Resources, Conservation and Recycling 104 (2015) 38–48

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Environmental assessment of recycled mineral wool and polypropylene utilized in wood polymer composites

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ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form 9 September 2015
Accepted 14 September 2015
Available online 17 October 2015

Keywords:
Wood polymer composite
Recycling
Mineral wool
Life cycle assessment
Polypropylene

ABSTRACT

Environmental performance is an important promotive factor in the future use of wood polymer composites. In this study, the environmental effects of replacing virgin glass fibers with recycled mineral wool fibers, as well as replacing virgin polypropylene with recycled polypropylene are investigated. Furthermore, the environmental performance of two different end-of-life options for composite waste, incineration for energy use and landfill deposition is evaluated. The recycled mineral wool was found to have better environmental performance compared to glass fiber in every impact category assessed. The utilization of recycled polypropylene proved to be advantageous in global warming potential and abiotic depletion categories. It was found that the end-of-life management of composite waste has an important role in the environmental performance of composites. Incineration of composite waste for energy use had better performance compared to landfill deposition in all the categories assessed, except for global warming potential. It is concluded that while the environmentally optimal recycling method for polypropylene waste must be evaluated case by case, recycled mineral wool seems to provide an environmentally superior option to glass fiber in wood polymer composite applications where properties obtainable by the use of a mineral filler are required.

1. Introduction

Construction and demolition (C&D) activities are a major source of waste; their share varies between 13% and 40% of the total solid waste generated, depending on the country (Huang et al., 2002; Yuan and Shen, 2011). It is estimated that about 46% of C&D waste generated is recycled in the EU27 countries and about 30% in the US (Monier et al., 2011a; Yuan and Shen, 2011). Concrete, masonry and asphalt are the three largest waste fractions generated in the EU27 area, followed by miscellaneous and other mineral waste (Monier et al., 2011b).

In many countries, the recycling of C&D waste is governed by environmental laws and regulations (Llatas, 2011). In the European Union, regulation of C&D waste recycling is included in the waste framework directive, which states that 70% of non-hazardous C&D waste has to be prepared for re-use, recycled or recovered by 2020 (European Commission, 2010). It is clear that the recycling rate of C&D waste must be improved. Natural fiber composites can provide many options for increasing the recycling rates of C&D waste, as many of the material fractions found in C&D waste can be used in the production of natural fiber composites.

Recycled thermoplastic polymers are commonly used as the matrix in natural fiber composites, and many studies describe the effects of using recycled polymer instead of virgin polymer on the functional properties of natural fiber composites (Adhikary et al., 2008; Bahlouli et al., 2012; Lei et al., 2007). While various recycled polymers are commercially available, some studies describe the utilization of polymers recovered from non-commercial sources. Ashori (2008) describes the municipal solid waste stream as a source of plastic and lignocellulosic fibers for natural fiber composite raw materials. Lei and Wu (2011) have used a polymer obtained from recycled oil containers to produce natural fiber composites. Jayaraman and Bhattacharyya (2004) have used both mixed and sorted plastic waste obtained from a curbside recycling scheme to produce natural fiber composites. The natural fibers used are often byproducts of agricultural or industrial processes. Corn stover, coir, bagasse and wheat or rice straws are examples of agricultural byproducts which can be used to produce natural fibers suitable for composite production (Reddy and Yang, 2005). Sawdust is a common example of an industrial byproduct that can be utilized in natural fiber composite production (Najafi et al., 2006). Höglmeier et al. (2013), as well as Diyamandoglu and Fortuna (2015) found that part of the wood waste recovered from building

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http://dx.doi.org/10.1016/j.resconrec.2015.09.009
0921-3449/

deconstruction is suitable for material re-use in bio-based products. Joshi et al. (2015) mention urban wood waste, such as wooden pallets and containers, as a possible source of recycled natural fibers for energy production, but a fraction of the urban wood waste could also be suitable for material re-use. Recycled newspaper and recycled paper sludge are also possible sources of natural fibers (Ashori and Nourbakhsh, 2009; Hamzeh et al., 2011; Huda et al., 2005; Qiao et al., 2003; Sanadi et al., 1994). While the different additives are often virgin materials, some of the inorganic filler materials may be of recycled origin (Valente et al., 2011; Zheng et al., 2010).

Reliable assessment of the environmental impacts of natural fiber composites is important, because the environmental performance is an important factor in promoting the use of natural fiber composites (Joshi et al., 2004). It is equally important to be able to assess the environmental effects of different end-of-life options for different materials. Life cycle assessment (LCA) is a method developed to address the potential environmental impacts and environmental aspects throughout the life cycle of a product (Finnish Standards Association, 2006).

The environmental effects of natural fiber composites have been reported on in multiple studies. Xu et al. (2008) found that the polymer matrix had a dominant effect on the environmental effects of composites, while 30% by weight loading of wood fibers had a relatively mild effect. It was also shown that transportation of the raw materials had no significant environmental effect in the composite production.

Joshi et al. (2004) have compared the environmental effects of natural fibers and glass fibers in polymer composites. They conclude that natural fibers have superior environmental performance compared to glass fibers in most applications, because of the lower emissions from the production of natural fibers compared to glass fibers, natural fiber composites have higher fiber content for equal functional performance, natural fibers can reduce the amount of more polluting polymers, natural fiber composites have lower weight compared to similarly performing glass fiber composites, which can reduce the emissions in transportation applications, and carbon and energy can be obtained from incineration of natural fibers. Pegoretti et al. (2014) also identify the lower weight of the composites containing recycled natural fibers as one of the most important factors affecting environmental performance in automotive applications.

Corbière-Nicollier et al. (2001) studied the replacement of glass fibers in polymer composites with China reed (CR) fibers. They found that the CR fiber composites had better environmental performance compared to the glass fiber composites, as long as the service life of the CR fiber composite was long enough (about 2.2 years compared to the 5-year service life of the glass fiber composite). The recycling rate also affected the environmental performance of the composites, but glass fiber composites would require extremely high recycling rates in order to pass CR composites in environmental performance. The biomaterial use of CR fibers was also considered as a more promising end-of-life option than direct heat production or production of biofuels.

Rajendran et al. (2012) compared the use of virgin and recycled polymer in natural fiber composite production. The composites containing recycled polymer exhibited clearly better environmental performance in non-automotive applications compared to composites containing virgin polymer. In automotive applications, virgin polymer had slightly better environmental performance due to its better functional performance which led to decreased part weight and therefore to decreased fuel consumption during automotive use phase. It should be noted that if the functional performance of the composite containing recycled polymer is equivalent to the composite containing virgin polymer, the environmental performance of the composite containing recycled polymer will be better also in automotive applications. In automotive applications, the use phase can contribute around 70–90% of the total environmental burden, unlike in non-automotive applications where the use phase of the composite product rarely consumes energy or generates emissions.

While the environmental impacts of replacing inorganic filler materials with natural ones are rather well studied, less information can be found about the environmental impacts of recycling mineral filler materials suitable for natural fiber composites. It is also important to compare the environmental impacts of material re-use and energy use of recycled material fractions to determine the environmental performance of different waste management options. The C&D waste stream contains many material fractions which could be utilized in natural fiber composite production. For example recycled mineral wool can be used as an inorganic filler (Väntsi and Kärki, 2014), and recycled plastics could be utilized as the polymer matrix in composites.

The purpose of this study is to present the environmental impacts of recycled mineral wool, compared to glass fibers, as an inorganic filler in natural fiber composites, as well as the environmental impacts of using plastics recovered from C&D waste stream as the polymer matrix.

2. Materials and methods

2.1. Definition of goal and scope

The main goal of the study is to compare the environmental performance of recycled mineral wool to glass fiber as a filler in natural fiber composites, as well as the environmental performance of recycled polymer collected from C&D waste stream to virgin polymer as the polymer matrix for natural fiber composites. The assessment in this study follows the cradle-to-grave approach, covering the production of virgin raw materials, collecting and sorting the recycled materials from C&D waste stream, the required pre-processing of the materials, manufacturing of the composites, transportation of the materials, and the end-of-life processing of the composites. The system boundaries are presented in Fig. 1. The use phase of the composites is excluded from the assessment, as it is assumed that no energy is consumed or significant emissions generated during the use phase of the composite decking boards.

The functional unit used in the assessment is 100 kg of extruded natural fiber composite decking board, and four different natural fiber composite production scenarios are presented. In each scenario, a natural fiber composite with a different composition from the other scenarios is produced. In all the scenarios where recycled materials are not used, it is assumed that a corresponding amount of waste material is deposited at landfill in the case of mineral wool or incinerated for energy production in the case of polypropylene. In cases where recycled materials are used, it is assumed that any burden from the manufacturing or use phase of the materials is not considered as a part of the life cycle of the recycled materials. This "zero burden" assumption has been applied in previous studies concerning the life cycle assessment of recycled materials (Vossberg et al., 2014).

Two different end-of-life scenarios for the composites are also considered, incineration for energy production and deposition at landfill. Thermal and electric energy are produced in the incineration of composites, and electric energy is produced from landfill gas utilization in the scenario where the composite waste is deposited at landfill. The thermal and electric energy produced from landfill deposition or incineration of materials is assumed to replace separate production of thermal and electric energy. A similar method to model the energy production from recycled materials has been applied in a study concerning the recycling of packaging waste (Koskela et al., 2014).

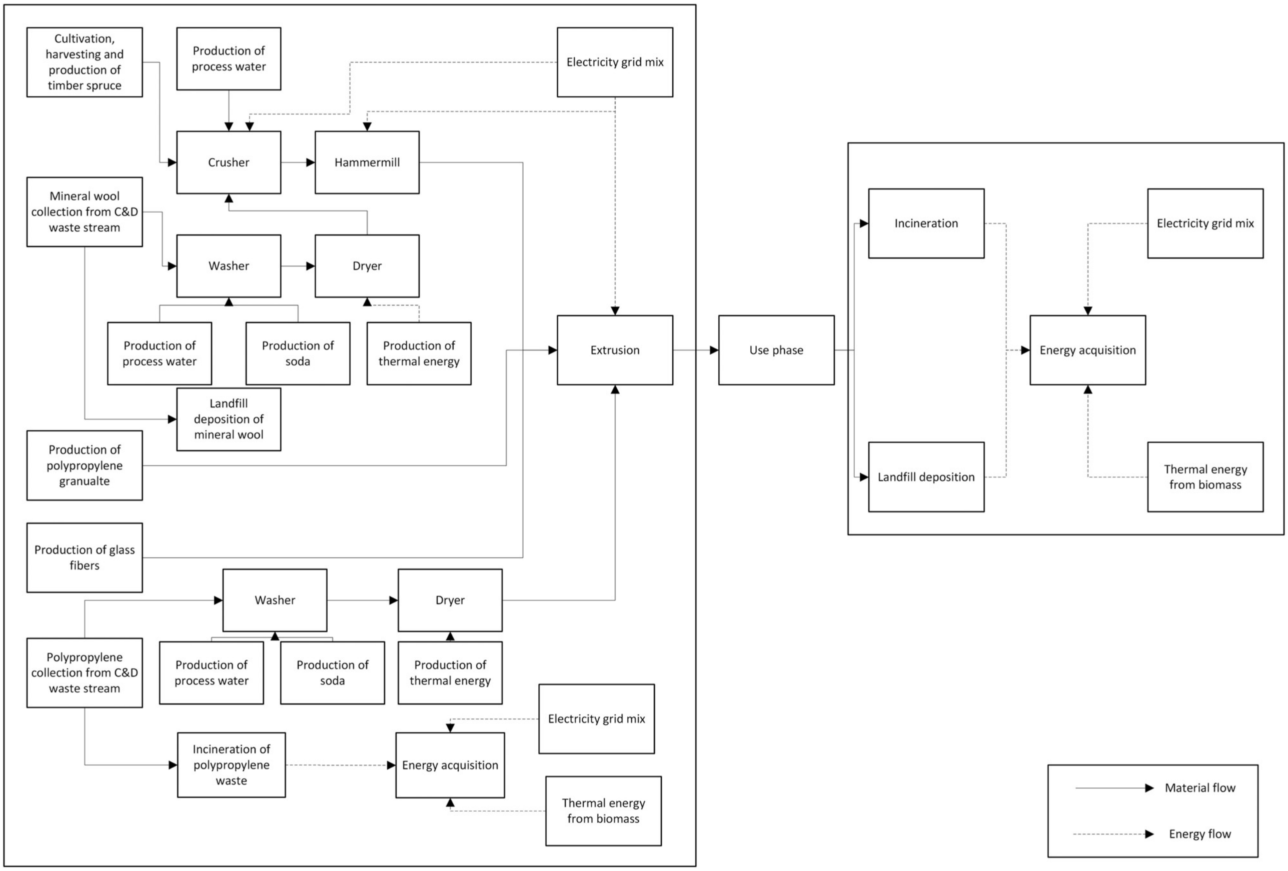

Fig. 1. System boundaries of the product system.

The energy use of plastic waste, while common, should not be considered as the primary end-of-life option, as the waste hierarchy introduced by the European Union directs member states to prioritize material re-use and recycling before energy use. Energy use is a prioritized end-of-life option only as compared to landfill deposition (Al-Salem et al., 2009; Lazarevic et al., 2010).

Despite the chosen end-of-life scenarios, material re-use or recycling should be the prioritized end-of-life option. As the main purpose of the assessment is to compare the different scenarios, and it is assumed that the material re-use or recycling requirements and processes for the different composites do not differ from each other significantly, material re-use and recycling as end-of-life options have been excluded from the assessment.

2.2. Materials and scenarios

Polypropylene can be used as the polymer matrix in wood polymer composites intended for automotive use, consumer products and building products, such as decking boards. The wood used in wood polymer composites is commonly in particulate form, either sawdust or short fibers and is often a by-product of mechanical wood processing industry. Different mineral fillers, such as glass fibers, talc and carbon fibers are commonly used in the plastics industry (Clemons, 2002). Hybrid filled polymer composites containing both wood and mineral filler have gained increased attention recently. Mineral fillers can improve many properties of wood polymer composites, such as moisture resistance, fire resistance or mechanical properties (Valente et al., 2011; Nikolaeva and Kärki, 2013; Väntsi and Kärki, 2014).

While many of the materials used in wood polymer composite production can be of recycled origin, the mineral fillers are often virgin materials. Some recycled materials suitable for use as mineral filler in wood polymer composites can still be found, for example recycled mineral wool (Väntsi and Kärki, 2014). Mineral wool is commonly used in building insulation, accounting for about 60% of the total insulation product market (Papadopoulos, 2005). Therefore, it is a material fraction commonly found in the C&D waste stream and often considered difficult to recycle, and is thus mainly disposed in landfill.

Different plastics account for about 0.2–2% of the total C&D waste generated in the EU27 countries (Al-Salem et al., 2009; Lazarevic et al., 2010). Recycled polymers from varying sources can be used in the production of wood polymer composites (Adhikary et al., 2008; Lei and Wu, 2011). In addition to providing good functional and economic performance, it has been shown that recycled polymers can also improve the environmental performance of composites (Rajendran et al., 2012).

As the polymer matrix of a wood polymer composite is often the main source of environmental burden, from the environmental point-of-view it is effective design to minimize the amount of polymer used (Xu et al., 2008). The amount of wood fibers in wood polymer composites can be as high as 80% by weight, but often the share of the fibers is in the range of 50–70% by weight (Kuo et al., 2009; Seefeldt and Braun, 2012). When mineral fillers, such as glass fiber, are added to wood polymer composites, the share of mineral filler is commonly 10–20% by weight (Valente et al., 2011). In our previous study concerning the effects of recycled mineral wool on the properties of wood polypropylene composites, acceptable mechanical properties were obtained by using mineral filler loading of 20% by weight when the amount polymer matrix was 30% by weight (Väntsi and Kärki, 2014).

The composites studied here contain 30% by weight of either virgin or recycled polypropylene as the polymer matrix in all the scenarios. As a result, the total filler content of the studied

Table 1
Components of the studied composites as weight percentages in the different scenarios.

Scenario	Wood flour	Glass fiber	Recycled mineral wool fiber	Virgin polypropylene	Recycled polypropylene
30VPP	70%	0	0	30%	0
20GF	50%	20%	0	30%	0
20MW	50%	0	20%	30%	0
30RPP	70%	0	0	0	30%

composites is 70% by weight. In the composites containing no mineral filler, the whole 70% share of the filler consists of wood fibers. In the composites containing a mineral filler, either virgin glass fibers or recycled mineral wool fibers, the share of the mineral filler is 20% by weight, leaving the share of the wood fibers as 50% by weight. The components of the composites studied in the different scenarios are listed in Table 1.

In scenario 30VPP, the studied composite contains only virgin polypropylene (30% by weight) and wood fibers (70% by weight). In scenario 20GF, part of the wood fibers are replaced by virgin glass fibers, and the studied composite contains 30% by weight of virgin polypropylene, 20% by weight of virgin glass fibers and 50% by weight of wood fibers. In scenario 20MW, the virgin glass fibers are replaced by recycled mineral wool, and the studied composite contains 30% by weight of virgin polypropylene, 20% by weight of recycled mineral wool and 50% by weight of wood fibers. In scenario 30RPP, the virgin polypropylene is replaced by recycled polypropylene, and the studied composite contains 30% by weight of recycled polypropylene and 70% by weight of wood fibers.

It is assumed that both recycled mineral wool and recycled polypropylene are obtained from a recycling center specialized in recycling C&D waste. The material fractions are separated from the C&D waste stream by using a skid steer excavator, which is a common separation method used in recycling centers.

2.3. Life cycle assessment methodology

The life cycle assessment has been conducted according to the requirements and guidelines presented in standards SFS-EN ISO 14040 and SFS-EN ISO 14044. GaBi 6.0 LCA software has been used to create the LCA model. All mandatory steps of LCA described in the standards: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and the interpretation of the obtained results are included in the current study.

The classification and characterization of the results has been done according the CML 2001 method, which focuses on the different environmental impact categories expressed in terms of emissions to the environment (Guinée, 2001; Vera et al., 2015). The impact categories studied are global warming potential during a 100-year time period (GWP), abiotic depletion of fossil and mineral resources separately (ADP (fossil) and ADP (element)), eutrophication potential (EP) and acidification potential (AP), as the emissions included in the inventory are related to these categories. Weighting and normalization, which are optional steps of LCA, have not been used in this study.

The input data of the current study compromises data from published sources, calculated data and estimated data. Average European (EU27) data from GaBi 6 database version 6.108 (PE International, 2015) is used for glass fiber, sawn timber and polypropylene production processes, transportation processes, energy production processes, and waste disposal processes. The recovery capacities of recycled mineral wool and polypropylene are estimated based on the data received from a recycling center located in Southern Finland. Emissions of the machinery used for recycled material recovery are calculated based on the data presented in the VTT Technical Research Center of Finland LIPASTO database (VTT Technical Research Center of Finland, 2012) and the estimated recovery capacity. The transportation distances used in the study are estimated based on the assumption that the extrusion plant is located in Lappeenranta, Eastern Finland and the raw materials are brought from and the waste materials are taken to the nearest suitable facility.

Allocation has not been necessary as no relevant by-products have been considered to exist, and all the processes modeled are single product processes. System expansion has been used to cover the energy production from the incineration and landfill deposition of the waste materials by including external energy production systems in the LCA model.

2.4. Life cycle inventory analysis

2.4.1. Cultivation, harvesting and production of spruce timber

Data from PE International (PE International, 2015) is used in the spruce timber inventory analysis. Spruce trees are harvested with harvesting machines. The lumber is transported by truck to a sawmill, and the transportation distance is assumed to be 144 km. The wood is debarked and cut into respective size. The sawn timber is transported by truck to the composite extrusion plant. The transportation distance to the extrusion plant is 50 km. The transportation distances used in the study are presented in Table 2.

2.4.2. Collection and treatment of recycled mineral wool fibers from C&D waste

Recycled mineral wool fibers are separated from the C&D waste stream using a skid steer excavator. It is assumed that the diesel consumption of the excavator is 12.68 kg/h and the mineral

Table 2
Transportation distances used in the study.

Transportation	Distance	Vehicle
Spruce timber to the extrusion plant	50 km	Truck trailer 33–40 t gross capacity, 27 t payload capacity
Soda to the recycled mineral wool washing site	400 km	Truck up to 7.5 t gross weight, 3.3 t payload capacity
Mineral wool from the recycling site to the extrusion plant	300 km	Truck trailer 33–40 t gross capacity, 27 t payload capacity
Polypropylene granulate to the extrusion plant	240 km	Truck trailer 33–40 t gross capacity, 27 t payload capacity
Glass fiber to the extrusion plant	150 km	Truck trailer 33–40 t gross capacity, 27 t payload capacity
Soda to the recycled polypropylene washing site	400 km	Truck up to 7.5 t gross weight, 3.3 t payload capacity
Recycled polypropylene from the recycling site to the extrusion plant	300 km	Truck trailer 33–40 t gross capacity, 27 t payload capacity
Composite waste to the landill site	40 km	Truck up to 7.5 t gross weight, 3.3 t payload capacity
Composite waste to the incineration site	250 km	Truck up to 7.5 t gross weight, 3.3 t payload capacity
Unrecovered mineral wool to the landfill site	40 km	Truck up to 7.5 t gross weight, 3.3 t payload capacity
Unrecovered polypropylene to the incineration site	40 km	Truck up to 7.5 t gross weight, 3.3 t payload capacity

Table 3
The recovery capacity, diesel consumption and emissions of the skid steer excavator used for waste separation.

Skid steer excavator	Recovery of recycled mineral wool	Recovery of recycled polypropylene	Sorting of C&D waste for landfill disposal	Source
Diesel Consumption	12.68 kg/h	12.68 kg/h	12.68 kg/h	estimation
Recovery capacity	1.05 t/h	1.2 t/h	1.5 t/h	estimation
Recovery fuel consumption	12.07 kg/t	10.56 kg/t	8.45 kg/t	calculated

Emissions to air		Unit	Source
CO_2	3085.207101	g/kg of fuel consumed	VTT Technical Research Center of Finland (2012)
CO	7.455621	g/kg of fuel consumed	VTT Technical Research Center of Finland (2012)
HC	2.011834	g/kg of fuel consumed	VTT Technical Research Center of Finland (2012)
NO_x	21.301775	g/kg of fuel consumed	VTT Technical Research Center of Finland (2012)
PM	0.828402	g/kg of fuel consumed	VTT Technical Research Center of Finland (2012)
CH_4	0.177515	g/kg of fuel consumed	VTT Technical Research Center of Finland (2012)
N_2O	0.084024	g/kg of fuel consumed	VTT Technical Research Center of Finland (2012)
SO_2	0.020118	g/kg of fuel consumed	VTT Technical Research Center of Finland (2012)
Heavy metals	0.000049	g/kg of fuel consumed	Maijala (2009)

wool fiber recovery capacity is 1.05 t/h. The diesel consumption is 12.07 kg per 1 metric ton of recovered mineral wool fibers. The diesel consumption, recover capacity, diesel consumption per ton of recovered material, and the generated emissions are listed in Table 3. Emissions of the excavator are calculated according to VTT Technical Research Center of Finland LIPASTO database (VTT Technical Research Center of Finland, 2012) and the study of Maijala (Maijala, 2009).

After recovery, the mineral wool fibers are washed. The washing process consumes 5.59 kg of process water and 0.000968 kg of soda (Na_2CO_3) per 1 kg of mineral wool fibers (Ingrao et al., 2014). The soda is transported to the recycling site by truck over a transportation distance of 400 km. The washed mineral wool fibers are then dried. The drying process consumes 2297 kJ of thermal energy per 1 kg of mineral wool fibers (Ingrao et al., 2014). Thermal energy is produced from biomass, and the emissions of the energy production are calculated according to the EU27 average data (PE International, 2015). Table 4 lists the resource consumption of the washing and drying processes. The washed and dried mineral wool fibers are transported by truck to the composite extrusion plant, the transportation distance to which is 300 km.

2.4.3. Collection and treatment of recycled polypropylene from C&D waste

Similarly to recycled mineral wool fibers, the recycled polypropylene is collected to the C&D waste stream using a skid steer excavator, washed and dried. The polypropylene recovery capacity of the excavator is assumed to be 1.20 t/h and the diesel consumption is 10.56 kg per 1 metric ton of recovered polypropylene. The assumed process parameters are listed in Table 3. The washing and drying of polypropylene are calculated similarly to recycled mineral wool, and the resource consumption is presented in Table 4. The transportation distance of recycled polypropylene from the recycling site to the composite extrusion plant is 300 km.

2.4.4. Production of virgin polypropylene and glass fibers

The production of virgin polypropylene granulate and glass fibers are calculated according to the data from PE International (PE International, 2015). The transportation distance of the polypropylene granulates from the manufacturing plant to the composite extrusion plant is 240 km. For glass fibers the transportation distance from the manufacturing plant to the extrusion plant is 150 km.

2.4.5. Separation of C&D waste for disposal

In the scenarios where the recycled materials are not used for composite production, they are either disposed to a landfill (recycled mineral wool) or incinerated for energy (polypropylene). They are still sorted for disposal at the recycling facility with an excavator, the sorting capacity is assumed to be 1.5 t/h and the diesel consumption is 8.45 kg per one metric ton of sorted waste. Table 3 shows the parameters used in the waste sorting process. The sorted materials are transported to the landfill site or the power plant by truck, and the transportation distance is assumed to be 40 km in both cases.

2.4.6. Extrusion plant

The operations at the extrusion plant include pre-treatment of some of the raw materials and the actual extrusion process. Spruce timber and recycled mineral wool are pre-treated with crusher and hammermill apparatuses. The glass fibers and polymer materials are assumed to be received in a ready-to-use form. The raw materials are compounded to composite products with an extrusion apparatus.

The crushing of the spruce timber and recycled mineral wool are assumed to consume 62.10 kJ of electric energy and 0.002 kg of water per 1 kg of crushed material (Gao et al., 2001). Possible treatment of the wastewater is excluded from this study. Treatment of the materials with the hammermill apparatus is assumed to consume 2500 kJ of electric energy per 1 kg of treated material (Miao et al., 2011). The extrusion process is assumed to have electric energy consumption of 1800 kJ per 1 kg of manufactured composite. The extruder apparatus is assumed to be a twin screw extruded with 100 kg/h maximum material output. The resource consumption of the extrusion plant equipment is listed in Table 4.

Table 4
Resource consumption of the crusher, hammermill, extruder, washer and dryer.

	Energy consumption	Process water consumption	Soda (Na_2CO_3) consumption	Source
Crusher	62.1 kJ/kg	0.002 kg/kg	0 kg/kg	Gao et al. (2001)
Hammermill	2500 kJ/kg	0 kg/kg	0 kg/kg	Miao et al. (2011)
Washer	0 kJ/kg	5.594 kg/kg	0.000968 kg/kg	Ingrao et al. (2014)
Dryer	2297 kJ/kg	0 kg/kg	0 kg/kg	Ingrao et al. (2014)
Extruder	1800 kJ/kg	0 kg/kg	0 kg/kg	Estimation

Table 5
Energies obtained and replacement energies produced in the different scenarios. All units in megajoules (MJ).

	VPP	20GF	20MW	RPP
Incineration of composite waste				
Electric energy from waste incineration	288 MJ	248 MJ	248 MJ	288 MJ
Thermal energy from waste incineration	933 MJ	804 MJ	804 MJ	933 MJ
Thermal energy from biomass	0 MJ	129 MJ	129 MJ	0 MJ
Electric energy from European grid mix	0 MJ	40 MJ	40 MJ	0 MJ
Incineration of polypropylene waste				
Electric energy from polypropylene waste incineration	158 MJ	158 MJ	158 MJ	0 MJ
Thermal energy from polypropylene waste incineration	521 MJ	521 MJ	521 MJ	0 MJ
Thermal energy from biomass	0 MJ	0 MJ	0 MJ	521 MJ
Electric energy from European grid mix	0 MJ	0 MJ	0 MJ	158 MJ
Landfill deposition of composite waste				
Electric energy from landfill gas utilization	43.5 MJ	31.1 MJ	31.1 MJ	43.5 MJ
Thermal energy from biomass	933 MJ	933 MJ	933 MJ	933 MJ
Electric energy from European grid mix	85.5 MJ	97.9 MJ	97.9 MJ	85.5 MJ

2.4.7. End-of-life options

The two different end-of-life options for composites are either deposition to a landfill or incineration for energy production. In the landfill deposition scenarios, average European data is used (PE International, 2015). The polymer matrix is considered as landfill of plastic waste, the wood particles are considered as landfill of wood waste, and the mineral wool and glass fibers are considered landfill of inert waste. It is assumed that electricity is produced from landfill gas emissions generated by the landfill of wood waste. This electric energy is used to replace electricity produced with technologies representing the average European grid mix.

In the incineration scenario, both thermal and electric energy are produced. Similarly to landfill deposition, the polymer matrix is considered as incineration of plastic waste, the wood fraction is considered as incineration of wood waste, and the mineral wool and glass fibers are considered as incineration of inert waste. The electric energy obtained from waste incineration is used to replace electric energy produced with technologies representing the average European grid mix, and the thermal energy is considered to replace thermal energy produced from biomass. Average European data is used for all the waste incineration processes (PE International, 2015). The data includes energy production, as well as transportation, treatment and disposal of the ashes. Certain metals are recovered from the ashes prior to landfill disposal. The amounts of metals recovered are Fe 10%, Al 1%, Cu, Zn and Pb 0.6% of generated bottom ash. Table 5 shows the energies obtained with both end-of-life options and possible replacement energy produced in each scenario.

3. Results and discussion

3.1. Life cycle impact assessment

3.1.1. Global warming potential

The global warming potential in the different scenarios is shown in Fig. 1. Scenario 20GF has the highest GWP in both end-of-life options. The global warming potential of 20MW is slightly lower than VPP, mainly because less emissions are generated in the end-of-life actions. In scenario 20MW the composite contains a larger amount of inert material compared to the composites in the 30VPP scenario, and therefore the emissions from the incineration of the composite waste are reduced. The difference in the energy production between incineration of the composite in scenario MW20 and 30VPP is replaced with thermal energy produced from biomass and electricity produced with technologies included in average European grid mix. These technologies generate less global warming -related emissions than the waste incineration operations per unit of energy produced. The 30RPP scenario has clearly the lowest global warming potential, since virgin polypropylene is not produced in this scenario. The share of virgin polypropylene production and transportation in global warming potential varies between 14% and 19% of total GWP, depending on the scenario and the end-of-life option. The electricity needed to operate the composite production line machinery is a notable source of emissions in all the scenarios; its share is 11–29% of the total GWP, again depending on the scenario and the end-of-life option. The harvesting, production and transportation of spruce timber has a negative GWP value, and therefore the scenarios where the composites have higher wood content (30VPP and 30RPP) receive more credit from the utilization of the wood material. However, it is not enough to offset the higher emissions generated by wooden material in end-of-life operations compared to inert materials. The sorting and treatment of recycled mineral wool causes less than 1% of the total GWP-related emissions in all the scenarios.

The end-of-life options have a great effect on the GWP of the composites. Incineration generates more GWP-related emissions than landfill deposition of the composite waste. Landfill deposition of the composites generates about 50% less emissions than incineration of composite waste, in all scenarios. The difference between energy production from landfill deposition and incineration of composites is covered with thermal energy from biomass and electric energy from the European grid mix, and as mentioned above, these technologies generate less emissions per unit of energy produced compared to composite waste incineration. Even with the GWP-related emissions from replacing energy production, the total GWP of landfill deposition of composite waste is clearly lower than that in the incineration option. In this study, 96% of the GWP-related emissions from landfill deposition could be attributed to degradation of the wooden fraction of the composite, as the plastic fraction of the composite degrades very slowly. According to Finnveden et al. (1995) 1–5% of the plastic fraction degrades in a 100-year period. The inert fraction generates less than 1% of the landfill deposition GWP-related emissions. In the incineration process, the polymer fraction is degraded and its share of the GWP-related emissions varies between 45% and 53%, depending on the scenario. In all scenarios, the plastic and wooden fraction together are responsible for 98% of the GWP-related emissions generated during the incineration of composite waste, including transportation of the waste to the incineration facility.

Witik et al. (2013) have studied the environmental impacts of different end-of-life options for polymer composites and obtained similar results regarding the GWP of polymer composites. Lazarevic et al. (2010) have analyzed a number of studies concerning the recycling options of plastic waste and note that when landfill deposition and incineration of plastic waste were compared, the GWP of landfill deposition was lower in most studies. They also note

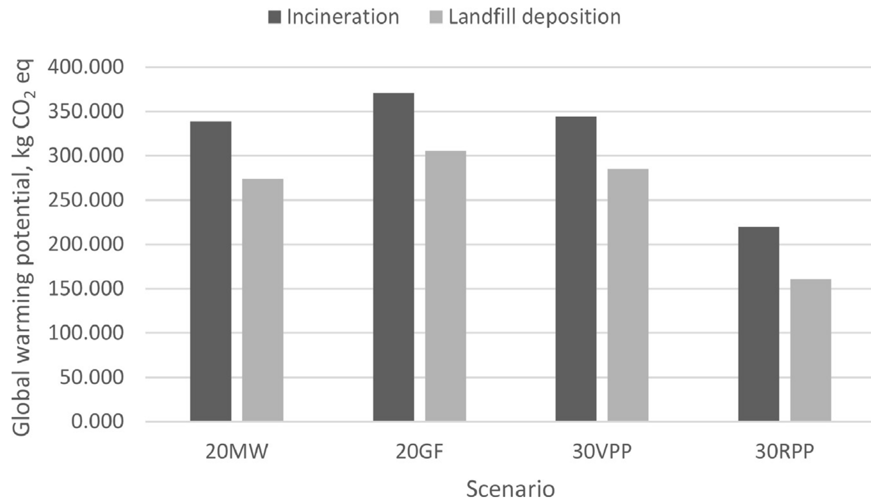

Fig. 2. Global warming potential of the different scenarios and end-of-life options.

that if the examination period is longer than 100 years, the GWP advantage of landfill deposition can be reduced, as more of the plastic fraction will degrade. Carpenter et al. (2013) have studied the end-of-life options for wooden C&D debris and found that incineration of the wooden debris had a positive GWP compared to landfill deposition (Fig. 2).

3.1.2. Acidification potential

The 30VPP scenario with incineration of the composite achieves the lowest acidification potential, followed by the 20MW scenario, also with incineration of the composite waste. Scenario 20GF has the highest acidification potential (AP) in both end-of-life options. The 30RPP scenario has a higher AP compared to 30VPP. The production of energy needed to operate the composite production line is a major source of AP-related emissions; its share varies between 21.7% and 54.6% of the total AP, depending on the scenario and the end-of-life option. Similarly, the energy produced to replace the energy from composite or recycled polypropylene incineration has a high contribution to the AP results. If the energies obtained from composite waste or recycled polypropylene incineration are replaced with thermal energy produced from biomass and electric energy produced with the European grid mix, an increase in the AP can be seen. This is because the zero burden assumption is applied to the composite and RPP waste, whereas the production and processing of the fuels are included in the replacing technologies. The advantage of recycled fuels in energy production is big enough to make the energy use a favorable end-of-life option for recycled polypropylene. Scenario 20GF is burdened by a high AP of glass fiber production, as well as a slight disadvantage from lower energy production from composite waste incineration compared to 30VPP. A similar disadvantage exists between scenarios 20MW and 30VPP, where scenario 20MW requires production of energy to replace the slightly lower energy acquisition from composite waste incineration. The acidification potential of the scenarios is presented in Fig. 3.

The difference between zero-burden recycled fuels and replacing energy production technologies can be most clearly seen in the comparison of the end-of-life options, where incineration is clearly a favorable option in all the scenarios presented. The wooden fraction is a major contributor of AP-related emission in both end-of-life options; its share is 27–36% in incineration and 62–73% in landfill deposition, depending on the scenario. The plastic fraction has a contribution of 18–19% in incineration and 18–21% in landfill deposition. The inert fraction causes 7% of AP-related emissions in incineration and 6% in landfill deposition. The transportation of the waste has a notable effect on the AP in the end-of-life options. In landfill disposal, where the waste transportation distance is shorter (40 km), the share of transportation is 9–12% of the total AP. In

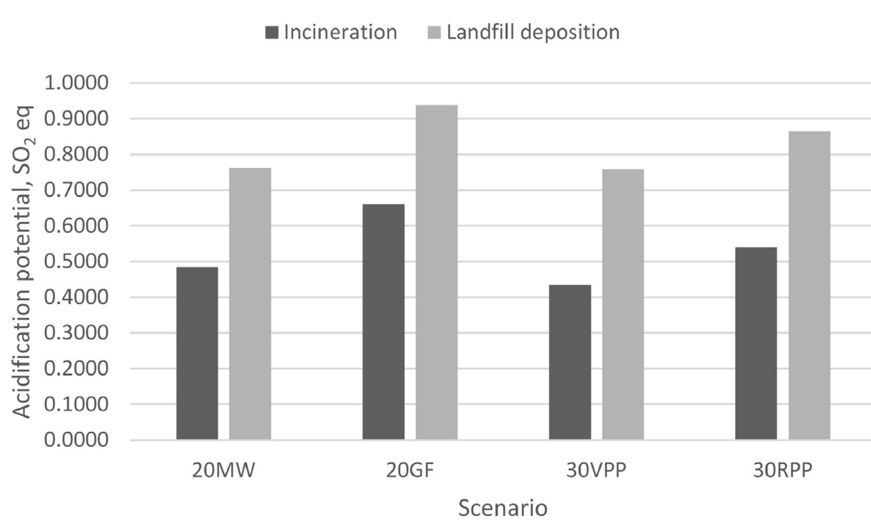

Fig. 3. Acidification potential of the different scenarios and end-of-life options.

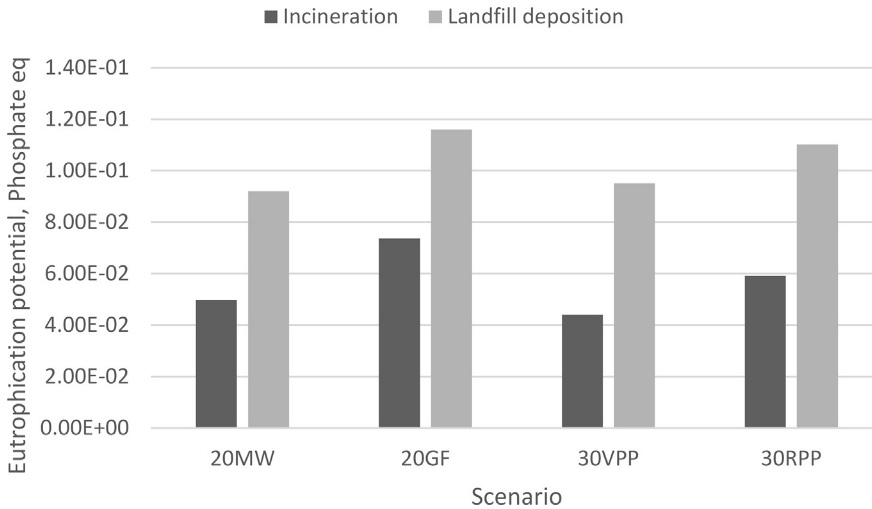

Fig. 4. Eutrophication potential of the different scenarios and end-of-life options.

incineration, where the transportation distance is 250 km, the share of AP-related emission originating from transportation is 46–48%.

Corbière-Nicollier et al. (2001) have compared the environmental properties of polymer composites filled with glass fibers and China reed fibers. It was shown in their study that the composites containing China reed had a lower AP compared to the glass fiber-filled composite. Similarly, in the present study the wood fiber had a lower AP compared to glass fibers. Lazarevic et al. (2010) have reviewed studies concerning incineration and landfill deposition of plastic waste and found that in most cases the AP of incineration was lower than the AP of landfill deposition. It should be kept in mind that in the present study, only 18–21% of AP-related emissions originated from the plastic fraction of the composites, therefore the total results cannot be directly compared to the results obtained for a pure plastic fraction. However, no studies discussing the AP of the end-of-life options for wood waste were found.

3.1.3. Eutrophication potential

Scenario 30VPP with incineration as the end-of-life option has the lowest eutrophication potential, followed by scenario 20MW, again with incineration as the end-of-life option. The 30RPP scenario has a notably higher eutrophication potential (EP) compared to the 30VPP scenario. Scenario 20GF has the highest EP. The eutrophication potential of the scenarios can be seen in Fig. 4. Energy production from biomass and the European grid mix are major sources of EP-related emissions, which largely explains the good EP of the 30VPP scenario, as no replacement energy is needed in the scenario. Production and transportation of both virgin polypropylene and glass fibers generate a relatively large amount of EP-related emissions. The share of virgin polypropylenes of the total EP varies between 9% and 24%, depending on the scenario. Glass fiber accounts for 24–38% of the total EP, depending on the end-of-life option. Recovery and transportation of mineral wool fibers generates 3–6% of the total EP-related emissions. When incineration is chosen as the end-of-life option, scenario 30VPP has lower EP compared to 20MW, because no replacement energy is needed. If the end-of-life option is landfill deposition, scenario 20MW performs better due to the lower wood material content of the composite. Compared to recycled mineral wool, wooden material generates more EP-related emissions when deposited to a landfill. Scenario 30RPP performs worse than 30VPP because of the replacement energy needed to cover the energy obtained from incineration of recycled polypropylene.

Landfill deposition of the composite waste generates considerably more EP-related emissions than incineration. Furthermore, more replacement energy from biomass and the European grid mix is needed in the landfill deposition option. In incineration, transportation of the composite waste to the incineration plant

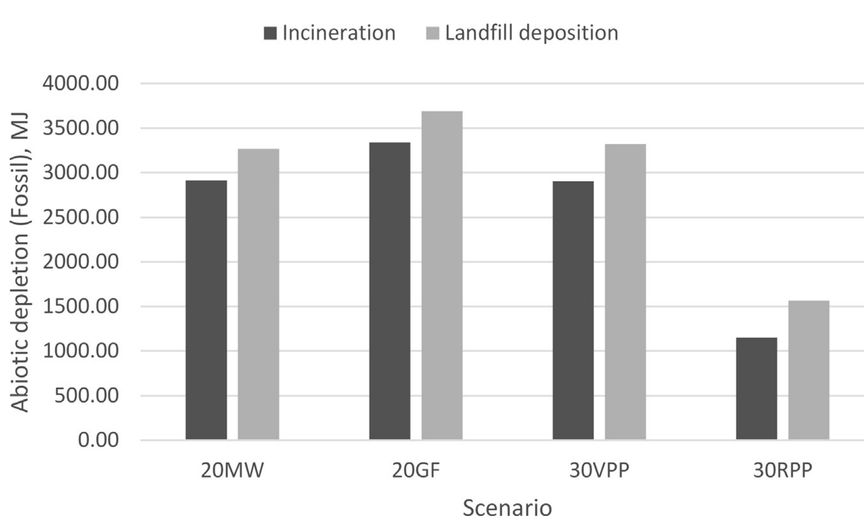

Fig. 5. Abiotic depletion (fossil) of the different scenarios and end-of-life options.

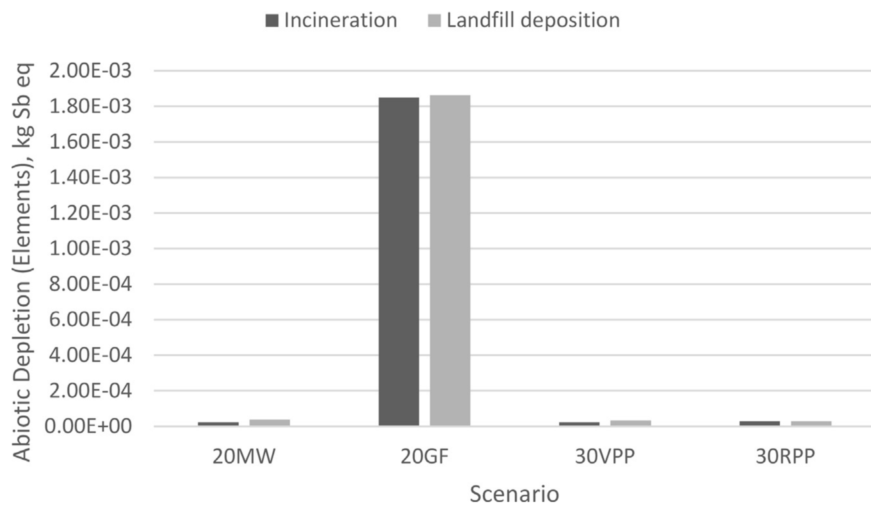

Fig. 6. Abiotic depletion (elemental) of the different scenarios and end-of-life options.

generates 57% of the total EP-related emissions. Incineration of the wooden material fraction generates 21–29% of the EP-related emissions. 15–16% of the EP-related emissions during the incineration of composite waste originate from the plastic material fraction. Incineration of inert waste generates 7% of the EP-related emissions in the scenarios where recycled mineral wool or glass fiber is used. In landfill deposition, only 5% of the EP-related emissions are caused by the transportation of the composite waste. The wooden material fraction is the biggest source of EP-related emissions in landfill deposition, accounting for 56–65% of the total EP-related emissions. The plastic material fraction is the second biggest source, responsible for 31–37% of the total-EP related emissions in landfill deposition. Inert waste causes 2% of the total EP-related emissions in landfill deposition in the scenarios where either recycled mineral wool or glass fiber are used.

Luz et al. (2010) have studied the end-of-life options for sugarcane bagasse-polypropylene composites and found that the EP of composite waste incineration was lower than the EP of landfill deposition. Lazarevic et al. (2010) state that most of the studies concerning recycling options for plastic waste report incineration to have a lower EP compared to landfill deposition.

3.1.4. Abiotic depletion

Abiotic depletion (ADP) of fossil resources is mainly caused by production of virgin polypropylene and energy. Transportation, harvesting of resources and waste sorting also cause ADP (fossil), but their role is less significant. The production of virgin polypropylene causes 54–69% of total ADP (fossil) in the scenarios where virgin polypropylene is used. As the production of virgin polypropylene is avoided in scenario 30RPP, it has clearly the best performance in the abiotic depletion of fossil resources. Scenarios 20MW and 30VPP have almost the same performance as far as ADP (fossil) is concerned. The production phase of scenario 30VPP has a slightly higher ADP (fossil), but the difference is evened out in the end-of-life phase, where scenario 20MW requires production of replacement energy. Scenario 20GF is again burdened by the production and transportation of glass fibers, which account for 14–15% of the total ADP (fossil) in the scenario. The recovery and treatment of recycled mineral wool in scenario 20MW causes less than 1% of the total ADP (fossil) of the scenario. The ADP (fossil) of the scenarios is presented in Fig. 5 and ADP (element) in Fig. 6.

The ADP (fossil) caused by the incineration process of the composite waste is roughly the same as the ADP (fossil) caused by landfill deposition, and in addition, replacement energy from biomass and the European grid mix is needed in the landfill deposition option. This explains the difference in the total ADP (fossil) between the end-of-life options. The ADP (fossil) caused by the replacement energy production is around 16% of the total ADP (fossil) in the 30RPP scenario and 12% of the total ADP (fossil) in all the other scenarios.

Comparisons with other studies are complicated because the abiotic depletion of fossil and element resources are rarely separated. The review of studies concerning the recycling of plastic waste by Lazarevic et al. (2010) reports incineration causing less ADP compared to landfill deposition. Luz et al. (2010) report the ADP of landfill deposition being lower compared to incineration of sugarcane bagasse-polypropylene composites. The difference in the results can be simply due to the different process parameters, such as transportation distances or energy production technologies chosen.

The production of glass fibers is by far the greatest cause of abiotic depletion of element resources; it is responsible for 99% of the ADP (element) in scenario 20GF. Incineration as the end-of-life option has a slight advantage compared to landfill deposition, as it is possible to receive some metals from the bottom ash generated in the incineration.

4. Conclusions

In this study, the environmental performance of glass fibers, recycled mineral fibers and recycled polypropylene as raw materials in wood–polymer composites were assessed. The environmental impacts of incineration for energy use and landfill deposition of the composite waste were also studied. The study shows that recycled mineral wool and recycled polypropylene can be environmentally viable raw materials for wood polymer composites. Incineration as the end-of-life option had better environmental performance in all impact categories except global warming potential.

The end-of-life operations had a notable contribution to the total environmental performance of the composites. Other major factors affecting the environmental properties were the production of virgin raw materials and production of energy needed to operate the composite manufacturing equipment. The recovery and treatment of the recycled raw materials did not have a notable effect on the environmental performance of the composites. Landfill deposition of recycled mineral wool waste was not a major source of emission. However, the end-of-life treatment of recycled polypropylene had a greater effect on the total emissions. The energy use of recycled polypropylene was an environmentally competitive option compared to material re-use due to the emissions generated by the replacing energy production systems needed in the cases where recycled polypropylene was utilized as raw material.

Recycled mineral wool had better environmental performance compared to virgin glass fiber in every impact category. The production of virgin glass fiber was a notable source of emissions in every impact category studied. As both recycled mineral wool and glass fibers are inert materials, they performed similarly in the end-of-life operations. When recycled mineral wool was compared to wood material, the environmental performance was slightly better in the global warming potential and eutrophication potential when landfill deposition was the end-of-life option, and slightly worse in the other studied impact categories. In this study, the wooden material was virgin raw material, but if the wooden material is from a recycled origin, it is possible that its environmental performance is improved.

The material re-use of recycled polypropylene performed well in the global warming potential and abiotic depletion (fossil) categories. In the rest of the categories, the performance was weakened by the emissions from the replacing energy production systems. Therefore, it can be said that the total environmental performance is greatly affected by the technologies used to produce the replacement energy. Only incineration and material use of polypropylene waste were included in this study. Still, in actual waste management scenarios, some amounts of polypropylene waste are deposited at landfills. Considering the importance of energy production and the emissions related to it, it can be assumed that material use is a very competitive end-of-life option compared to landfill deposition of polypropylene waste.

It can be concluded on the basis of the study that recycled mineral wool is an environmentally friendly option in polymer composite applications where properties obtainable by the use of a mineral filler are required. The environmentally optimal option for the recycling of polypropylene obtained from C&D waste stream must be decided case by case. The environmental performance of polymer composites is an increasingly important driver for the future use of composites, and the utilization of recycled raw materials can improve the environmental performance further.

Acknowledgements

This work was supported by the Finnish Cultural Foundation, South Karelia Regional fund, Grant Number 05141712.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2015.09.009.

References

Adhikary, K.B., Pang, S., Staiger, M.P., 2008. Dimensional stability and mechanical behaviour of wood–plastic composites based on recycled and virgin high-density polyethylene (HDPE). Compos. B: Eng. 39, 807–815, http://dx.doi.org/10.1016/j.compositesb.2007.10.005.

Al-Salem, S.M., Lettieri, P., Baeyens, J., 2009. Recycling and recovery routes of plastic solid waste (PSW): a review. Waste Manag. 29, 2625–2643, http://dx.doi.org/10.1016/j.wasman.2009.06.004.

Ashori, A., 2008. Municipal solid waste as a source of lignocellulosic fiber and plastic for composite industries. Polym. Plast. Technol. Eng. 47, 741–744, http://dx.doi.org/10.1080/03602550802188565.

Ashori, A., Nourbakhsh, A., 2009. Characteristics of wood–fiber plastic composites made of recycled materials. Waste Manag. 29, 1291–1295, http://dx.doi.org/10.1016/j.wasman.2008.09.012.

Bahlouli, N., Pessey, D., Raveyre, C., Guillet, J., Ahzi, S., Dahoun, A., et al., 2012. Recycling effects on the rheological and thermomechanical properties of polypropylene-based composites. Mater. Des. 33, 451–458, http://dx.doi.org/10.1016/j.matdes.2011.04.049.

Carpenter, A., Jambeck, J.R., Gardner, K., Weitz, K., 2013. Life cycle assessment of end-of-life management options for construction and demolition debris. J. Ind. Ecol. 17, 396–406, http://dx.doi.org/10.1111/j.1530-9290.2012.00568.x.

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

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

Diyamandoglu, V., Fortuna, L.M., 2015. Deconstruction of wood-framed houses: material recovery and environmental impact. Resour. Conserv. Recycl. 100, 21–30, http://dx.doi.org/10.1016/j.resconrec.2015.04.006.

European Commission, 2010. Commission Staff Working Document Accompanying the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Thematic Strategy on the Prevention and Recycling of Waste.

Finnish Standards Association, 2006. SFS-EN ISO 14044: Environmental management. Life cycle assessment. Requirements and guidelines (ISO 14044:2006).

Finnveden, G., Albertsson, A., Berendson, J., Eriksson, E., Höglund, L.O., Karlsson, S., et al., 1995. Solid waste treatment within the framework of life-cycle assessment. J. Clean. Prod. 3, 189–199, http://dx.doi.org/10.1016/0959-6526(95)00081-X.

Gao, W., Ariyama, T., Ojima, T., Meier, A., 2001. Energy impacts of recycling disassembly material in residential buildings. Energy Build. 33, 553–562, http://dx.doi.org/10.1016/S0378-7788(00)00096-7.

Guinée, J., 2001. Handbook on life cycle assessment: operational guide to the ISO standards. Int. J. Life Cycle Assess. 6, 255.

Hamzeh, Y., Ashori, A., Mirzaei, B., 2011. Effects of waste paper sludge on the physico-mechanical properties of high density polyethylene/wood flour composites. J. Polym. Environ. 19, 120–124, http://dx.doi.org/10.1007/s10924-010-0255-3.

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

Huang, W.-L., Lin, D.-H., Chang, N.-B., Lin, K.-S., 2002. Recycling of construction and demolition waste via a mechanical sorting process. Resour. Conserv. Recycl. 37, 23–37, http://dx.doi.org/10.1016/S0921-3449(02)00053-8.

Huda, M.S., Drzal, L.T., Misra, M., Mohanty, A.K., Williams, K., Mielewski, D.F., 2005. A study on biocomposites from recycled newspaper fiber and poly(lactic acid). Ind. Eng. Chem. Res. 44, 5593–5601, http://dx.doi.org/10.1021/ie0488849.

Ingrao, C., Lo Giudice, A., Tricase, C., Rana, R., Mbohwa, C., Siracusa, V., 2014. Recycled-PET fibre based panels for building thermal insulation: environmental impact and improvement potential assessment for a greener production. Sci. Total Environ. 493, 914–929, http://dx.doi.org/10.1016/j.scitotenv.2014.06.022.

Jayaraman, K., Bhattacharyya, D., 2004. Mechanical performance of woodfibre–waste plastic composite materials. Resour. Conserv. Recycl. 41, 307–319, http://dx.doi.org/10.1016/j.resconrec.2003.12.001.

Joshi, O., Grebner, D.L., Khanal, P.N., 2015. Status of urban wood-waste and their potential use for sustainable bioenergy use in Mississippi. Resour. Conserv. Recycl. 102, 20–26, http://dx.doi.org/10.1016/j.resconrec.2015.06.010.

Joshi, S.V., Drzal, L.T., Mohanty, A.K., Arora, S., 2004. Are natural fiber composites environmentally superior to glass fiber reinforced composites? Compos. A: Appl. Sci. Manuf. 35, 371–376, http://dx.doi.org/10.1016/j.compositesa.2003.09.016.

Koskela, S., Dahlbo, H., Judl, J., Korhonen, M., Niininen, M., 2014. Reusable plastic crate or recyclable cardboard box? A comparison of two delivery systems. J. Clean. Prod. 69, 83–90, http://dx.doi.org/10.1016/j.jclepro.2014.01.045.

Kuo, P., Wang, S., Chen, J., Hsueh, H., Tsai, M., 2009. Effects of material compositions on the mechanical properties of wood–plastic composites manufactured by injection molding. Mater. Des. 30, 3489–3496, http://dx.doi.org/10.1016/j.matdes.2009.03.012.

Lazarevic, D., Aoustin, E., Buclet, N., Brandt, N., 2010. Plastic waste management in the context of a European recycling society: comparing results and uncertainties in a life cycle perspective. Resour. Conserv. Recycl. 55, 246–259, http://dx.doi.org/10.1016/j.resconrec.2010.09.014.

Lei, Y., Wu, Q., 2011. Recycling engine oil containers to prepare wood-plastic composites. J. Appl. Polym. Sci. 122, 964–972, http://dx.doi.org/10.1002/app.34212.

Lei, Y., Wu, Q., Yao, F., Xu, Y., 2007. Preparation and properties of recycled HDPE/natural fiber composites. Compos. A: Appl. Sci. Manuf. 38, 1664–1674, http://dx.doi.org/10.1016/j.compositesa.2007.02.001.

Llatas, C., 2011. A model for quantifying construction waste in projects according to the European waste list. Waste Manag. 31, 1261–1276, http://dx.doi.org/10.1016/j.wasman.2011.01.023.

Luz, S.M., Caldeira-Pires, A., Ferrão, P.M.C., 2010. Environmental benefits of substituting talc by sugarcane bagasse fibers as reinforcement in polypropylene composites: ecodesign and LCA as strategy for automotive components. Resour. Conserv. Recycl. 54, 1135–1144, http://dx.doi.org/10.1016/j.resconrec.2010.03.009.

Maijala, A., 2009. LIFE-CYCLE ASSESSMENT Summary translation of the original Finnish report: Elinkaaritarkastelut. LIFE06 ENV/FIN/000195, http://projektit.ramboll.fi/life/stable/images/Life-cycle_assessment.pdf (accessed 16.02.15).

Miao, Z., Grift, T.E., Hansen, A.C., Ting, K.C., 2011. Energy requirement for comminution of biomass in relation to particle physical properties. Ind. Crops Prod. 33, 504–513, http://dx.doi.org/10.1016/j.indcrop.2010.12.016.

Monier, V., Hestin, M., Trarieux, M., Mimid, S., Domröse, L., van Acoleyen, M., et al., 2011a. Study on the management of construction and demolition waste in EU. Final report for the European Commission (DG Environment), 07.0307/2009/540863/SER/G2.

Monier, V., Mudgal, S., Hestin, M., Trarieux, M., Mimid, S., 2011b. Service contract on management of construction and demolition waste – SR1 Final Report Task 2, ENV.G.4/FRA/2008/0112.

Najafi, S.K., Hamidinia, E., Tajvidi, M., 2006. Mechanical properties of composites from sawdust and recycled plastics. J. Appl. Polym. Sci. 100, 3641–3645, http://dx.doi.org/10.1002/app.23159.

Nikolaeva, M., Kärki, T., 2013. Influence of mineral fillers on the fire retardant properties of wood–polypropylene composites. Fire Mater. 37, 612–620, http://dx.doi.org/10.1002/fam.2160.

Papadopoulos, A.M., 2005. State of the art in thermal insulation materials and aims for future developments. Energy Build. 37, 77–86, http://dx.doi.org/10.1016/j.enbuild.2004.05.006.

PE International, 2015. GaBi 6 database version 6.108.

Pegoretti, T.d.S., Mathieux, F., Evrard, D., Brissaud, D., Arruda, J.R.d.F., 2014. Use of recycled natural fibres in industrial products: a comparative LCA case study on acoustic components in the Brazilian automotive sector. Resour. Conserv. Recycl. 84, 1–14, http://dx.doi.org/10.1016/j.resconrec.2013.12.010.

Qiao, X., Zhang, Y., Zhang, Y., Zhu, Y., 2003. Ink-eliminated waste paper sludge flour-filled polypropylene composites with different coupling agent treatments. J. Appl. Polym. Sci. 89, 513–520, http://dx.doi.org/10.1002/app.12281.

Rajendran, S., Scelsi, L., Hodzic, A., Soutis, C., Al-Maadeed, M.A., 2012. Environmental impact assessment of composites containing recycled plastics. Resour. Conserv. Recycl. 60, 131–139, http://dx.doi.org/10.1016/j.resconrec.2011.11.006.

Reddy, N., Yang, Y., 2005. Biofibers from agricultural byproducts for industrial applications. Trends Biotechnol. 23, 22–27, http://dx.doi.org/10.1016/j.tibtech.2004.11.002.

Sanadi, A.R., Young, R.A., Clemons, C., Rowell, R.M., 1994. Recycled newspaper fibers as reinforcing fillers in thermoplastics: Part I. Analysis of tensile and impact properties in polypropylene. J. Reinf. Plast. Compos. 13, 54–67.

Seefeldt, H., Braun, U., 2012. Burning behavior of wood–plastic composite decking boards in end-use conditions: the effects of geometry, material composition, and moisture. J. Fire Sci. 30, 41–54, http://dx.doi.org/10.1177/0734904111423488.

Valente, M., Sarasini, F., Marra, F., Tirillò, J., Pulci, G., 2011. Hybrid recycled glass fiber/wood flour thermoplastic composites: manufacturing and mechanical characterization. Compos. A: Appl. Sci. Manuf. 42, 649–657, http://dx.doi.org/10.1016/j.compositesa.2011.02.004.

Väntsi, O., Kärki, T., 2014. Utilization of recycled mineral wool as filler in wood–polypropylene composites. Constr Build. Mater. 55, 220–226, http://dx.doi.org/10.1016/j.conbuildmat.2014.01.050.

Vera, L., Sun, W., Iftikhar, M., Liu, J., 2015. LCA based comparative study of a microbial oil production starch wastewater treatment plant and its improvements with the combination of CHP system in Shandong, China. Resour. Conserv. Recycl. 96, 1–10, http://dx.doi.org/10.1016/j.resconrec.2014.09.013.

Vossberg, C., Mason-Jones, K., Cohen, B., 2014. An energetic life cycle assessment of C&D waste and container glass recycling in Cape Town, South Africa. Resour. Conserv. Recycl. 88, 39–49, http://dx.doi.org/10.1016/j.resconrec.2014.04.009.

VTT Technical Research Center of Finland, 2012. LIPASTO – a calculation system for traffic exhaust emissions and energy consumption in Finland, Available from: http://lipasto.vtt.fi/indexe.htm (accessed 22.03.15).

Witik, R.A., Teuscher, R., Michaud, V., Ludwig, C., Månson, J.-E., 2013. Carbon fibre reinforced composite waste: an environmental assessment of recycling, energy recovery and landfilling. Compos. A: Appl. Sci. Manuf. 49, 89–99, http://dx.doi.org/10.1016/j.compositesa.2013.02.009.

Xu, X., Jayaraman, K., Morin, C., Pecqueux, N., 2008. Life cycle assessment of wood-fibre-reinforced polypropylene composites. J. Mater. Process. Technol. 198, 168–177, http://dx.doi.org/10.1016/j.jmatprotec.2007.06.087.

Yuan, H., Shen, L., 2011. Trend of the research on construction and demolition waste management. Waste Manage. 31, 670–679, http://dx.doi.org/10.1016/j.wasman.2010.10.030.

Zheng, Y., Shen, Z., Ma, S., Cai, C., Zhao, X., Xing, Y., et al., 2010. Influence of the recycled glass fibers from nonmetals of waste printed circuit boards on properties and reinforcing mechanism of polypropylene composites. J. Appl. Polym. Sci. 118, 2914–2920, http://dx.doi.org/10.1002/app.32589.