adequately, due to improper sorting, the associated chemicals may enter otherwise clean feedstocks for recycling (Augustsson et al., 2016; Krook et al., 2004, 2006). Similarly, persistent

organic pollutants (POPs) may be present in wood preservatives for weathering resistance (e.g. phenols such as PCP), adhesives used in panelboard production (e.g. polycyclic aromatic hydrocarbons – PAHs; Höglmeier et al., 2014; Vis et al., 2016, Wilson, 2009) and wood floor finishes (e.g. polychlorinated biphenyls – PCBs), or as a result of contamination with oils (European Commission, 2006). The presence of these chemicals may potentially limit recyclability in a circular economy, as they could persist in sequential recycling loops (UNECE, 2010).

So far, the presence, types and properties of material impurities in WW collected for recycling have not been addressed in the literature. On the other hand, several studies have addressed the problem of chemical impurities, albeit only with respect to heavy metals in WW for incineration and the consequences for ash utilisation (e.g. Astrup et al., 2011, Demirbas, 2005, Edo et al., 2015), despite their presence in WW for recycling may challenge a clean recycling industry. Very little attention has been paid to the causes of presence of organic compounds such as PAHs, phenols and PCBs in wood waste for recycling. For example, despite being classified as toxic carcinogens, PAHs have been studied mostly in relation to biomass combustion ashes (Edo et al., 2017, Gao et al., 2017, Lavric et al., 2004, Johansson and Van Bavel, 2003, Sarenbo, 2009). Nevertheless, one of the most important sources of PAHs includes creosote-treated wood (Ravindra and Sokhi, 2008), which may contaminate clean WW for recycling due to improper sorting: of the approximately 150-200 chemicals constituting creosote, 85% are PAHs and 10% phenolic compounds (Mueller et al., 1989). Potentially, the presence and type of impurities may be associated with specific sources or subtypes of wood waste; however, sufficiently detailed information about the physicochemical properties of WW for recycling is not available. In order to improve wood waste recycling, avoid spreading of potential contaminants in material loops and enhance the quality and properties of the products based on recycled wood, such data are needed.

The overall aim of this study is to assess to what extent the wood waste composition affects the quality of recycled wood, thereby providing consistent characterisation of the resource quality of wood waste recovered for recycling and linking this to the source of the recovered wood waste. The focus is placed on the presence of physical and chemical impurities in WW collected at Danish recycling centres and then recycled into particleboard. The aim was achieved by: i) sampling at three recycling centres and classifying the WW with respect to material amounts, sources, application types and quality grade, ii) quantifying physical (material) and chemical impurities in the WW samples,

and iii) evaluating impurity levels with respect to levels in pre-consumer wood, to assess the extent to which the composition of the wood differs after the use phase of the products. Potential consequences of presence of impurities are discussed with respect to WW recyclability and cleaner production.

2 Materials and methods

2.1 Sampling campaign and processing of samples

The sampling campaign involved three recycling centres (RCa to RCc) in the following Danish municipalities: Middelfart (RCa), Gelsted (RCb) and Glamsbjerg (RCc, see Table A.1 for definitions). They were selected because having identical sorting guides for WW, which is collected in separate containers as ‘clean wood’. Additional containers are available for ‘impregnated wood’. Clean wood is sent for recycling as particleboard, whereas impregnated wood is incinerated in authorised plants in Germany. In this study, samples of WW were retrieved solely from the ‘clean wood’ container.

WW sampling followed the principles set out in Boldrin and Christensen (2010): one container for each recycling centre (representing 4063 kg, 1697 kg and 2512 kg for RCa, RCb and RCc, respectively, sampled over two days and corresponding to wood waste generation of about 1 week) was unloaded on the ground in piles (representing primary samples of 2-4 tonnes). The WW was then sorted manually into individual material fractions according to the classification scheme described in Section 2.2; these fractions represented secondary samples. The weights of these individual material fractions were registered to determine overall material composition. All secondary samples were shredded on site, using a mobile shredder (ARP SC 2000, Denmark). The shredded samples were subsequently sampled through 1D lot splitting (Gy, 1998) to obtain seven to thirteen representative subsamples (hereafter called ‘lab samples’) of 10-15 kg from each of the three recycling centres (34 individual samples in total). These samples were stored in 30L plastic barrels with a hermetic lid during transport and until further handling in the lab. Prior to chemical analysis, the lab samples were processed in four steps: sorting of impurities, mass reduction, size reduction, drying and storage (for further details, see Appendix B).

2.2 Classification of wood waste

While no harmonised definitions of wood waste exist (Vis et al., 2016), and individual countries and sectors implement their own standards (WRAP, 2012a), we designed a tiered classification method addressing i) the source (application) of the waste, ii) the type of item and iii) the quality grade (see Table 1). The first level involves five categories: Off-cuts (O), Packaging (P), Construction and demolition wood (C), Furniture (F) and Misplacements (M). The second level involves a number of classes and defines further the type of wood waste item, mostly focusing on the presence of fibreboard, as this type of wood-based panel is currently not used in particleboard recycling (Humbert-Droz and Coutrot, 2016). Finally, the third level represents the overall quality

Table 1. Tiered classification of waste wood (WW) according to (1) origin, (2) type and (3) quality grade/level of contamination of the WW sample.

Level 1: Origin	Level 2: Type of item	Level 3: Quality grade	Sample codes
O: Off-cuts	Off-cuts, left-over or large wood chips (solid wood, untreated)	I, II	O1
	Off-cuts, with fibreboard ^a and/or treated wood	III	O2
P: Packaging	Pallets, (untreated, no fibreboard) ^a	I, II	P1
	Pallets, with fibreboard and/or treated wood	III	P2
	Other wood packaging, clean wood (boxes, crates, etc.)	I, II	P3
C: Construction and demolition (C&D)	Wood from C&D and rebuilding, solid wood or with engineered wood construction (no fibreboard) ^a – indoor use	I, II	C1
	Old wood from demolition and rebuilding, with fibreboard and/or treated wood, indoor use	III	C2
	Old wood from demolition and rebuilding, with fibreboard and/or treated wood, outdoor use	III	C3
F: Furniture	Furniture, solid wood or with engineered wood construction (no fibreboard) ^a	I, II	F1
	Furniture, with fibreboard and/or treated wood	III	F2
	Furniture, upholstered	III	F3
M: Misplacements	Impregnated wood (wood treated with CCA, creosote or PCP)	IV	M1
	Composite building materials from C&D	III	M2
	Wood, rotten or covered by plants	III	M3
	Miscellaneous (items made out of plastic, glass, metal, cardboard)	III	M4

^a Particleboard producers make clear technological differentiations on acceptance criteria in the recycled input stream. Fibreboard, and more specifically MDF, is the most problematic material in the input mix (due to the stability of the obtainable particleboard product) and is therefore unwanted (ARC, 2013, Humbert-Droz and Coutrot, 2016, Vis et al., 2016).

grade of the material (I to IV) according to Altholz V (2012), Vis et al. (2016) and WRAP (2012a): Grade I (clean, recyclable wood waste with minor contamination), Grade II (clean wood waste with some contamination), Grade III (wood waste with considerable contamination and mainly suited for incineration) and Grade IV (wood waste characterised as hazardous waste according to Annex III of the Waste Framework Directive 2008/98/EC). Details about grade definitions are provided in Table C.1. Unique sample codes (O1 to M4) are assigned to all individual tiers (see Table 1).

2.3 Wood waste characterisation: material and chemical impurities

All WW samples were characterised with respect to the presence of both physical (material) and chemical impurities. The material impurities were categorised according to the following three types: misplacements, interfering materials and low-quality wood waste. This classification, which in principle is applicable to any resource collected for recycling, includes the information on the material fraction of the impurity and whether it is avoidable or not, besides allowing for identification of the distinct consequences caused on wood waste recycling chain. Definitions and relevant sample codes are provided in Table 2.

Table 2. Definition of impurities associated with waste wood (WW) samples.

Type of impurity	Definition	Avoidable	Wood is the main material	Sample codes	Examples
Misplacements	Items that do not match the guidelines for collecting WW and shall be collected separately in other containers present on site at the RC	Yes	Can be	M1, M2, M3, M4	Glass, metals, impregnated wood, cardboard, bamboo
Interfering materials	Non-wooden items that were essential during the use phase of the wood waste	No	No	Are present in all samples	Nails, plastics layers, textile upholstery
Low grade WW	Wooden items whose properties would lower the quality of a recycled product. It is considered impurities only when the purpose is to achieve high-quality feedstock for recycling. Corresponds to quality grade III in Table 1, Table C.1 and Figure H.1	Yes	Yes	O2, P2, C2, F2	Panel products such as fibreboard (limited potential for material recovery); treated wood

The chemical analyses included 65 inorganic chemical elements and three types of organic compounds (27 PAHs, 15 phenols and 7 PCBs); see Table D.1, D.2 and D.3 for further details. All analyses were performed in triplicate. The method for analysing inorganic elements was adapted from available literature (Edo et al., 2015, EPA, 1980, Tafur-Marinos et al., 2016). All samples were measured through microwave-assisted acid digestion (Anton Paar, Multiwave 3000), followed by measurements with either inductively coupled plasma mass spectrometry, ICP-MS (Agilent Technologies, 7700x series) or inductively coupled plasma optical emission spectrometry, ICP-OES (Varian, Vista-MPX), depending on the elements and concentration levels. Analysis of PAHs, phenols and PCBs was achieved by microwave-assisted extraction (MAE) followed by solid-phase extraction (SPE) clean-up and quantification by gas chromatography mass spectrometry (GC-MS). As the methodology for analysis of PAHs and phenols was developed specifically for this study (no analysis method could be found that suitably addressed these classes of organic contaminants in WW), further details can be found in Appendix D. While the full dataset for all 65 chemical elements is made available in Appendix D, in the Results and discussion section, emphasis is placed on contaminants with existing regulatory limits (see Table F.1) as well as those typically associated with alloys, paints and wood preservatives, namely As, Cd, Cr, Cu, Pb, Fe, Al, Mg, Mn, Ni, Zn, Co, Sb, Ti, V and B.

The results from chemical analysis were compared with concentration values found in:

- i. Pre-consumer wood. Examples of different pre-consumer wood materials were obtained at the retail level (e.g. hardware stores): solid wood, particleboard, plywood, MDF, hardboard and impregnated wood (in total seven samples, see Table E.1 for details). Characterisation and analyses were identical to the WW lab samples collected from recycling centres.
- ii. Wood waste for incineration. Data were retrieved from available scientific literature.
- iii. Virgin wood. Data were retrieved from available scientific literature as well as online databases (IEA Bioenergy Task 32, Phyllis2).
- iv. Industry standards. In the absence of European regulation defining maximum contamination levels in recycled wood, industry standards adopted by the European Panel Federation (EPF) were applied for comparison (see Table F.1 for details).

3 Results and discussion

3.1 Composition of wood waste

Although the overall composition (Level 1 in Table 1) of recyclable wood waste collected at the three recycling centres was comparable, considerable differences in the more detailed composition and shares of impurities were observed, as illustrated in Figure 1a. RCa had high shares of untreated furniture and C&D waste, both clean and with low grade wood, for indoor and outdoor uses (subcategories F1, C1, C2 and C3). Waste from RCb included large amounts of untreated pallets, untreated C&D waste for indoor uses and untreated furniture (subcategories P1, C1 and F1). RCc had high shares of untreated pallets, C&D waste for indoor and outdoor uses and untreated furniture (subcategories P1, C1, C3 and F1). This indicates that the quality of wood waste routed to recycling may vary significantly over time and according to location.

Some overall trends were identified: Offcuts and Misplacements represented a small share of the total WW, which was dominated mostly by C&D and Furniture alongside a smaller contribution by Packaging materials. In particular, C&D represented the largest share of WW for all recycling centres (35–61% of containers; see Figure G.1). Packaging was found in the range 5–27%; comparable results were found for the UK (Defra, 2012), where packaging wood waste accounts for 21% of WW. Subcategories that contributed very little were Off-cuts with fibreboard and/or treated wood (O2, 1% of total wood sampled), Pallets with fibreboard and/or treated wood (P2, 3%), Other packaging, untreated, no fibreboard (P3, 0.1%), Furniture, upholstered (F3, 2%) and Wood, rotten or covered by plants (M3, 1%). The largest subcategories were Furniture, untreated, no fibreboard (F1, 21% of total wood sampled), Wood from C&D and rebuilding (untreated, no fibreboard) – indoor use (C1, 20%) and Old wood from demolition and rebuilding (with fibreboard and/or treated) – indoor use (C2, 18%), overall representing 59% of the total WW sampled for this study. Considering that waste management constitutes the second-most important environmental impact in the building sector (The Ecocycle Council for the Building Sector, 2003), and that the wood fraction constitutes about 20% of C&D waste in Germany (European Commission, 2015), 35% in Finland (Meinander et al., 2012) and 41% in UK (Defra, 2012), the compositional variations observed in this study may suggest that wood waste composition should be addressed specifically when assessing

Figure 1. a) Amounts (kg, wet weight (ww)) and composition of wood waste (WW) collected from the wood containers at recycling centres in the municipalities of Middelfart (RCa), Gelsted (RCb) and Glamsbjerg (RCc). Original data from Econet (2016). b) Impurity composition (average over three recycling centres) of sampled WW in terms of WW suitable for recycling to particleboard (quality grades I and II), misplacement, interfering material and low-quality WW (grade III).

the environmental impacts associated with the recycling and management of these waste flows.

3.2 Composition of material impurities

The shares of WW that may be recycled according to the strict definition (within Grades I and II) were 41%, 87% and 49% for RCa, RCb and RCc, respectively (Table 3 and Figure G.2). Low-quality wood was the most abundant type of impurity for RCa and RCc, whereas WW from RCb was affected mainly by presence of Misplacements. Overall, Misplacements accounted for 5–17% of WW, while Interfering materials accounted for 1–2% and Low-quality wood waste for 3–53% of the wood waste for recycling. While our results showed higher levels of impurities than previously reported by Edo et al. (2015) (who reported misplacements and interfering materials to represent 1.1%), a British study (WRAP, 2012b) found that 59.5% of WW collected at recycling centres was wood waste within quality Grades III and IV, i.e. comparable with this study. It appeared that throughout the sampled recycling centres the magnitude of the contamination of the WW depended on the WW category (Figure 1b): the category Packaging was the least contaminated (<5% impurities), followed by Off-cuts and Furniture (around

15% impurities). Impurities constituted 60% of C&D WW (that represented the largest share of WW), while Misplacements include impurities by definition. Such conclusion is paramount as it indicates that the purity of WW can be improved by knowing WW sources and limit the recycling to the cleanest ones.

Table 3. Amounts (kg, by ww), composition and relative share (% , by ww) of WW (grades I, II), misplacement, interfering material and low-quality WW (grade III) collected at Middelfart (RCa), Gelsted (RCb) and Glamsbjerg (RCc).

	Rca - Middelfart		RCb - Gelsted		RCc - Glamsbjerg	
	Kg	%	kg	%	kg	%
WW (grades I, II)	1659.6	40.8	1556.7	87.2	1312.8	52.5
Misplacement	209.8	5.2	130.9	7.3	411.1	16.4
Interfering material	33.1	0.8	38.7	2.2	38.5	1.5
Low-quality WW (grade III)	2160.4	53.2	58.7	3.3	738.6	29.5
<i>Total WW</i>	<i>4063.0</i>	<i>100.0</i>	<i>1785.0</i>	<i>100.0</i>	<i>2501.0</i>	<i>100.0</i>
Misplacement						
Metal	11.0	5.3	0.9	0.7	6.4	1.6
Textile	2.8	1.3	2.2	1.6	0.5	0.1
Plastic	0.5	0.3	1.8	1.3	4.0	1.0
Inert	0.0	0.0	0.9	0.7	0.9	0.2
Impregnated wood	81.6	38.9	104.4	79.7	60.6	14.8
Composite materials	86.2	41.1	20.3	15.5	246.2	59.9
Cardboard	5.0	2.4	0.5	0.4	0.7	0.2
Garden waste	22.6	10.8	0.0	0.0	33.5	8.2
Wood rotten	0.0	0.0	0.0	0.0	58.3	14.2
<i>Total misplacement</i>	<i>209.8</i>	<i>100.0</i>	<i>130.9</i>	<i>100.0</i>	<i>411.1</i>	<i>100.0</i>
Interfering material						
Metal	30.4	91.7	38.4	99.4	37.0	96.2
Textile	0.1	0.4	0.0	0.0	0.3	0.7
Plastic	2.6	7.8	0.2	0.6	1.2	3.1
<i>Total interfering materials</i>	<i>33.1</i>	<i>100.0</i>	<i>38.7</i>	<i>100.0</i>	<i>38.5</i>	<i>100.0</i>
Low-quality WW (grade III)						
Fibreboard	1451.0	67.2	21.9	37.2	299.6	40.6
Treated/outdoor	662.8	30.7	36.9	62.8	392.4	53.1
Upholstered furniture	46.6	2.2	0.0	0.0	46.6	6.3
<i>Total low quality WW</i>	<i>2160.4</i>	<i>100.0</i>	<i>58.7</i>	<i>100.0</i>	<i>738.6</i>	<i>100.0</i>

It is evident that impurities constituted a considerable share of the WW collected for recycling (12–59%). Considering the potential competition with the energy sector (wood utilisation as fuel is subsidised in the EU (FAO/UNECE, 2016)) and the fact that wood waste from industry may be of better quality than wood waste from recycling centres (Vis et al., 2016), the presence of impurities may limit the collected wood waste from being accepted for recycling (EPF, 2006). This suggests that the amount of wood waste accepted at recycling facilities and eventually recycled is lower than what is collected for recycling at recycling centres. Ignoring this aspect in recycling statistics may result in overestimating actual recycling rates and substitution of primary wood. As recycling targets are typically defined on a weight basis, this may favour large and heavy waste streams rather than support the separation and recovery of high-quality material fractions (Arm et al., 2016), such as Grades I and II, representing 41–87% of the sampled WW in this study. When high purity is not a requirement, Low-quality WW may be recycled along with Grades I and II, thereby increasing the recycling rate to 82–94% (see Table 3). This clearly illustrates that recycling rates determined based on waste input quantities offer little information with respect to actual resource savings.

Although the environmental consequences of including impurities in wood waste recycling activities have not been investigated to date, the effect on the recycled product varies according to the class of material impurity (Table 4). Potential effects on the recycling chain include increases in heavy metal concentrations in recycled products, caused mainly by the presence of impregnated wood and Low-quality wood waste (see also Sections 3.3, 3.4 and 3.5), stability and processing issues during recycling, mostly due to the content of wood fibres and glue that constitute fibreboards and other wood-based panels (Vis et al., 2016) and visual impurities in recycled products, which can be a key factor in deciding on applications where recycled particleboard can substitute its virgin counterpart (Wiebesiek, 2016). While impregnated wood (Grade IV) constituted a relatively low share of the composition of WW in this study (2–6% of sampled WW), the significant presence of Low-quality wood waste may require dilution with virgin wood, thereby decreasing the content of recycled wood in finished products. As the use of wood-based panels grows and recycling targets increase, measures to maintain high quality recycling are requested in order to compete with virgin materials.

Table 4. Overview of key types of impurities and their role in the wood waste recycling chain.

Type of impurities	Main material fractions	Potential reason for their presence in clean WW	Fate of impurities at the recycling facility	Potential effects on the recycling chain	Additional comments
Misplacements	Composite materials (16-60%), impregnated wood (15-80%), garden waste (0-11%)	Visual similarity with clean wood waste	Hand-sorting is likely to be needed, although not all impregnated wood may be recognised	Chemicals in impregnated wood may enter new products through recycling	Creosote railway sleepers may be recycled if direct human contact is avoided (cannot be used for particleboard) ¹ . Low concentrations of impregnated wood (as in this study) may be diluted
Interfering materials	Metals (92-99%)	Their presence in post-consumer WW is unavoidable by definition	Metals are separated thanks to magnetic and eddy current separation. Control and removal of plastic/textiles is impossible once the wood has been shredded	Visual impurities in recycled products. High concentration of heavy metals in recycled products. Advanced separation technologies exist but require significant capital investments	
Low quality WW	Fibreboard (37-67%), treated wood/outdoor applications (31-63%)	Visual similarity with solid wood products. Unawareness of citizens	Because WW is crushed inside waste containers to facilitate transport, it is not possible to recognise and divert low-quality WW	Rejection of WW for recycling. High concentrations of heavy metals and organic compounds. Fibreboard may cause stability and processing problems during recycling	Although fibreboard is the main cause of quality downgrading (it has limited potential for recovery, and some facilities set limits for wood-based panels at 5-10%), acceptance limits may be given for all wood-based panels

¹ (International Union of Railways, 2003).

3.3 Characterisation of chemical impurities: inorganic elements

Out of the 65 analysed elements, 27 had concentrations below the detection limit (BDL) in more than 50% of cases, an overview of which is provided in Table I.1. Descriptive statistics (mean, median, min-max, quartiles) for all analysed elements are presented in Table I.2. Concentration levels of the selected elements (see Section 2.4) are plotted according to source classes in Figure 2 and Figure 3.

Packaging wood materials, mainly consisting of clean pallets (Grade I), generally had low levels of inorganic elements. Concentration levels were higher in Furniture (F), Misplacements (M) and Off-cuts (O). While this could be expected, as Misplacements included impregnated wood and Furniture included wood treated with anti-stains, paints and lacquers (Umney and Rivers, 2003) as well as non-wood materials such as textiles (see Table 1), generally Off-cuts can be expected to be cleaner. The observed levels of e.g. metals in Off-cuts may be due to i) contamination of the materials during waste collection, or ii) prior treatments of the materials. Wood waste from the C&D sector was a heterogeneous fraction: construction timber was relatively clean, while wood from demolition appeared contaminated by coating, such as paints and preservatives (Meinander et al., 2012). The Pre-consumer wood samples (V) showed significantly smaller concentrations for all elements, except for Cd, Mn and Ti, where the measurements were of the same order of magnitude as the waste materials in Furniture, Misplacement, and Off-cuts.

To the extent that data have been reported in literature, the element concentrations observed here were in the same order of magnitude as indicated by other studies (Edo et al., 2015, Krook et al., 2004), although these studies addressed wood waste as feedstock for combustion rather than wood waste intended for recycling.

Cd, Pb, Sb, Co and Ti were found in high concentrations in wood waste from C&D and Furniture, likely owing to the use of these elements in pigments, paints and coatings as well as lacquers for floor and furniture treatment (Fjelsted and Christensen, 2007). However, the high concentrations of Pb, Cd and Sb may also originate from PVC present in C&D wood waste, as these elements are commonly used in PVC as heat stabilisers (Mesch, 2010). Krook et al. (2006) identified surface-treatments and the presence of plastic as potential sources of Pb in wood waste.

Figure 2. Concentrations (part per million, dry weight – ppm dw) of (right to left) As, Cr, Cu, Cd, Pb, Fe, Al and Mg in waste wood (WW). The grey area distinguishes results for the pre-consumer wood samples. The y-axis is displayed using a logarithmic scale. O= Off-cuts; P= Packaging; C= C&D; F= Furniture; M= Misplacements; V= Pre-consumer wood.

Figure 3. Concentrations (ppm dw) of (right to left) Mn, Ni, Zn, Co, Sb, Ti, V and B in waste wood (WW). The grey area distinguishes results for the pre-consumer wood samples. The y-axis is displayed using a logarithmic scale. O= Off-cuts; P= Packaging; C= C&D; f= Furniture; M= Misplacements; V= Pre-consumer wood.

Although the observed levels of As, Cr and Cu were lower than found in other studies (Frighetto Ferrarini et al., 2016; Johansson and Van Bavel, 2003b), the high concentrations in Misplacements (M) were likely caused by presence of impregnated wood. Table J.1 summarises the differences in concentrations of As, Cr and Cu for the lab sample with the highest concentrations (M1) and values found by Frighetto Ferrarini et al. (2016) and Janin et al. (2009), who measured initial concentrations of these compounds in wood waste from Eucaliptus poles and CCA-treated Red Pine poles, respectively. The values in our study were of the same order of magnitude for Cu, albeit one order of magnitude (for Cr) and three orders of magnitude (for As) smaller than found by Frighetto Ferrarini et al. (2016) and Janin et al. (2009).

Levels of Zn were highest in Misplacements, possibly due to the use of Zn in wood preservatives such as ammoniacal copper-zinc-arsenate (ACZA) (US EPA, 1992). However, relatively high Zn levels were found also in Packaging, C&D waste and Furniture, which may rather reflect the widespread use of Zn in galvanised fastening systems (Krook et al., 2006). Fe concentrations were high in all sample types, probably due to the high concentration of iron in water- and solvent-based paints, wood preservatives and lacquers (Fjelsted and Christensen, 2007) as well as migration from metals (nails, joints, etc.). Al, Ni and Mg levels were very high in some samples, possibly due to contamination from metallic components such as nails, joints, etc. and inert materials.

Overall, it is possible to distinguish between elements whose composition is relatively similar across the various wood waste categories (e.g. Cd, Al, Mg, Mn, Ni, Co, V, B) and elements which are present primarily in selected categories (e.g. As, Cr, Cu, Pb, Zn, Sb, Ti). As the concentration levels of some of these elements (see Figures 2 and 3) varied considerably, this suggests that wood waste cannot be regarded as a homogeneous waste fraction but rather that the composition of the individual material types within wood waste have to be considered. Based on the results presented herein, it is possible to estimate contamination levels based on the source of the wood waste, thereby improving a quality-oriented selection of wood waste which is necessary in order to achieve a cleaner production. It should be noticed that the cleanest material type, namely Packaging, was present only in relatively low amounts (14% of total WW). Compared to the Pre-consumer wood samples, WW for recycling showed significantly higher concentrations for Cr, Cu, Pb, Fe, Al, Mg, Zn, Co, Sb, Ti and V. As these elements are generally associated with preservation (Cr, Cu, Zn), painting and coating (Pb, Co, Sb, Ti, Fe) and metals and alloys (Pb, Al, Mg, Zn, Fe, V), the results may indicate that concentrations

of these elements increased during the use phase, owing to the indiscriminate use of paints and treatments by consumers (while making the presence of contaminants untraceable), although it could also be caused by migration of contaminants during waste collection.

Overall, element concentrations complied with the limits defined by the EPF (EPF, 2014) for maximum limit values of selected compounds in wood-based panels containing recycled wood (see Table K.1). Although in some cases maximum values in lab samples were one (for Cr and Pb) or two (for Cu) orders of magnitude higher than the thresholds, mean values were below the limits, except for the case of Cu, whose mean concentration was two-fold the limit value. Lab samples exceeding the EPF limits belonged predominantly to the impurity classes Misplacements (samples M1, impregnated wood) and Low-quality wood waste (C3, M2, O2), confirming that the effect of the presence of impurities in wood waste for recycling is not to be underestimated.

3.4 Characterisation of chemical impurities: organic compounds

Most of the analysed organic compounds were BDL: while the full dataset is provided in Table L.1, the following discussion focuses on total contents. Figure 4 provides an overview of concentration levels for PCP, total sum of PAHs, total sum of phenols and total sum of PCBs.

Overall, the observed concentration levels were relatively low and never higher than 10 ppm. PCP was found mainly in furniture and misplacements. The EPF limit for PCP (5 ppm, Table K.1) was exceeded by a single sample in the Misplacement category (M1 at 9.13 ppm), possibly due to the use of PCP as wood preservative for outdoor applications. The total sum of phenols was within the same order of magnitude for all samples, except for Packaging wood, which had lower concentrations. Phenols may be added as phenolic or phenol-formaldehyde resins to wood during the production of engineered boards as binders and adhesives (Li et al., 2016). Although the median concentrations never exceeded 1 ppm, phenols are toxic even in low concentrations and may potentially be spread to the environment during outside storage prior to recycling (US EPA, 1985).

The total sum of PAHs was observed within 10⁻⁵ and 10⁺¹ ppm, which is significantly lower than concentrations of 10⁺⁴ ppm found by Löser et al. (1999) in PAH-contaminated wood waste. Total PAH levels of around 16 ppm were reported for ashes from incinerating pure wood chips (Bundt et al., 2001)

Figure 4. Concentrations (ppm dw) of (right to left) PCP, PAHs (total sum), phenols (total sum) and PCBs (total sum) in waste wood (WW) samples. The grey area distinguishes results for the pre-consumer wood samples. The y-axis is displayed using a logarithmic scale.

and in the range of 0.48-3.59 for ashes from municipal solid waste incineration (Johansson and Van Bavel, 2003b). PAH levels were found comparable in Off-cuts and Furniture, whereas the other categories were lower. As an indicator for creosote (EPF, 2014), Benzo(a)pyrene (BaP) was detected only in two samples (O2 and F2), albeit in concentrations below the EPF limits (0.5 ppm). While BaP levels in creosote-treated wood may have been around 20-35 ppm (Erlandsson and Almemark, 2009), the relatively lower levels observed here suggest that contamination with creosote-impregnated wood is not a major concern. Despite the low concentrations, both PAHs and phenols are classified as POPs, which preferably should be destroyed rather than recycled (UNECE, 2010). Of the three detected PAHs (BaP, benzo(b)fluoranthene and benzo(k)fluoranthene) specified as the most carcinogenic compounds by the UNECE (2010), BaP was detected at 0.10-0.24 ppm, benzo(b)fluoranthene at 0.14-0.85 ppm and benzo(k)fluoranthene at 0.09-0.54 ppm.

PCBs were not detected in most samples. The highest concentrations were observed in Furniture category, with the highest value of 0.253 ppm in the clean furniture subgroup (sample F1). Abb et al. (2010) reported a maximum value of 0.14 ppm total PCBs in wood waste of grades I and II, and up to 1.2

ppm in wood waste of grades III and IV. PCBs may originate from contamination, e.g. due to stabilisers in fluorescent lights or home appliances, elastic sealants, insulating board and sound-insulating board treated with agents containing PCBs, cement and other building materials, oil used during the wood chipping process, adhesives and wood floor finishes (Herrick et al., 2004; Robson et al., 2010; Andersson et al., 2003; Rudel et al., 2008). PCBs have also been used in the past as plasticisers in paints and in flame-retardant coatings (Butera et al., 2014; Jartun et al., 2009a, b), which may potentially have caused their higher concentrations in the Furniture samples. It should be noticed that PCBs could not be extracted from samples containing cement/asphalt (sample code M2), as the sample matrix analysed by GC-MS was too complex. PCBs are (similarly to phenols and PAHs) classified as POPs and their production and utilisation is banned (UNEP, 2009). As such, recycling should be avoided, and any contamination of these compounds into products should be minimised.

3.5 Recommendations for wood waste collection, sorting and recycling

Figure 5 provides an overview and comparison of chemical levels in clean wood waste (Grades I, II) relative to the levels in Low quality wood waste (Grade III) and hazardous wood waste (Grade IV). The figure clearly emphasises that WW belonging to Grades III and IV contained higher concentrations for all inorganic elements and organic compounds. In some cases, concentrations were three times higher (for As, Pb, PCP, B, Al, Mg, Fe), seven times higher (for Cr, Sb), ten times higher (for PAHs, V) and even 26 times higher (for Cu) than the values for clean WW (Grades I, II), which suggests that the separate collection and alternative disposal of Grades III and IV may dramatically decrease the level of chemicals in wood waste for recycling. Therefore, Low quality wood waste (Grade III) should be collected separately from clean WW (Grades I, II), in order to avoid unwanted contaminations of chemicals. Moreover, considering that fibreboards make up 37-67% of the composition of low-quality wood waste in this study (cfr. Table 3), and that fibreboard production in Europe has been rather stable at 15.5 million m³/year throughout 2007-2016 (FAO/UNECE, 2016; Wollf, 2016), it may be expected that comparable quantities will also be discarded in the near future. Nevertheless, incineration of fibreboard, as an alternative to recycling, may possibly release organic pollutants (Edo et al., 2017). For example, Gao

et al. (2017) reported polychlorinateddibenzo-p-dioxins levels in products

Figure 6. Concentration levels of selected inorganic and organic compounds in wood waste (WW) for quality grades I/II, quality grade III and quality grade IV. Due to their low concentration, and for the sake of readability, PCBs are excluded. The size of the bubbles is proportional to the mean concentration for all four quality grades (vertical). The areas of all bubbles within each subfigure are further scaled relative to the highest concentration in each subfigure (20 ppm in a) and 4628 ppm in b).

from torrefaction of particleboard 267 times higher than other wood feedstock, therefore calling for studies on the appropriate management of this class of wood waste.

Comparing the concentration levels found in this study with available scientific publications and databases revealed that our samples were cleaner than the wood waste intended for incineration addressed in other studies (see Figure M.1). This was the case for all contaminants apart from Mg and Co. Significantly higher levels were observed in the literature for As, Cr and Zn in wood waste for incineration. These comparisons should be used cautiously due

to differences in methodology among studies, e.g. sampling activities, processing of samples, type of chemical analyses: also, the extent to which impurities are removed depend on the kind of sorting (manual or mechanical such as screening and sieving). Comparisons are shown here only as illustrative of the diverse order of magnitude that the composition of wood waste may assume depending on its treatment route. In selected market situations (e.g. shortage of raw materials), WW from quality Grade III could be included in the clean feedstock for recycling, provided sufficient dilution with clean feedstock and/or recycling in applications without risk to users or further spreading in the environment. In all cases, it is recommended that quality Grade IV materials are maintained separately, to avoid risk-cycling of contaminants. The fact that this study identified Grade IV materials in the wood waste fraction otherwise sent for recycling clearly indicates that the potential for quality improvement exists through improving collection procedures. Furthermore, this suggests that additional monitoring measures (information campaigns, assistance at recycling centres, etc.) could be implemented to minimise the presence of impregnated wood in WW for recycling: impregnated wood was already separately collected at the recycling centres involved in this study. With EU policies favouring cascading recycling of materials, multiple recycling loops involving the same waste materials may lead to the potential accumulation of chemicals in recycled products, if the contaminated materials are not controlled appropriately. Measures such as standardising wood waste classes according to contamination and material composition, labelling, monitoring and advanced separation technologies may potentially improve the quality – and hence the recoverability – of the material.

As discussed in the previous sections, some wood types generally had higher concentrations of chemical contaminants in the individual wood subcategories (types, all grades) than others (see Table N.1), namely ‘Off cuts, or large wood chips (with fibreboard and/or treated wood)’ (O2, 12 chemicals), ‘Other packaging (untreated, no fibreboard)’ (P3, 7 chemicals), ‘Old wood from demolition and rebuilding (with fibreboard and/or treated wood) – outdoor use’ (C3, 7 chemicals), ‘Furniture (with fibreboard and/or treated wood)’ (F2, 9 chemicals), ‘Impregnated wood’ (M1, 11 chemicals) and ‘Composite building materials from C&D’ (M2, 13 chemicals). Not surprisingly, almost all of these subcategories (except for P3) fall into quality Grades III or IV, highlighting the fact that, if unsorted, the level of impurities in the recycled wood products may increase if included in the wood waste for recycling. Preferably, these

more contaminated wood waste types should be collected and managed separately from the cleaner fractions.

With respect to recycling, focus should be placed on ‘Off-cuts (untreated, no fibreboard)’ (O1), ‘Pallet (untreated, no fibreboard)’ (P1), ‘Wood from C&D and rebuilding (untreated, no fibreboard) – indoor use’ (C1) and ‘Furniture (untreated, no fibreboard)’ (F1), as these fractions contained the lowest levels for all chemicals. Within this study the role of impurities and quality of wood waste has been discussed mainly with respect to a cleaner particleboard production, as this material application is capable to absorb a large share of post-consumer wood waste. However, some qualities of wood waste can also be re-used in building applications. While recycling as building construction material is certainly beneficial, some parameters such as the dimension and structural properties of the wood waste may limit the usable feedstock. Nevertheless, the abovementioned considerations on the categories and type of wood to prioritize are applicable also to building material applications. A harmonised classification of wood waste, and the implementation of quality criteria across all sectors, may be needed to ensure clean material flows for wood recycling and at the same time offer a basis for recycling facilities to reject unwanted fractions prior to reprocessing.

4 Conclusions

Eight tonnes of wood waste (WW) collected for recycling were sampled at three different recycling centres in Denmark. The wood waste was separated manually into 34 fractions and analysed with respect to different material classes (Off-cuts, Packaging, Construction & demolition – C&D, Furniture and Misplacements), quality grade (I to IV) as well as content of physical and chemical impurities. The C&D sector represented the largest source of WW, followed by Furniture, Packaging and Off-cuts. Material impurities accounted for 59%, 12% and 50% of the total WW collected for recycling at each of the three recycling centres. This clearly indicates that considerable potential for improving wood waste quality exists. The concentration levels of As, Cd, Cr, Cu, Pb, Al, Mg, Mn, Ni, Zn, Fe, Co, Sb, Ti, V, B, PCP, PAHs, phenols and PCBs varied between wood waste classes, generally with higher levels for Low-quality WW (Grade III) and hazardous wood waste (Grade IV). To ensure the lowest overall level of contaminants, emphasis should be placed on recycling fractions such as ‘Off-cuts’, ‘Pallets’, ‘Wood from C&D and rebuilding (untreated, no fibreboard) – indoor use’ and ‘Furniture’, while fractions containing fibreboard, treatments and/or composite materials from

C&D should be minimised in recycled material. While existing limit standards set by particleboard producers were met by all WW samples in this study, the results clearly indicated that technological, operational and regulatory improvements associated with the collection, sorting, management and recycling of WW from recycling centres may decrease the levels of material and chemical impurities in products based on waste wood. Moreover, WW collected for recycling should not be regarded as a single material flow but rather as the sum of a wide range of individual fractions whose properties and contamination level depend on the type and source of the materials. To enhance further clean wood waste recycling and circular economy solutions involving wood, this study demonstrates that specific knowledge of wood waste quality is critical.

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Appendices

Supplementary data files related to this article can be found at ...

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