Consequential life-cycle assessment of treatment options for repulping reject from liquid packaging board waste treatment

Khan Md. Musharof Hussain, Havukainen Jouni, Niini Arvo, Leminen Ville, Horttanainen Mika

DOI: 10.1016/j.wasman.2022.10.026

Consequential life-cycle assessment of treatment options for repulping reject from liquid packaging board waste treatment

Md. Musharof Hussain Khan*[a], Jouni Havukainen[a], Arvo Niini[b], Ville Leminen[b] , Mika Horttanainen[a]

[a] Lappeenranta Lahti University of Technology LUT, School of Energy Systems, Department of Sustainability Science, Lappeenranta Lahti University of Technology LUT, Yliopistonkatu 34, P.O. Box 20, 53851, Lappeenranta, Finland.

[b]Lappeenranta Lahti University of Technology LUT, School of Energy Systems, Department of Mechanical Engineering, Lappeenranta Lahti University of Technology LUT, Yliopistonkatu 34, P.O. Box 20, 53851, Lappeenranta, Finland.

*Corresponding author: Md. Musharof Hussain Khan, Sustainability Science, School of Energy Systems, Department of Sustainability Science, Lappeenranta Lahti University of Technology LUT, Yliopistonkatu 34, P.O. Box 20, 53851, Lappeenranta, Finland.
E-mail: musharof.khan@lut.fi

Abstract

Liquid packaging board is one of the highly demanded packaging mediums for liquid food and beverages, generating substantial waste each year. Even though the fibre part of the liquid packaging board is recycled through a repulping process, the plastic and aluminium are usually used for energy recovery and as alternative raw materials in cement factories. This practice reduces the life span and economic value of plastic and aluminium, which does not fit within a circular economy. The plastic and aluminium from liquid packaging board waste can be recycled mechanically and chemically. This study used the consequential life-cycle assessment method to compare the environmental impact of the recovery options of rejected materials from liquid packaging board waste treatment. Four scenarios were established: (1) energy recovery by waste incineration, (2) composite pallet production by mechanical recycling, (3) plastic pallet production by mechanical recycling, and (4) plastic pallet production by chemical recycling. The study showed that when the consumed energy was supplied from renewable sources, plastic pallet production by mechanical recycling process had the lowest environmental impact, and energy recovery by waste incineration had the highest impact. A sensitivity analysis revealed that composite pallet production by mechanical recycling process showed the best impact if the energy was sourced from the average production mix, and plastic pallet production by chemical recycling had the lowest impact when mechanically recycled plastic substituted for 0%, 30%, and 50% of virgin plastic. These results should be of interest to liquid packaging board manufacturers and other related stakeholders.

1 Introduction

The market for liquid packaging board (LPB) is one of the fastest growing liquid packaging in the world. The demand for LPB is increasing, resulting in over 900 kilotonnes of LPB in the European market each year (ACE, 2020). Due to its unique material structure, LPB can protect beverages and food from light and oxygen over its entire lifetime, maintaining the nutritional value of the products during transportation, while for sale in a shop and at home. LPB is made of paperboard covered with thin layers of plastic and aluminium (Al). A standard structure of LPB consists of 80% fibre, 15% plastic and 5% Al (Khan et al., 2021b). LPB contributes to a low-carbon circular economy by using renewable materials and recycling at the end of life (EoL).

Due to the complex nature of LPB waste, recycling it with other cardboard waste proves inefficient. In a normal cardboard recycling process, paper-based waste is soaked in water for 2–4 minutes, which is inadequate for LPB waste due to its laminated layers (Lahme et al., 2020). In a recycling plant, LPB waste undergoes a drum pulping process, where it is soaked in water at an ambient temperature for 20 minutes. This helps in the separation of the fibre from the plastic and Al. After the drum pulping process, the fibre portion is put through a series of high- and low-density separation processes. Contaminants, such as glass, grit and stones, are removed by a high-density separation process; plastic and Al are separated using a low-density separation process. Around 20 specialised mills in the EU recycle LPB waste (ACE, 2021). Currently, 51% of LPB waste in the EU is recycled, mainly due to the recycling of fibre parts (Khan et al., 2021). The repulping reject containing plastic, Al and some fibre is incinerated for energy in a waste incineration plant or used as an alternative fuel in the cement industry. A mechanical process can recycle the rejected plastic and Al (Khan et al., 2021; Georgiopoulou et al., 2021; Robertson, 2021). However, mechanically recycled plastic residues of LPB cannot be used to produce high-quality products such as source-separated plastic waste (Khan et al., 2021; Robertson, 2021), making the process financially unfeasible (Lahme et al., 2020). Due to impurities, the extrusion of mechanically recycled plastic produces carbon and water vapour, resulting in a compromise in quality (Robertson, 2021). Another way of recycling rejected plastic and Al is with a pyrolysis process, in which pyrolysis oil is produced from separated plastic (Khan et al., 2021). The pyrolysis oil can be used for recycled, high-quality plastic production or as a fuel. In addition to the conventional mechanical and chemical recycling processes, plastic and Al can also be recycled mechanically by producing composite products. All of the aforementioned recycling processes have environmental impacts. Therefore, a thorough investigation of these processes is needed to find the best environmentally friendly recycling process for repulping rejected LPB waste.

Several studies have been conducted on the environmental impact of the EoL of LPB waste. By analysing available studies, the environmental impacts were found for the four different EoL options for LPB waste: (1) energy production (Khan et al., 2021; Bisinella et al., 2018; Ruttenborg, 2017), (2) fibre production (Bisinella et al., 2018; Ruttenborg, 2017; Verghese et al., 2012), (3) landfilling (Verghese et al., 2012), and (4) plastic granulate production from mechanical and chemical recycling processes (Khan et al., 2021). This research work continues the study conducted by Khan et al., (2021). In that study, only light-density polyethene (LDPE) was considered as a plastic residue, while high-density polyethene (HDPE) used in the LPB cap was excluded. In addition, the study did not focus on the role of renewable energy in the recovery options of LPB waste. The source of energy may significantly impact the recovery options of LPB because the processes involve a substantial amount of energy consumption. So far, no studies have analysed the environmental impact of the recovery options of repulping reject when using renewable energy. A composite product from fibre, plastic and Al could be another recycling option for repulping reject. The environmental impact of composite product manufacturing from repulping reject was not investigated in any studies. In considering this knowledge gap, the following questions were formulated and consequently addressed in this study:

1. What is the environmental performance of the recovery options in repulping reject?
2. What are the differences in the environmental impacts among energy recovery from incineration, plastic products from a mechanical or chemical recycling process and composite products from a mechanical recycling process?
3. What are the main contributors to environmental impacts?
4. What is the role of renewable energy on the environmental impact of the recovery options of repulping reject from LPB waste?

2 Materials and methods

The environmental impact assessment of repulping reject was conducted with life-cycle assessment (LCA), a well-established method to analyse the environmental impact of a product's or service's entire life cycle (EN ISO 14044:2006, 2006). The following sections describe the study's goal and scope, system boundary and inventory data and used life-cycle impact assessment (LCIA) to explain the results. This study also used sensitivity analysis to highlight the impact of specific parameters on the results of the study. As an LCA modelling tool, GaBi (version 10.5.0.78) by Sphera was used, and Microsoft Excel was used for the data analysis.

2.1 Goal and scope

The study aimed to investigate the environmental impacts of four material and energy recovery options for repulping reject collected from the LPB treatment process. The study focused on the context of Finland. However, this study can be used globally, especially in the EU countries where proper waste management systems exist. This investigative work can be used for policy development. This is why this study used consequential LCA (CLCA). CLCA investigates the environmental impacts of products in which demand or supply changes with the production or use of the studied product (Khan et al., 2021a).

The CLCA of the study applied the system expansion method, which means that the additional functions that arise from the treatment options of repulping rejects, such as recovered energy and materials, were considered. System expansion can be modelled by two approaches: (i) additional approach and (ii) avoided production approach (Horttanainen et al., 2020). An additional approach is used when unequal amounts of materials and energy are produced from different treatment options. In this method, materials and energy are supplied to the system from outside sources so that every treatment option has an equal amount of materials and energy output, which makes the comparison difficult. In the avoided production method, credit is given to the system when any product or energy is recovered to avoid the emissions that would otherwise be generated to produce these resources. In this study, the recovered energy and materials from different recovery options were used to substitute the primary product; therefore, the substitution method was used.

A functional unit is needed to be established to determine the reference flow. In this study, one tonne of repulping reject was selected as reference flow, and the treatment of one tonne of repulping reject was selected as the functional unit of this study. The shares of plastic:fibre:Al in the repulping reject were 73:11:16 based on laboratory tests (details are in the supplementary materials).

2.2 System boundaries

This research used a cradle-to-gate LCA approach, which means this study investigated the environmental impacts of the waste management phase of repulping the reject and manufacturing of the product from recovered materials of different recovery options. The summarised version of the system boundary of this study is presented in **Figure 1**. More details of the system boundary can be found from supplementary materials **Figure 1-4.** As part of the LPB waste treatment process, the fibre component is separated from the plastic and Al through a repulping process. The system boundary is established starting from the treatment options for repulping reject, such as incineration and mechanical and chemical recycling processes, and ends after materials and energy are recovered. This study excluded the repulping process because the environmental impacts of the repulping of LPB waste were the same for all the studied treatment options.

The analysis included the environmental impacts of the energy production required for the repulping reject treatment. In the CLCA, electricity and heat were supplied from marginal production sources. Marginal technologies are those that are most likely to respond to small changes in demand (Khan et al., 2021a). By 2030, biomass will be Finland's primary heat-supplying source (Ministry of Employment and the Economy, 2017); wind and solar will be the prime electricity-supplying sources (Ministry of Employment and the Economy, 2017; SKM Market Predictor, 2019). Therefore, a biomass-based heat source was included as the marginal heat-supplying source, and wind and solar were included as the marginal electricity-supplying sources.

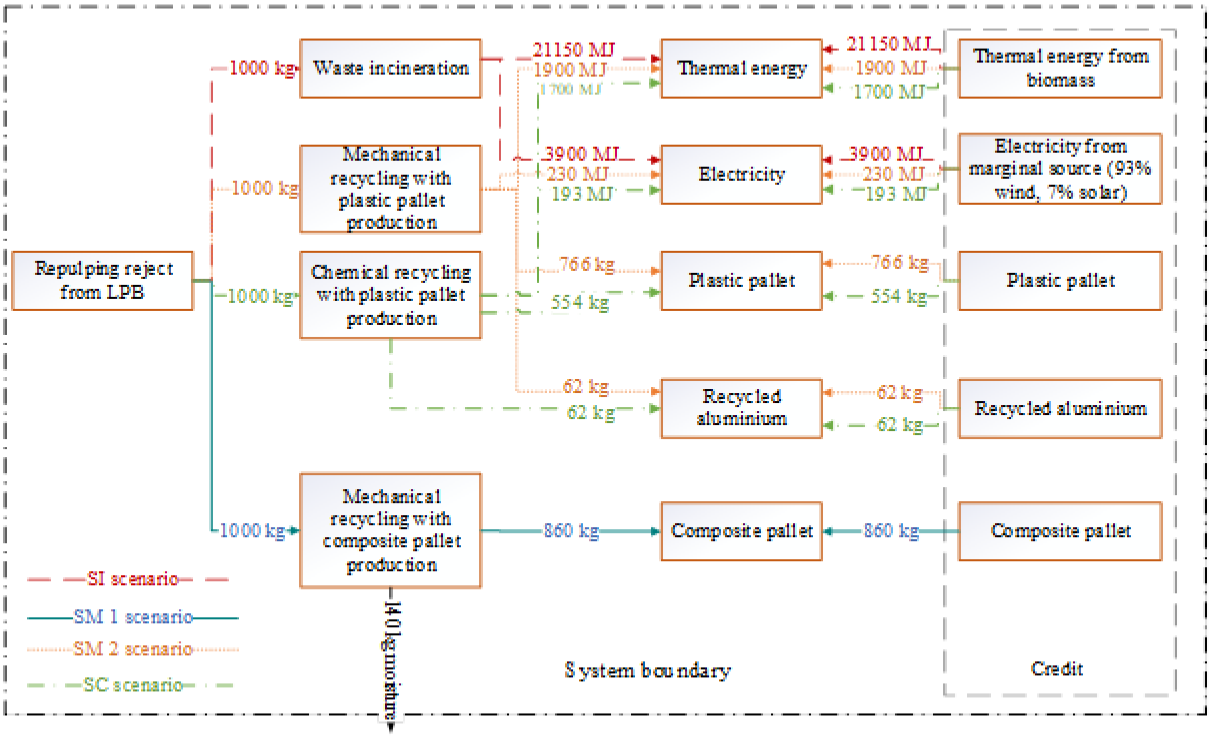


Figure 1. The system boundary of the study with different scenarios: SI, waste incineration; SM 1, mechanical recycling with composite pallet production; SM 2, mechanical recycling with plastic pallet production; and SC, chemical recycling with plastic pallet production.

2.3 Scenario analysis

Four scenarios were established for the treatment of repulping reject: a waste incineration scenario (SI), a chemical recycling scenario (SC) and two mechanical recycling scenarios (SM 1 and SM 2). It was assumed that energy was recovered from the SI, SM 2 and SC scenarios. In addition to energy, fibre-polymer composite pallets and plastic pallets were considered the recovered material in the scenarios.

Waste incineration scenario (SI)

The repulping reject was incinerated in a waste to energy plant in the SI scenario. The environmental impact of repulping reject incineration was included in this study. The produced electricity and heat were assumed to substitute for an equal amount of thermal energy from biomass and marginal electricity production. The system boundary of this scenario is presented in more detail in Figure 1 of the supplementary materials.

Mechanical recycling scenarios (SM 1 and SM 2)

This study considered two mechanical recycling processes: mechanical recycling with composite pallet production (SM 1) and mechanical recycling with plastic pallet production

(SM 2). In SM 1, the rejected materials were not separated; instead, they were used for composite pallet production. A composite pallet or recycled plastic pallet can provide the same functional quality as a virgin plastic pallet (Khan et al., 2021a). Therefore, in this study, it was considered that the produced composite pallet substituted a plastic pallet made from virgin plastic and gained credit for avoiding plastic pallet production.

In contrast, the rejected materials were separated in the SM 2 scenario. The separated plastic was used for pallet production, which substituted plastic pallets made from virgin plastic. The substituted plastic pallet in both scenarios (SM 1 and SM 2) was assumed to be produced from high-density polyethene (HDPE) plastic using an average production mix. More information about the background process of plastic pallet production can be found in supplementary materials Table 1. The credits in the SM 2 scenario were obtained when thermal energy and electricity from separated fibre incineration substituted thermal energy from biomass and electricity from marginal sources, produced plastic pallets substituted virgin plastic made pallets, and separated Al substituted the average Al production mix (60% virgin Al and 40% recycled Al). More information on the substituted average Al production mix can be found in the supplementary materials Table 1.

Chemical recycling scenario (SC)

Resembling SM 2, plastic was separated from fibre and Al in the chemical recycling scenario (SC). The separated plastic went through a pyrolysis process in which ethylene was produced, which was later used for HDPE granulate production. The produced HDPE granulate was used for plastic pallet production. Similar to the SM 2 scenario, the separated fibre was used for energy production, and the Al was used for Al ingot production. In this scenario, the credits were obtained by replacing plastic pallets, biomass thermal energy and electricity from marginal sources, and the average Al production mix. Substituted Al and plastic were assumed to be produced similarly to the mechanical recycling scenario. More info about background processes are available in supplementary materials Table 1.

2.4 Inventory analysis

The inventory data were collected from the life-cycle stages of the repulping reject treatment options: mechanical recycling with mono material production, mechanical recycling with composite production, a pyrolysis process and the production of additional materials and energy. The LCI data were collected from the literature, personal communications, Sphera

GaBi database and real-time industrial data. The background dataset used in this study is given in the supplementary materials Table 1.

Incineration of repulping reject

At the beginning of the SI scenario, the collected repulping reject went through a drying process to remove moisture and improve its lower heating value as received (LHVar). In a laboratory test, the moisture content of the repulping reject was found to be 15% after drying (details are in the supplementary materials). The energy demand for drying was 0.2 MJ kg^{-1} repulping reject (get recycling, 2021). After drying, the repulping reject was mechanically separated by an eddy current separator with 85% efficiency into plastic, fibre and Al. The plastic and fibre were incinerated in a plant for those materials, whereas the Al was treated in an inert waste incineration plant. According to Reimann (2012), the thermal efficiency of the CHP plant in Northern Europe was 72.6%, and the electrical efficiency was 11%. Furthermore, it is found that annual CHP power plant efficiency in Finland is between 80-90% (Pöyry, 2012; Suojansalo, 2020); therefore, the thermal efficiency of 72.6% and electrical efficiency of 11% were considered in this study.

Mechanical recycling

Similar to scenario SI, in the SM 1 scenario, the repulping reject was dried to remove moisture. After drying, the residue went through an agglomeration process, where different additives, such as lubricants and maleic acid, were mixed with the residue. In the end, the composite pallets were produced by a compression process. The inventory data for the composite pallets and plastic pallet production are given in **Table 1**.

In the plastic pallet production by mechanical recycling process (SM 2), the rejected residue went through several processes, such as shredding, washing, drying, extruding and injection moulding. The residue was crushed in a shredding process followed by wet disintegration in a hydrocyclone to remove fibre residues, Al, foreign substances and impurities. The separated plastic residue was dried before sending it to the extrusion process. After extrusion, the recycled plastic was cooled down and formed into small grains, from which a plastic pallet was produced through injection moulding. An eddy current process separated the Al from the fibre-Al mixture, which later substituted the Al ingot. The fibre part was used for energy production through the incineration process.

Table 1. LCI data for mechanical recycling processes.

Parameter	Value	Unit	Reference
Composite pallet			
Electricity for pneumatic transport	0.02	MJ kg^{-1} pallet	Khan et al., 2021a
Diesel for pneumatic transport	0.004	MJ kg^{-1} pallet	Khan et al., 2021a
Electricity for agglomeration	0.5	MJ kg^{-1} pallet	Khan et al., 2021a
Electricity for compression	0.4	MJ kg^{-1} pallet	Khan et al., 2021a
Polypropylene granulate	0.002	kg kg^{-1} pallet	Khan et al., 2021a
Lubricants	0.002	kg kg^{-1} pallet	Khan et al., 2021a
Maleic acid	0.0001	kg kg^{-1} pallet	Khan et al., 2021a
Plastic pallet			
Electricity for shredding	4	MJ kg^{-1} repulping reject	Laboratory test*
Electricity for wet disintegration	1	MJ kg^{-1} repulping reject	Laboratory test*
Electricity for screening	3	MJ kg^{-1} repulping reject	Laboratory test*
Electricity for mechanical dewatering	0.2	MJ kg^{-1} repulping reject	get recycling, 2021
Electricity for injection moulding	18	MJ kg^{-1} pallet	Khan et al., 2021a
Electricity for extrusion	0.6	MJ kg^{-1} pallet	Khan et al., 2021a
Electricity for plastic pallet crushing	0.1	MJ kg^{-1} pallet	Khan et al., 2021a

Chemical recycling

Similar to mechanical recycling with the plastic pallet production process (SM 2), in chemical recycling (SC), the repulping reject also went through shredding, wet disintegration and mechanical dewatering. After that, the separated plastics were segregated into LDPE and HDPE using a cyclone separator with an efficiency of 99%. Pure LDPE and HDPE then went to a pyrolysis process. Pyrolysis is the thermal degradation of plastic waste at different temperature ranges of 300–900℃ into valuable energy resources, such as pyrolysis gas, oil and char (Sharuddin et al., 2018). In this process, plastic is heated without oxygen to degrade longer polymer molecules into smaller ones. The pyrolysis process requires pure polyethene, polypropylene and polystyrene (Ragaert et al., 2017; Selina et al., 2021). It was assumed that the plastics are free of O, Cl, N, S and other heteroatoms because, in this research work, HDPE and LDPE passed through several separation processes. Therefore, the studied plastics were an ideal feedstock for the pyrolysis process.

The polymers are broken down into condensable and non-condensable gases during the pyrolysis process (Jeswani et al., 2021). Condensable gas can be converted into pyrolysis oil through distillation. However, non-condensable gas can be used for supplying energy to the pyrolysis process. The yield of pyrolysis oil, gas and char depends on the operating temperature, reactor and residual time. This study assumed that the pyrolysis process was performed in a batch reactor at 500 ℃ with a residual time of 20 minutes. For LDPE, the pyrolysis oil yield was 95% and the gas was 5%; for HDPE, the yield was 85% oil, 10% gas and 5% char (Sharuddin et al., 2018). The char was sent to an incineration plant for energy recovery. An ultimate analysis of the char showed that HDPE pyrolysis char had 51.4% volatile matter, 42.65% C, 3.06% H and 0.43% N (Jamradloedluk and Lertsatitthanakorn, 2014), which is similar to that of HDPE (92.9% volatile matter, 79.9% C, 12.6% H and 0.55% N) (Kumar and Singh, 2011). Because the chemical components of the char were similar to HDPE, it was assumed that char incineration had the same environmental impact as the HDPE incineration process.

The LDPE and HDPE pyrolysis process inventory data are given in **Table 2**. Pyrolysis oil from the LDPE and HDPE was processed to remove impurities, such as H, N and CO, with a purification efficiency of 97% (BASF, 2020). The purified pyrolysis oil was used as feedstock in a thermal cracker to produce ethylene, which was later polymerised into HDPE granulate. The efficiency of the thermal cracker was considered to be 81.3%, and the polymerisation was 98% (Joosten et al., 2001).

Table 2. Inventory data for the production of ethylene from LDPE and HDPE pyrolysis.

Parameter	Value used	Unit	Reference
Pyrolysis process			
Electricity	3.26	MJ $tonne^{-1}$ pyrolysis oil	Jeswani et al., 2021
Thermal energy	0.47	MJ $tonne^{-1}$ pyrolysis oil	
LHVar of pyrolysis char	20	MJ kg^{-1}	Jamradloedluk and Lertsatitthanakorn, 2014
Purification			
Electricity	3.51	MJ $tonne^{-1}$ pyrolysis oil	BASF, 2020
Thermal cracking			
Electricity	0.29	GJ $tonne^{-1}$ pyrolysis oil	Joosten et al., 2001
Thermal energy	23	GJ $tonne^{-1}$ pyrolysis oil	
Ethylene production			
Thermal energy	0.291	GJ $tonne^{-1}$ pyrolysis oil	Joosten et al., 2001
Electricity	1.96	GJ $tonne^{-1}$ pyrolysis oil	

2.5 Sensitivity analysis

The results of the LCA can be affected by methodological approaches and initial assumptions, for example, the system expansion method and allocation rules (Cellura et al., 2011). In addition, many of the required input parameters in LCA are uncertain. Therefore, a sensitivity analysis was conducted to study the key parameters influencing the product system, the robustness of the results and their sensitivity to uncertain factors (Wei et al., 2015). It is an essential tool for analysing the effects on the output of the study results due to the methodological approach and input data (ISO, 2006). Scenario analysis is a type of sensitivity analysis that is often used in LCAs (Junnila and Horvath, 2003). In this study, four scenario analyses were conducted based on a “one at a time approach”, where each input parameter was changed individually to investigate the influence of each on the results.

Scenario Analysis 1—Changing the repulping reject composition

The repulping reject composition was considered based on a laboratory test in the modelling. Only LPB waste was analysed in the laboratory to investigate its composition. In contrast to the laboratory results, the industry-based repulping reject composition differs. In Finland, LPB is collected and treated along with cardboard waste. Therefore, the share of materials in the repulping reject differs from the laboratory-based result. The LPB waste used in Scenario Analysis 1 was collected along with the cardboard waste from the source and measured in the laboratory. The data for Scenario Analysis 1 are presented in **Table 3**.

Scenario Analysis 2—Virgin plastic replacement ratio

It is impractical to consider 100%-virgin plastic replacement with recycled plastic. Recycled plastic has a weaker structure compared to virgin plastic; therefore, it is downcycled to lower-quality products (Julie, 2019). This study assumed that the fibre-polymer composite plastic from scenario SM 1 had comparable properties to the recycled plastic pallet from scenario SM 2. Considering the downcycling issue, three different virgin plastic replacement ratios (see **Table 3**) for fibre-polymer composite pallets and recycled plastic pallets were used in Scenario Analysis 2.

Table 3. Parameters for scenario analysis.

Plastic:fibre:Al ratio			
Ratio 1 50:39:11	Base 73:11:16	Ratio 2 42:44.14	
Changing Energy Source			
Virgin plastic replacement ratio			
0%	30%	50%	80%

Scenario Analysis 3—Changing energy source

For the modelling, marginal heat and electricity were considered the energy sources for different treatment processes and substitutions. The robustness of the LCA study was analysed by changing the marginal heat and electricity production to average heat and electricity production mix. In Scenario Analysis 3, the average heat and electricity production mix was considered based on 2017 production data in Finland (electricity: peat 4.13%, hard coal 8.73%, coal gases 0.87%, natural gas 4.92%, fuel oil 0.27%, biomass 16.22%, biogas 0.62%, waste 1.53%, nuclear 33.49%, hydro 22.01%, wind 7.14% and photovoltaics 0.07%; heat: biomass 36.4%, hard coal 30.5%, peat 17%, natural gas 14.1%, light fuel oil 1%, and heavy fuel oil 1%).

2.6 Assumptions and limitations

It was assumed that all treatment options had the same transportation; therefore, transportation was excluded from this study. The recycled plastic from the mechanical recycling system was assumed to substitute 100% virgin plastic because the fibre and Al were separated adequately with almost 100% separation efficiency from plastic. Therefore, it was assumed that the mechanical properties of the plastic were the same as virgin plastic. It was also assumed that composite pallets by mechanical recycling could substitute 100% virgin plastic based on the functionality of the composite pallet. The composite pallet has similar mechanical properties as a plastic pallet (Khan et al., 2021a); therefore, 100% virgin plastic substitution by composite material was assumed. However, in the sensitivity analysis, the environmental impact of substituting 0%, 30%, 50%, and 80% virgin plastic by composite pallet and plastic pallet production by mechanical recycling process were analysed to show the impact of virgin plastic replacement ratio on the different mechanical recycling processes.

The data used in the pyrolysis of the plastic from LPB waste were unavailable from a single source. Therefore, the data of different sections of the pyrolysis process, for example, purification, thermal cracking, and ethylene production, were collected from different sources.

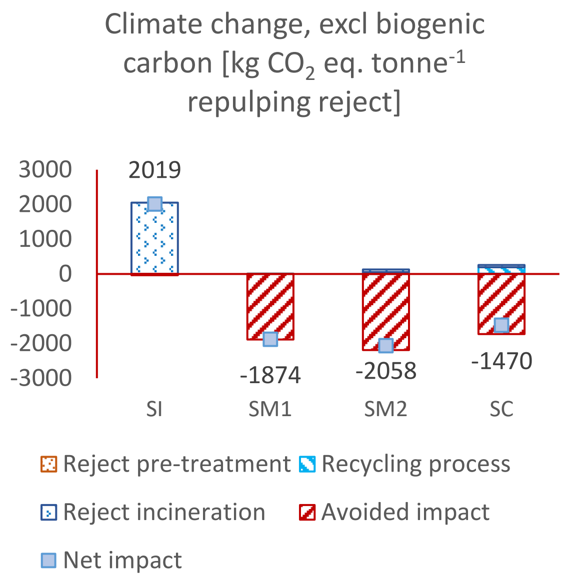
It was assumed that the data from different sources did not have a significant impact on the output of the pyrolysis process because the output of one stage of the pyrolysis from one study is almost similar to the input of the next stage of the pyrolysis process from another study.

2.7 LCIA

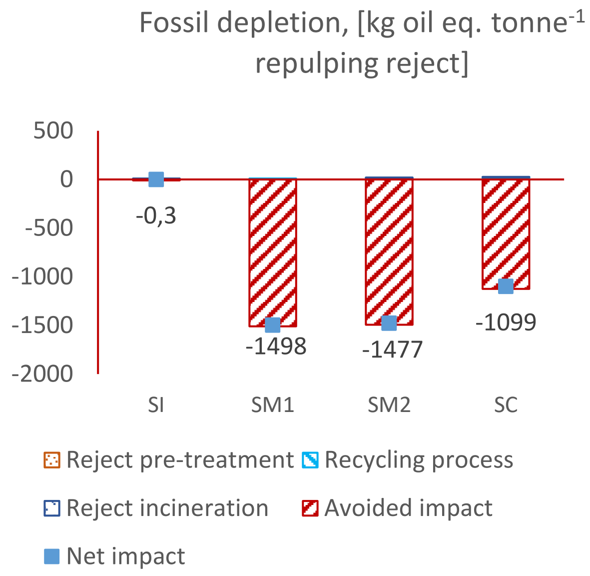
This study assessed the environmental impact using ReCiPe 2016 v1.1 (midpoint hierarchist time-frame) methods. This method is widely used in LCA studies globally (Hischier et al., 2010; Abdulkareem et al., 2021) and is included here to analyse the environmental performance associated with the treatment of repulping reject materials. ReCiPe 2016 v1.1 has 19 impact categories. It is challenging to discuss all of the impact categories; therefore, the most important impact categories were discussed in this study such as climate change (excluding biogenic carbon), fossil depletion, freshwater eutrophication, human toxicity (cancer), photochemical ozone formation (POF) (ecosystems) and terrestrial acidification. More detailed information regarding the impact assessment results, including other impact categories, such as fine particulate matter formation, freshwater consumption, freshwater ecotoxicity, freshwater eutrophication, human toxicity (non-cancer), ionising radiation, land use, marine ecotoxicity, metal depletion, stratospheric ozone depletion and terrestrial ecotoxicity, are provided in Table 2 of the supplementary material.

3 Results

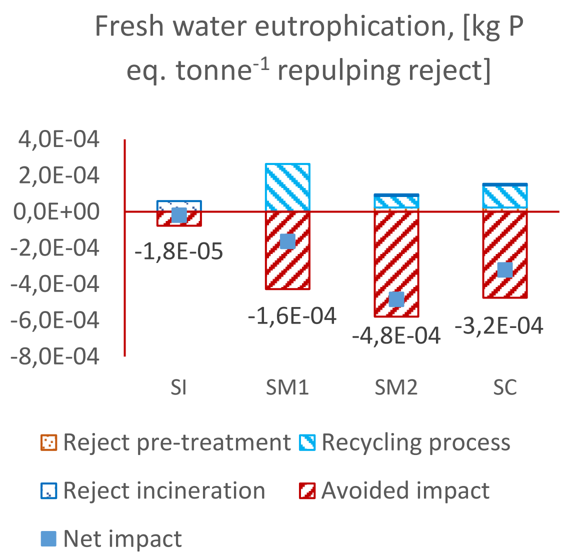
In this section, the environmental impacts of the four different treatment processes of repulping reject are compared. The results of the study are illustrated in Figure 2. The study revealed that mechanical recycling with plastic pallet production (SM 2) had a substantially lower environmental impact than the SI, SM 1 and SC scenarios in all categories, except for Fossil depletion (Figure 2 (b)) and Human toxicity (Figure 2 (d)). In these two categories, SM 1 had the lowest environmental impact. In contrast, SI had a significantly higher environmental impact compared to the other scenarios because of the incineration of the reject materials and lower avoided environmental impact. A more detailed result is presented in the supplementary materials in Table 2.

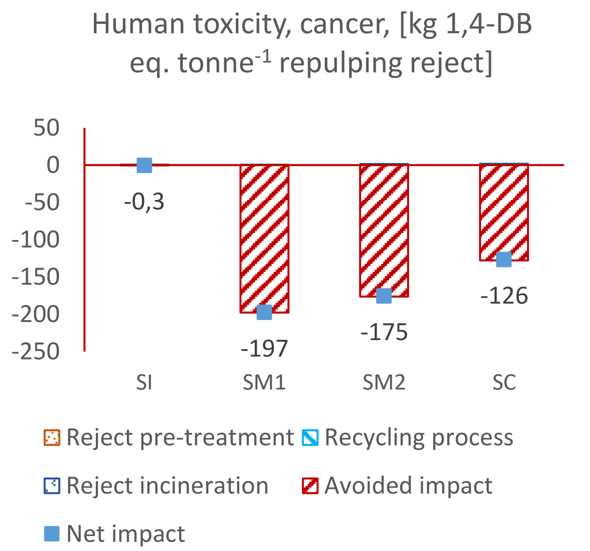

Climate change, excl biogenic carbon [kg CO_2 eq. tonne^{-1} repulping reject]
3000
2000
1000
0
-1000
-2000
-3000
2019
-1874
-2058
-1470
SI
SM1
SM2
SC
Reject pre-treatment
Recycling process
Reject incineration
Avoided impact
Net impact

(a)

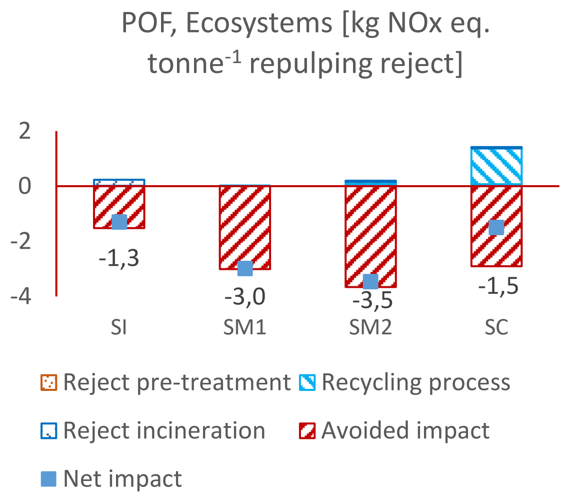

Fossil depletion, [kg oil eq. tonne^{-1} repulping reject]
500
0
-500
-1000
-1500
-2000
-0,3
-1498
-1477
-1099
SI
SM1
SM2
SC
Reject pre-treatment
Recycling process
Reject incineration
Avoided impact
Net impact

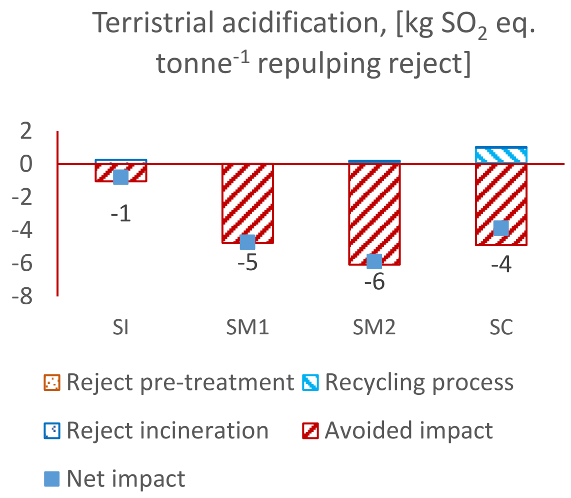
(b)


Fresh water eutrophication, [kg P eq. tonne^{-1} repulping reject]
4,0E-04
2,0E-04
0,0E+00
-2,0E-04
-4,0E-04
-6,0E-04
-8,0E-04
-1,8E-05
-1,6E-04
-4,8E-04
-3,2E-04
SI
SM1
SM2
SC
Reject pre-treatment
Recycling process
Reject incineration
Avoided impact
Net impact


Human toxicity, cancer, [kg 1,4-DB eq. tonne^{-1} repulping reject]
50
0
-50
-100
-150
-200
-250
-0,3
-197
-175
-126
SI
SM1
SM2
SC
Reject pre-treatment
Recycling process
Reject incineration
Avoided impact
Net impact

(c) (d)





(e) (f)

Figure 2. Environmental impacts from different treatment processes of repulping reject materials. Here, SI, waste incineration; SM 1, mechanical recycling with composite pallet production; SM 2, mechanical recycling with plastic pallet production; and SC, chemical recycling with plastic pallet production.

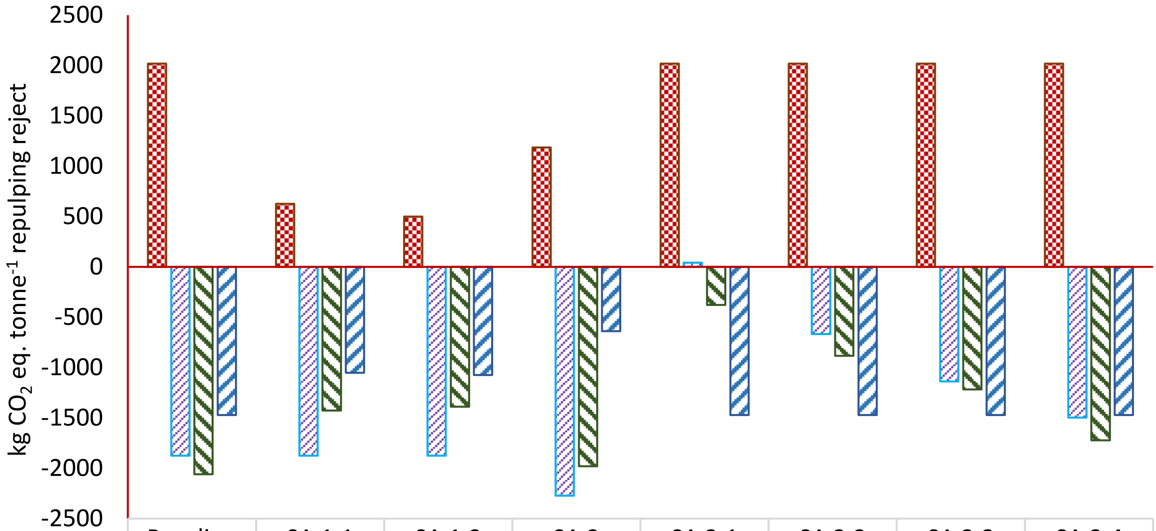
By analysing the results, it was found that substituted heat, electricity and materials significantly impacted the overall emissions of the different recovery options. The total substituted heat and electricity were 21150 MJ and 3900 MJ, respectively, in the SI scenario; 1900 MJ and 230 MJ, respectively, in the SM 2 scenario and 1700 MJ and 193 MJ, respectively, in the SC scenario. The negative value in the result was due to the avoided environmental impact of substituting energy and materials. The avoided CO_2 emissions were 32 kg CO_2 eq. tonne^{-1} repulping reject in SI, 1885 kg CO_2 eq. tonne^{-1} repulping reject in SM 1, 2187 kg CO_2 eq. tonne^{-1} repulping reject in SM 2 and 1726 kg CO_2 eq. tonne^{-1} repulping reject in SC. Scenario SM 2 had the maximum avoidance in climate change (Figure 2 (a)) due to the substitution of higher quantities of materials: 766 kg of plastic pallet and 62 kg of Al compared to the 860 kg of plastic pallet in SM 1, and 295 kg of plastic pallet and 62 kg of Al in the SC scenario. For a similar reason, SM 2 also had the lowest impact on Freshwater eutrophication (Figure 2 (c)), POF (Figure 2 (e)), and Terrestrial eutrophication (Figure 2 (f)). In contrast, SM 1 had the highest avoidance in Fossil depletion (Figure 2 (b)) and Human toxicity (Figure 2 (d)); therefore, it had the lowest impact in those categories.

The net climate change impact (Figure 2 (a)) was 2051 kg CO_2 eq. tonne^{-1} repulping reject without the avoided emissions in SI, 11 kg CO_2 eq. tonne^{-1} repulping reject in SM 1, 129 kg CO_2 eq. tonne^{-1} repulping reject in SM 2 and 256 kg CO_2 eq. tonne^{-1} repulping reject in the SC scenario. In the SI scenario, incineration of the reject materials had almost a 100% share, while 0% in SM 1, 60% in SM 2 and 23% in SC. The recycling process was responsible for 99% of the total emissions in the SM 1 scenario, 29% in SM 2 and 72% in the SC scenario.

In the SC scenario, 185 kg CO_2 eq. $tonne^{-1}$ repulping reject was generated from recycling, of which 108 kg CO_2 eq. was generated from the pyrolysis process. The emissions from the pyrolysis process were dominated by the pyrolysis of the plastic (20%), purification (20%) and thermal cracking (49%).

4 Sensitivity analysis results

The results of the sensitivity analysis are presented in **Figure 3** with three estimated aspects: (i) reject composition, (ii) virgin plastic replacement ratio and (iii) energy production mix. Climate change is one of the policy drivers that is also reflected in the waste management and energy sectors. Therefore, the discussion of the sensitivity analysis focuses on climate change impact. The details of the result can be found in supplementary materials Table 3-9. The results in **Figure 3** show that changing the plastic, fibre and Al ratio impacted the SI, SM 2 and SC scenarios. In the SI scenario, the climate change impact was lowered by reducing the plastic and increasing the fibre share because fibre incineration generates less CO_2 emissions than plastic. However, in the SM 2 and SC scenarios, the impact of climate change increased when the plastic share decreased due to the substitution of a lower amount of plastic pallet. Changing the composition in the SM 1 scenario did not impact climate change, because the total substituted amount of plastic pallet was unchanged.



	Baseline	SA 1.1	SA 1.2	SA 2	SA 3.1	SA 3.2	SA 3.3	SA 3.4
SI	2019	626	500	1186	2019	2019	2019	2019
SM1	-1874	-1874	-1874	-2272	40	-666	-1136	-1497
SM2	-2058	-1427	-1389	-1979	-379	-883	-1218	-1722
SC	-1470	-1053	-1074	-639	-1470	-1470	-1470	-1470

Figure 3. Climate change impact of different recovery options of repulping reject. Here, SI, waste incineration; SM 1, mechanical recycling with composite pallet production; SM 2, mechanical recycling with plastic pallet production; and SC, chemical recycling with plastic pallet production. Three sensitivity analyses were presented: SA 1.1 (plastic:fibre:Al = 50:39:11, SA 1.2 = 42:44:14); SA 2 (changing thermal energy and electricity source district heating and electricity production in 2017 in Finland); SA 3.1 (0% virgin plastic replacement); SA 3.2 (30% virgin plastic replacement); SA 3.3 (50% virgin plastic replacement); and SA 3.4 (80% virgin plastic replacement).

The substituted energy source significantly impacted climate change in all scenarios. In Sensitivity Analysis 2, it was found that CO_2 emissions were reduced by 41% in SI and 21% in the SM 1 scenario. In contrast, the emissions increased by 4% in SM 2 and 57% in the SC scenario. The SI scenario consumed 198 MJ of thermal energy, and the SM 1 scenario had 158 MJ of electricity and 800 MJ of thermal energy consumption. In contrast, SM 2 had 19,218 MJ of electricity and 671 MJ of thermal energy consumption; SC had 10,256 MJ of electricity and 9752 MJ of thermal energy consumption. Electricity and thermal energy were supplied from marginal sources in the baseline scenarios. Therefore, the emissions from energy consumption were not significant. In contrast, substantial emissions were generated by changing the thermal energy and electricity source from the marginal to average production mix. It is evident from Scenario Analysis 2 that mechanical recycling with composite pallet production can have the lowest environmental impact than other recovery options if the energy is supplied from average production sources.

Virgin plastic replacement also had a significant impact in the SM 1 and SM 2 scenarios. It was found that SM 1 and SM 2 had a lower environmental impact than the SC scenario only when these scenarios substituted 80% or more virgin plastic, or else SC had the lowest environmental impact. At a 50% virgin plastic replacement rate, the SM 2 and SC scenarios had almost the same environmental impact.

5 Discussion

Even though energy can be recovered by the waste incineration process, the lifespan and economic value of materials are reduced if the material is incinerated before reuse and recycling. This study found that the waste incineration of rejected materials had more environmental impact than mechanical and chemical recycling processes. It is difficult to compare the results with other literature because not many studies have analysed the environmental impact of the repulping reject. In addition, different studies have used different system boundaries, energy mixture, credit to the system, etc. Khan et al. (2021), had 1933 kg CO_2 eq. tonne^{-1} repulping reject, which was 86 kg CO_2 eq. more than the present study. This is due to differences in the plastic:fibre:Al ratio. In that study, the plastic:fibre:Al was 75:20:5, while in this study, the ratio was 79:9:12. However, in both studies, waste incineration had a more significant environmental impact than mechanical and chemical recycling processes.

Mechanical recycling is widely used for EoL of plastic products, as it transforms plastic into new products. Even though this recycling process has not reached its full potential, it is a useful method for recycling a single polymer, such as LDPE or HDPE. However, this recycling method is ineffective for multilayer plastics, such as multilayer food packaging waste. Mechanical recycling usually produces mediocre products from mixed plastic waste. As a result, it has become a critical issue in the LCA sector to deal with reduced plastic quality when comparing the EoL impacts fairly. This study assumes that plastic pallets from mechanically recycled plastic could replace 100%-virgin plastic pallets. Perhaps this is not always true; therefore, a sensitivity analysis was performed to show the environmental impact with different virgin plastic replacement ratios. However, this assumption depends to a large extent on the market, which will likely to differ over time and in different locations. Furthermore, it also depends on technological development. A 100% virgin plastic replacement would be possible if the separation efficiency reached 100%. The quality of mechanically recycled plastic can be improved over time due to steering for more recycled content in plastic products.

The environmental and economic impact largely depends on the yield of the chemical recycling process, and the yield depends on the quality of the plastic waste. Any impurities or mix of different types of plastic reduces the yield ratio (Ragaert et al., 2017; Selina et al., 2021). Chemically recycled plastic can replace virgin plastic (BASF, 2020). However, this is an energy-intensive process that may render it unsuitable as a sustainable process. Even though by-products such as char and gas can be used for energy, this does not make it a net-energy positive process (Rollinson, 2018). Due to the high energy consumption, chemical recycling is considered a low-value recycling process compared to mechanical recycling (Tabrizi et al., 2020).

By analysing the study, it was found that energy sources significantly impact the life cycle of the repulping reject. Renewable energy sources have lower emissions than fossil sources. Consequently, any product that uses renewable energy in the process has a lower environmental impact than fossil energy. Similarly, when renewable energy is substituted, the product obtains lower credit than when substituting fossil energy. This study showed that SM 2 had a lower impact compared to SM 1, even though it consumed more energy than SM 1 because the energy was consumed from renewable sources and had more avoided impact by substituting Al and plastic pallets than SM 1. In contrast, SM 1 had a better environmental impact than SM 2 when fossil energy was consumed in the process, even though the avoided amount of plastic pallets and Al was unchanged.

In summary, waste incineration should be the last option for repulping reject because it has a higher environmental impact than the chemical and mechanical recycling processes. Composite production could be a better option if energy is sourced from the average production mix. However, composite pallet production from repulping reject could not be considered as a proper closed loop recycling. Separating plastic, Al, and fibre is technically challenging at the EoL stage of the composite materials. So far, the most feasible way to treat composite material waste is to incinerate it in the waste incineration plant. Therefore, the materials in the composite do not circulate in the system for a long time. On the contrary, recycled plastic pallet production by mechanical recycling and chemical recycling close the loop because, in those recycling processes, the same plastic can be recycled several times.

Plastic pallet production from repulping reject by mechanical recycling could be a better option when the energy is supplied from renewable sources. Chemical recycling could be environmentally friendlier than mechanical recycling if mechanically recycled products can not substitute more than 50% of virgin plastic. However, more research should be done on chemical recycling to minimise energy consumption and increase the yield ratio. The mechanical and chemical recycling processes should be used to complement each other rather than as replacements. It could be possible to recycle more plastic in a more environmentally friendly way by using both processes. However, technological advancement and investment are required to gain the maximum benefit from both mechanical and chemical recycling processes.

6 Conclusion

This study investigated the environmental impact of the recovery options of the rejected materials from the liquid packaging board waste treatment process using the consequential life cycle assessment method. Four scenarios were established: waste incineration, mechanical recycling with composite pallet production, mechanical recycling with plastic pallet production and chemical recycling with plastic pallet production. Nevertheless, three areas of sensitivity were also investigated in this study.

The results of this study showed that mechanical recycling with plastic pallet production had the lowest environmental impact and waste incineration had the highest impact. The avoided impact of substituting materials and energy played a significant role in the environmental impact of the recovery options. In addition to energy sources, the virgin plastic replacement ratio also played an influential role in the study results, which was revealed by conducting a sensitivity analysis. It was found that mechanical recycling with composite pallet production had a 13% lower environmental impact than mechanical recycling with plastic pallet production when the energy consumed was sourced from the average production mix. In addition, chemical recycling showed the lowest impact when the mechanical recycling processes (including mechanical recycling with composite pallet and mechanical recycling with plastic pallet) substituted 0%, 30% and 50% of virgin plastic.

Author contributions

Conceptualization, M.K., J.H., A.N., V.L., M.H.; methodology, M.K.,. and J.H.; data analysis, M.K. and J.H.; writing—original draft preparation, M.K.; writing—review and editing, J.H., V.L., M.H.; visualization, M.K.; supervision, J.H., and M.H.; funding acquisition, M.H.

Acknowledgements

This study was conducted under the PLASTin - All-in for Plastics Recycling project (8907/31/2019). Funding for the project was received from Business Finland.

References

Abdulkareem, M., Havukainen, J., Nuortila-Jokinen, J., Horttanainen, M., 2021. Environmental and economic perspective of waste-derived activators on alkali-activated mortars. J. Clean. Prod. 280. https://doi.org/10.1016/j.jclepro.2020.124651

ACE, 2021. Taking Up the Challenge: The Beverage Carton Industry Drives Transformation for Sustainable Packaging [WWW Document]. URL https://www.euractiv.com/section/energy-environment/opinion/taking-up-the-challenge-the-beverage-carton-industry-drives-transformation-for-sustainable-packaging/ (accessed 10.29.21).

ACE, 2020. Home - Beverage Carton [WWW Document]. URL https://www.beveragecarton.eu/ (accessed 10.27.21).

BASF, 2020. Evaluation of pyrolysis with LCA - Critical Review statement.

Bisinella, V., Albizzati, P., Astrup, T., Damgaard, A., 2018. Life Cycle Assessment of management options for beverage packaging waste, Danish Ministry of Environment and Food.

Cellura, M., Longo, S., Mistretta, M., 2011. Sensitivity analysis to quantify uncertainty in Life Cycle Assessment: The case study of an Italian tile. Renew. Sustain. Energy Rev. 15, 4697–4705. https://doi.org/10.1016/j.rser.2011.07.082

EN ISO 14044:2006, 2006. Environmental Management-Life Cycle Assessment-Principles and Framework Management Environmental.

Georgiopoulou, I., Pappa, G.D., Vouyiouka, S.N., Magoulas, K., 2021. Recycling of post-consumer multilayer Tetra Pak® packaging with the Selective Dissolution-Precipitation process. Resour. Conserv. Recycl. 165, 105268. https://doi.org/10.1016/j.resconrec.2020.105268

get recycling, 2021. Plastic Dewatering Machine for PP/PE Film Manufacturers - Best Price & Low Cost Plastic Dryer for Sale - GET RECYCLING [WWW Document]. URL http://www.getrecyclingtech.com/plastic-dryer/plastic-dewatering-machine-for-pp-pe-fil.html (accessed 11.23.21).

Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M., Nemecek, T., 2010. Implementation of Life Cycle Impact Assessment Methods Data v2.2 (2010), ecoinvent Report No. 3.

Horttanainen, M., Liikanen, M., Havukainen, J., Deviatkin, I., 2020. Sustainable Solid Waste Management Using Life Cycle Modeling for Environmental Impact Assessment. IOS Press, pp. 16–33. https://doi.org/10.3233/FAIA200003

ISO, 2006. ISO 14040:2006(en), Environmental management — Life cycle assessment — Principles and framework [WWW Document]. URL https://www.iso.org/obp/ui/#iso:std:37456:en (accessed 3.11.19).

Jamradloedluk, J., Lertsatitthanakorn, C., 2014. Characterization and Utilization of Char Derived from Fast Pyrolysis of Plastic Wastes. Procedia Eng. 69, 1437–1442. https://doi.org/10.1016/J.PROENG.2014.03.139

Jeswani, H., Krüger, C., Russ, M., Horlacher, M., Antony, F., Hann, S., Azapagic, A., 2021. Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. Sci. Total Environ. 769, 144483. https://doi.org/10.1016/j.scitotenv.2020.144483

Joosten, L.A.., Worrell, E., Turkenburg, W.C., 2001. Energy and CO2 analysis of the Western European plastics 61–126.

Julie, 2019. Why Recycling Plastic Doesn't Solve Plastic Pollution [WWW Document]. URL https://darkbluejournal.com/why-recycling-plastic-doesnt-solve-plastic-pollution/ (accessed 6.17.21).

Junnila, S., Horvath, A., 2003. Environmental Sensitivity Analysis of the Life-cycle of an Office Building. Proceeding Integr. Lifetime Eng. Build. Civ. Infrastructures, ILCDES 2003 215–220.

Khan, M.M.H., Deviatkin, I., Havukainen, J., Horttanainen, M., 2021a. Environmental impacts of wooden, plastic, and wood-polymer composite pallet: a life cycle assessment approach. Int. J. Life Cycle Assess. 26, 1607–1622. https://doi.org/10.1007/s11367-021-01953-7

Khan, M.M.H., Laitinen, V., Havukainen, J., Horttanainen, M., 2021b. Carbon footprint of different recovery options for the repulping reject from liquid packaging board waste treatment process. Waste Manag. 136, 93–103. https://doi.org/10.1016/j.wasman.2021.10.003

Kumar, S., Singh, R.K., 2011. Recovery of hydrocarbon liquid from waste high density polyethylene by thermal pyrolysis. Brazilian J. Chem. Eng. 28, 659–667. https://doi.org/10.1590/S0104-66322011000400011

Lahme, V., Daniel, R., Marsh, P., Molteno, S., 2020. Recycling of multilayer composite packaging: the beverage carton.

Ministry of Employment and the Economy, 2017. Background report on the national energy and climate strategy until 2030.

Pöyry, 2012. A report on the energy use of waste and emissions trading.

Ragaert, K., Delva, L., Van Geem, K., 2017. Mechanical and chemical recycling of solid plastic waste. Waste Manag. 69, 24–58. https://doi.org/10.1016/j.wasman.2017.07.044

Reimann, D.O., 2012. CEWEP Energy Report III.

Robertson, G.L., 2021. Recycling of aseptic beverage cartons: A review. Recycling 6. https://doi.org/10.3390/RECYCLING6010020

Rollinson, A.N., 2018. Fire, explosion and chemical toxicity hazards of gasification energy from waste. J. Loss Prev. Process Ind. 54, 273–280. https://doi.org/10.1016/J.JLP.2018.04.010

Ruttenborg, V., 2017. Life Cycle Assessment of fresh dairy packaging at ELOPAK. Norwegian University of Science and Technology.

Selina, M., Markus, B., Daniel, S., Renato, S., 2021. Wet-mechanical processing of a plastic-rich two-dimensional-fraction from mixed wastes for chemical recycling. Waste Manag. Res. 39, 731–743. https://doi.org/10.1177/0734242X21996435

Sharuddin, S.D.A., Abnisa, F., Daud, W.M.A.W., Aroua, M.K., 2018. Pyrolysis of plastic waste for liquid fuel production as prospective energy resource. IOP Conf. Ser. Mater. Sci. Eng. 334. https://doi.org/10.1088/1757-899X/334/1/012001

SKM Market Predictor, 2019. Scenario calculations for electricity generation until 2050.

Suojansalo, R., 2020. Waste utilization in energy production.

Tabrizi, S., Rollinson, A.N., Hoffmann, M., Favoino, E., 2020. Understanding the

Environmental Impacts of Chemical Recycling Ten concerns with existing life cycle assessments. Zero Waste Eur.

Verghese, K., Lockrey, S., Clune, S., Sivaraman, D., 2012. Life cycle assessment (LCA) of food and beverage packaging. Emerg. Food Packag. Technol. Princ. Pract. https://doi.org/10.1016/B978-1-84569-809-6.50019-1

Wei, W., Larrey-Lassalle, P., Faure, T., Dumoulin, N., Roux, P., Mathias, J.-D., 2015. How to conduct a proper sensitivity analysis in life cycle assessment: taking into account correlations within LCI data and interactions within the LCA calculation model. Environ. Sci. Technol. 49, 377–85. https://doi.org/10.1021/es502128k