Life Cycle Assessment of Take-Away Food Containers

An Analysis of Dry Moulding Compared to Traditional Methods

Master's thesis in Industrial Ecology

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Cover:
In order: A dry moulded bowl, a wet moulded bowl, and a plastic bowl. Printed with permission from The Loop Factory.

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SUMMARY

Packaging is a vital part of everyday life, and its wide-spread global use has led to concerns about the environmental impact it can cause. Regulations appearing as a result of these concerns are fuelling the exploration of new packaging technology which reduces the environmental impact. The aim of this study was to explore sustainability efforts occurring in companies working with the Loop Factory with regards to the packaging they use and to conduct a life cycle assessment (LCA) on dry moulded packaging technology being developed by The Loop Factory in comparison to other alternatives in order to assess the environmental impact of the technologies. The packaging application in this study was food takeaway trays. The life cycle assessment conducted was a cradle-to-grave study of dry moulded, wet moulded, and polypropylene food trays. The results of customer interviews show an increased pressure on companies to design and produce packaging with a minimized environmental impact. The results of the LCA list impacts for global warming, acidification, eutrophication, abiotic resource use, and cumulative energy demand. Also shown is a sensitivity analysis for a range of recycling rates, as well as a sensitivity analysis which added a wet moulded tray which was produced in Europe, as the original wet moulded tray shown in the results is made in China, The results of the life cycle assessment show a favourable performance for dry moulded trays in many cases, though particular attention must be paid to the use of different energy systems used when attempting to compare the results, as the wet moulded trays are produced in China, while the rest of the trays are produced in Europe. Sensitivity analysis varying the recycling rate and production location showed the change in the results possible with different choices and allowed for better comparison between the trays. The results emphasize the importance of disclosing modelling choices and transparency when using life cycle assessment. When choosing packaging in the future, users will need to weigh the importance of different environmental impact categories, material choices, and end-of-life treatment in order to decide the best option for packaging.

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Keywords: life cycle assessment, moulded pulp, packaging, sustainability

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Preface

This master thesis of 30 ECTS is carried out as a part of the Master of Science program Industrial Ecology at Chalmers University of Technology. It has been conducted during the spring of 2021 at the Division of Environmental Systems Analysis at the Department of Technology Management and Economics.

This thesis has been completed in collaboration with The Loop Factory, and I would like to thank Maria Englander and Anna Altner for their time and guidance throughout this project, as well as everyone else at The Loop Factory, who have offered their continued help and encouragement throughout the thesis. I would also like to give thanks to my examiner, Magdalena Svanström, for taking on this project, and my supervisor, Frida Hermansson, for her endless advice and valuable discussions throughout this project.

Finally, I would like to thank my family and friends for their constant support and encouragement throughout my time at Chalmers.

Amanda Svensson

Gothenburg, June 2021

Abbreviations

CFCs	Chlorofluorocarbons
CO_2	Carbon Dioxide
DM	Dry Moulded
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LHV	Lower Heating Value
NO_x	Nitrogen Oxides
PBAT	Polybutylene Adipate Terephthalate
PCL	Polycaprolactone
PFAS	Polyfluoroalkyl Substances
PHA	Polyhydroxyalkanoate
PLA	Polylactic Acid
PP	Polypropylene
SO_2	Sulphur Dioxide
SUP	Single Use Plastics Directive
WM	Wet Moulded

1 Introduction

Packaging is one of many industries trending toward more sustainable processes and materials. There is a need to transition to packaging products with a lower environmental impact, due to concerns with issues like plastic entering the oceans and the climate impact of fossil-based production (Material Economics, 2018). This is significant because in Europe, the packaging industry accounted for the largest demand for plastic in industry in 2015 at about 40% (Plastics Europe, 2019).

The packaging industry is involved in endless aspects of everyday life. Whether it is ordering goods, buying food, or any other number of things, where there are products there is packaging. This integral part of our lives has led to issues of waste and environmental impact. Plastic packaging, which makes up 26% of the total volume of plastic used, is particularly cited as an issue (Ellen MacArthur Foundation, 2016). The rate of recycling of plastic packaging is far below that of others like paperboard, approximately 40% of plastic compared to 80% of paperboard in European systems (Feber et al., 2020). Additionally, the Ellen MacArthur Foundation (2016) found that in 2013, only 2% of recycled plastic was in a closed loop system, where plastics are recycled into products of similar quality. Among the rest of the plastic waste flow, Ellen MacArthur (2016) found that 72% of plastic packaging was not collected for any kind of recovery, instead going to landfill, or not being collected in any formal way. Additionally, degradation of plastic in the recycling process often makes it difficult to recycle many plastics to their original use, like with food grade plastic packaging, and this varies with the type of plastic used (Brouwer et al., 2020). It is systems like this that lead to continued fossil resource extraction, which contributes to emission of greenhouse gases, and lead to degradation of the environment like the oceans. Despite these issues, the benefits that plastic packaging provides, like its highly customizable shape and the ability to extend food shelf life, and as a result reduce the food waste and environmental impact, are still needed, as packaging itself is a growing industry and these capabilities are still sought after.

In an attempt to curb the issue of most plastic not being recovered at the end-of-life, and instead generating large amounts of waste, policies which limit the use of plastics are being introduced globally (Feber et al, 2020). The Single Use Plastics (SUP) Directive was approved in the EU in May of 2019, and it targets certain products made of or containing plastic (including bio-based and biodegradable plastic) which are produced with the intention of only using them once (Directive 2019/904). Products with alternatives to plastic available, such as cutlery, straws, and plates will be banned from the market by mid-2021 (Copello de Souza, 2019). For products with fewer alternatives available, like food containers, the SUP Directive requires countries to greatly reduce consumption of these products (Copello de Souza, 2019). This legislation also requires the creation of extended producer responsibility schemes for collecting and properly treating waste and raising awareness for the problems associated with single use plastics as well as alternative options (Copello de Souza, 2019).

Aside from single use plastics, packaging in general is a large source of waste. The Packaging and Packaging Waste Directive was established in the EU in 1994, with the latest amendment coming in 2018, and lays out requirements for member states to prevent packaging waste and minimize the environmental impact of packaging, regardless of the material it is made from (Directive 94/62/EC, Directive 2018/852). Recycling targets for the collection of packaging waste were established, with 70% of all packaging waste required to be recycled by December of 2030 (Directive 2018/852). Other rules created in this directive include minimizing the amount of material and hazardous substances and designing for reuse and recovery of the packaging (Directive 94/62/EC). Like the SUP Directive, this legislation requires the creation of producer responsibility schemes which seek to incentivize production of packaging that can be reused or recycled to a high quality in order to minimize environmental impacts (Directive 94/62/EC).

The EU directives incentivize the use of materials other than plastics. From raw materials, production methods, and waste management, all parts of the packaging life cycle can contribute to sustainability and environmental impact improvements. Being sourced from renewable materials and having a much higher rate of recovery, fibre-based packaging can come in as an alternative material for these purposes (Feber et al., 2020). One type of fibre-based packaging is moulded pulp, which is pressed into a 3D shape to be used for holding and protecting its contents (Didone et al., 2017). There are different methods of moulding fibres into packaging. Dry moulding is a method created in recent years by which pulp is broken into fibres, laid into a mat with the use of air, and pressed into a shape for use as packaging (PulPac, 2021). Wet moulding is a process dating back to the 1960s, which combines pulp with water to create a slurry, which is then formed into packaging with a vacuum and dried (Didone et al., 2017). Compared to traditional wet fibre moulding, dry moulding has been seen to require less resources and can be completed in faster cycle times (The Loop Factory, 2020).

The company initiating this thesis is The Loop Factory, a Swedish company who are pioneering a fibre-based dry forming technology known as Yangi to be used as 3D-shaped packaging. They seek to explore the drivers for sustainable packaging in companies that they are collaborating with and assess the environmental impact of their packaging product technology. Through interviews with these collaborating companies, it can be better understood what is motivating their sustainability choices regarding packaging and what their current efforts and future plans are. The environmental impact of The Loop Factory's dry moulding technology will be assessed using life cycle assessment (LCA) on a food tray, and the scope of the LCA will include a comparison to food trays made from more established methods of wet moulding and plastic thermoforming. Using the results of the communications and the LCA, The Loop Factory's packaging technology can be further developed and contribute to the efforts to reduce the use of plastic in packaging.

The research area of this LCA, takeaway food packaging, with particular focus on moulded pulp, is largely unexplored. A life cycle assessment was completed by Huo and Saito (2009), which explored wet moulded production systems in China. Didone et al. (2017) explored the manufacturing processes for moulded pulp technology available at the time, though they do not include an environmental impact assessment, and they note the need for future LCA studies of moulded pulp products. The study makes no mention of dry moulded technology. Hermansson (2013) performed an LCA study of bio-composites containing cellulose pulp and polymer, which were then made into products using compression moulding. The study showed that overall, the bio-composites which contained a smaller portion of polymer input resulted in a lower environmental impact, but it did not include a purely cellulose-based product. Gallego-Schmid et al. (2019) performed what is thought to be the first LCA comparing takeaway food packaging, though this study did not include fibre-based packaging in the scope. Schenker et al. (2021) present a simplified LCA on cellulose and plastic packaging, which explored dry moulded pulp technology in background information, but did not present results which included dry moulded packaging specifically. It was found that cellulose fibre-based packages resulted in a lower climate change impact compared to plastic when similar packaging weights were used. There is an expectation seen from these studies where fibre-based packaging performs better in terms of environmental impact over plastic. To the knowledge of the author, an LCA study exploring this area which includes dry moulding has not previously been completed. This report seeks to fill the gap of life cycle assessment for fibre-based takeaway packaging, specifically for dry moulding, and show the comparison between different options of food packaging.

2 Background

This thesis will focus on dry moulded fibre packaging being used as food trays compared to established methods of wet moulding as well as plastic packaging. There is a push in legislation to reduce plastic consumption and increase recycling rates of packaging (Copello de Souza, 2019; Directive 2018/852), and as a result of the regulations, alternatives to plastic containers are becoming increasingly sought after (Feber et al., 2020).

2.1 Research Questions

Based on the aims of the study and the requirements for producing food trays, the specific questions to be answered in this study include:

- What are the drivers of sustainability in packaging according to collaborators of The Loop Factory, and what are their plans for addressing environmental concerns regarding their packaging in the future?
- What is the environmental impact of the packaging product produced using the Loop Factory´s dry moulding technology, with regards to different barriers needed for use as food trays, and how does it compare to established alternatives?

2.2 Technology description

Food packaging is commonly made from materials like metal, paper, glass, and polymers (Berk, 2018). Polymers take a large segment of this due to their versatile properties suitable for a wide range of applications. This LCA will include the use of plastic, wet moulded (WM) and dry moulded (DM) trays.

The plastic tray in this assessment is made of polypropylene (PP), which is sourced from fossil fuels, and utilizes a process called thermoforming, where a polymer sheet is formed to fit a certain shape (Throne, 2017). However, plastic has been criticized for many years due to the single-use nature and low recycling rate of much plastic packaging, which has contributed to the issue of plastic waste and environmental problems (Feber et al., 2020). Though plastic is still widely used for packaging, many companies are turning to other options like fibre-based packaging (Feber et al., 2020).

One long used fibre-based packaging option for food is wet moulded packaging. The fibres used in moulded pulp processes are made up of cellulose (Didone et al., 2017). These products can be used for many applications, including egg cartons, food trays and bowls, and industrial packaging for the protection of products (Didone et al., 2017). The cellulose fibre used in the wet moulded process in this LCA comes from bagasse, a byproduct of sugar production (Nikodinovic-Runic et al., 2013). In wet moulded packaging, a pulp is created using plant-based raw materials and water, and in the case of this LCA, moulding and drying the product to the desired shape using thermoforming (Didone et al., 2017). Barrier chemicals are added and dispersed into the pulp for the protection of food in the container (Fogg, 2020). In wet moulding, one common type of barrier chemicals are polyfluoroalkyl substances (PFAS). These have been criticized and scrutinized due to their ability to accumulate in the human body and cause adverse health effects (United States Environmental Protection Agency [EPA], 2021).

Yangi is a technology for dry moulding fibres to create shaped packaging. Dry moulded fibre packaging is made in a relatively recently created process which utilizes the water within the cellulose raw material itself to create a rigid package (The Loop Factory, 2020). Pulp moulding involves connecting fibres using hydrogen bonding to create strength (Didone et al., 2017). Wet moulded processes achieve this with the addition of water, used to dissolve fibres and create a consistent mould formation, while dry moulding relies on a small amount a water to create these bonds, with air being used to evenly distribute fibres (The Loop Factory, 2020). This means that using dry moulding instead of wet moulding requires less water resources and energy use from drying than wet moulding requires, leading to an expected advantage in terms of environmental impact. Dry moulded products use airlaid formation, where an air stream separates dry pulp fibres and conveys them to form a fibre network, which is then pressed, and finally shaped into a 3D product using a mould (Wagner, J.R., 2009). The cellulose fibre used in The Loop Factory dry moulded process comes from softwood kraft pulp (The Loop Factory, 2020). For use in food applications, barrier addition is needed. These create protection from things like oxygen, water, and fats in order to ensure that the package does not break down and ensures that contents inside do not spoil. There exist standards for testing the rates of oxygen, water vapor, and other chemicals permeation through barriers in order to ensure an acceptably low transmission for protection of food (Sangroniz et al., 2019). These can come in multiple forms, including polymer-based laminates which are added to the surface of the package, or chemical additives incorporated into the packaging material (Galić, 2015). Dry moulded packaging can achieve a performance to match that of wet moulded, and the push for sustainable packaging solutions makes it an appealing alternative.

Though much fibre-based packaging for food is single use, in the EU, the recycling rate of paper and paperboard packaging consistently has the highest recycling rate of the different types of packaging (Eurostat, 2021a). Additionally, the cellulose fibre used in moulded pulp packaging comes from renewable sources rather than fossil-based ones and can be used in many of the same functions as their plastic counterparts. As a result, fibre-based packaging offers many benefits over plastic. There may be concern when sourcing pulp from locations with weak environmental regulations, where issues of land occupation and biodiversity loss might cause problems. Ensuring proper planning of the pulp source cultivation will be important for minimizing these impacts.

2.3 The Life Cycle Assessment Procedure

Life cycle assessment is a method used to evaluate the environmental impacts of a product or process over its life cycle. The methodology for LCA has been standardized and follows specific steps (International Organization for Standardization [ISO], 2006a, 2006b). The process is iterative, with interpretation and possible iteration and modification occurring after each step as data is collected, as represented in Figure 1 by arrows going in both directions. The specific details of the LCA in this project can be found in the Methodology section 3.

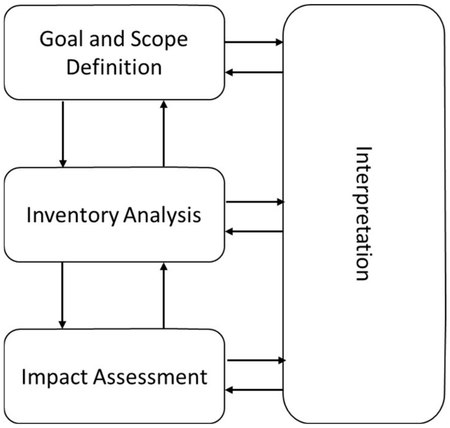

Figure 1 A visual representation of the LCA framework adapted from Baumann & Tillman (2004)

The goal and scope definition is the first step of an LCA**.** According to the ISO standard, the goal definition of an LCA must state the intended application, reason for carrying out the study, and the intended audience (ISO, 2006a). Baumann and Tillman (2004) explain that the scope of the study consists of decisions that must be made about the modelling. This includes the specific products or processes, which must be able to be compared using the same reference. The functional unit is a reference value to which all other material and energy flows are related. Also in the scope, the system boundaries, including geographical, technical, and time are set. The method for allocating the impacts to processes which have multiple inputs or outputs are all chosen as well.

The **inventory analysis** is usually the longest step and consists mainly of gathering data on the processes being studied. Both quantitative and qualitative data are needed to understand and examine the life cycles. Having direct access to information on the processes is the most convenient way to gather data, but this is not always possible, especially when it comes to up and downstream processes that the LCA practitioner does not have easy access to, and this requires other sources to be consulted. Typical data gathered includes inputs of raw materials, energy, and process chemicals, outputs of the product and by-products, emissions to air and water, and waste (Baumann & Tillman, 2004).

When modelling processes, there are often cases where multiple inputs or outputs appear. The ISO standard states that when this is the case the product system should be divided into sub-processes and more specific inventory data should be collected, or the product system should be expanded to include co-products (ISO, 2006b). When it is not possible to apply these methods, allocation is used to partition the environmental impact into the different products (Baumann & Tillman, 2004). There are different methods of allocation, including physical and economic allocation. The ISO standard 14044:2006 specifies that physical allocation should be preferred before economic allocation (ISO, 2006b). Physical allocation bases the partitioning on the mass or other physical property of each product, while economic allocation bases partitioning on the cost of each product (Bhatia et al., 2011). Despite the ISO standard preference for physical allocation, economic is commonly used, as the value of the products in a process can be seen as the main driver for the process (Ardente & Cellura, 2012).

When recycling is used for end-of-life treatment of a product, allocation needs to be done to distribute the environmental impacts of the recycling process. It must be determined how to include the process within the system boundary, and whether it should appear in the first or second product, or some combination of both (Allacker et al., 2017). Multiple formulas for determining this allocation exist, with guidelines coming from sources like The Greenhouse Gas Protocol and British Standards Institution, which present different formulas for this purpose, the choice of which depends on factors like how recycled material is used in the product system, and the lifetime of the product (British Standards Institution [BSI], 2011; Bhatia et al., 2011).

The **impact assessment** seeks to communicate the results of the inventory analysis and compare the environmental impacts of the products studied. This is done by taking the numerical values of the inputs in outputs from the inventory analysis and calculating in order to present them in terms of different environmental impacts. There are different methods of calculating the impact assessment, the choice of which may depend on the geographical scope of the study or the impacts that are to be reported. Some methods have been developed based on regional data, and as a result are better to be used for certain areas while others may be used globally. Some methods report more aggregated data, while others are more detailed. The choice depends on the wishes of the LCA commissioner.

Once the impact assessment method is chosen, the impact categories should be decided. According to Baumann and Tillman (2004), they are chosen according to relevance to a system, as certain emissions contribute to some impacts, but not others. Midpoint categories connect inventory data to different impact categories. These may be further aggregated into endpoint categories of resource use, ecological consequences, and human health, in order to look at the overall effects that may occur due to a product system (Baumann & Tillman, 2004). These are generally easier for non-experts to understand; however, the lack of detail means that the causes for the size of the impact are not shown. In this study, midpoint categories will be used in order to present results in detail for multiple environmental impacts and identify trade-offs between processes.

2.4 Prospective LCA

This study uses a future perspective in order to examine the Yangi dry moulding technology when it is expected to be fully developed, and as such, this LCA will have a prospective view. As the dry forming technology is still in development, it has been scaled to the future, about ten years ahead to 2030, when it is expected to be fully scaled to the point where it can compete with the production capabilities of the alternatives. This will allow for an analysis truer to the intended production using the technology.

A prospective LCA is one which differs from the more traditional LCA that looks at a product in a retrospective way. The definition of this method varies somewhat among authors. Cucurachi et al. (2018) defines ex-ante LCA as a study that assesses the scaling-up of a technology in development or compares "the emerged technology at scale with the evolved incumbent technology" (p. 464). Arvidsson et al. (2018) states that a prospective LCA "refers to studies of emerging technologies in early development stages, when there are still opportunities to use environmental guidance for major alterations" (p. 1287). One reason for conducting a prospective LCA has to do with the Collingridge dilemma, which states that there is much freedom to change a technology in the beginning of its development, while at the same time, knowledge of the technology is limited. As development occurs, the freedom to modify the technology decreases as the design is established, the technology diffuses, and costs to change parameters increase (Collingridge, 1980). Therefore, applying prospective LCA when a product is still in development can be helpful in decision making when it is relatively easier to implement changes. In this case, the LCA is comparing packaging made using the emerging dry moulding technology to packaging made using the incumbent technologies of plastic and wet moulding. By doing so, it is possible to determine differences in environmental impact and find any possible areas of concern in the life cycle of the wet moulding technology.

In prospective LCA, the system or product in development may be modelled in comparison to alternative incumbent technologies, which in the present time fulfill the purpose or purposes that the new technology seeks to cover. In order to be able to properly compare the emerging technology to the incumbent, it is necessary to scale the technology to a point in the future where it has been developed and is in production (Arvidsson et al., 2018). To do so, the foreground and background systems of the product must both be modelled at the same point in the future. The foreground system of the new technology consists of those parts that the decision makers can directly control. These include the parameters of the process and product itself like material inputs and location of production. The background system is that which the decision makers cannot directly affect, for example, the electricity mix (Buyle et al., 2018). Scenarios can then be used to explore possible futures by changing different parameters in the product systems. Sources of data for a prospective LCA may include expert opinions, experimental data, scientific articles, and models of the process (Arvidsson et al., 2018). One must examine both the foreground and background systems in the same future period, as well as the incumbent technology, which may have changed (Cucurachi et al., 2018).

3 Methodology

The methodology of this study is divided into two sections. The first explains the interviews held with The Loop Factory customers, and the second part details the specifics of the life cycle assessment performed. Based on the customer interviews and their views on future packaging expectations, different future possibilities will be examined.

3.1 Communication with Customers

An investigation of customer efforts surrounding their packaging has been done in order to gain an understanding of the motivators behind them. These are customers involved with collaborating on the development of the Yangi technology with The Loop Factory who were willing to have a discussion on these topics. Staying in compliance of regulations is vital for companies and brands, so this examination seeks to understand trends in packaging in terms of materials being used, end-of-life goals and expectations of future legislation. Discussions were held, asking questions regarding their customer requests, impact of regulations, and future efforts for packaging sustainability:

- What are drivers for your sustainability needs?
- What are customers asking for? Has there been a change in their requests as new legislation is approved?
- What regulations have you found to be most impactful in your sustainability efforts, and how have they influenced the direction of your environmental efforts?
- What direction do you see your efforts going in the future in terms of your packaging?

Two customers, who will not be named, were interviewed. The customers are in different markets, with Customer A being a food packaging supplier, and Customer B being a luxury retail brand. As they are in very different sectors, it was interesting to explore the similarities and differences in their sustainability perspectives. Both were interested in the LCA, as they want to learn about the environmental impact of dry moulded trays made with Yangi technology. Due to time constraints and availability, only two companies were included in However, in the future, being able to interview more companies using packaging in other markets would be valuable for greater understanding. Using the above questions, information could be gathered on what materials and packaging technologies were of interest to explore for the comparison in the LCA. It was also possible to gather information on parts of packaging life cycles that were of interest to these companies and therefore worth highlighting in the LCA. The interview results were used to guide the LCA in terms of the methodological choices that were made, and the sensitivity analyses were completed, see Section 4.1.

3.2 Life Cycle Assessment

This section details the specifics of the choices made when completing the LCA for the food trays being studied.

3.2.1 The Goal Definition

In this LCA, the goal is to assess the environmental impact of The Loop Factory’s dry moulded fibre packaging made using Yangi technology for use as a food tray. This technology will be compared to polypropylene and wet moulded trays in order to understand the differences in environmental performance over the life cycle of the products. The wet-moulded and polypropylene modelling choices are based on actual production being completed by Customer A. The results of this study may be used to support decisions on the future development of the dry moulded packaging. The intended audience includes The Loop Factory, and those who are interested in developments in packaging technology.

3.2.2 Scope and Modelling

The specific alternatives to be studied are dry moulded, wet moulded, and polypropylene plastic food trays. Different barriers have been modelled with the dry moulded tray, including two laminate barriers and one chemical, the details of which can be found in the Product Systems Section 4.

3.2.2.1 Functional Unit

The functional unit has been chosen as one 900 mL food tray. Each of the trays is considered to be single use. With this reference, the trays of different materials can be compared, as they are expected to perform the same function. The volumetric functional unit accounts for the fact that the trays have different masses. The data in the inventory analysis and the impact assessment are presented using this functional unit as a basis. Tillman and Baumann (2004) state that the functional unit should be examined to ensure that it is relevant and will allow for a fair comparison. In this case, the function of a food tray is considered to be the food that it will hold, so using the volume of the tray will provide a comparison that is as equal as possible. Additionally, Gallego-Schmid (2019) performed an LCA comparing takeaway food containers which utilized a volumetric functional unit as well. The mass of each tray is used as the reference flow, respectively. This is due to the fact that inputs and outputs of each process are based on the final mass of a tray. The additional mass of the barriers in the tray will further differentiate the reference flows for the dry moulded trays.

Table 1 Tray products studied and reference flows for the dry moulded, wet moulded, and polypropylene trays

Tray Type	Barrier	Mass (kg)	Material Composition (% by mass)
Dry Moulded – A	Laminate – Barrier A	0.024	93% Cellulose, 7% Barrier A
Dry Moulded – B	Laminate – Barrier B	0.026	89% Cellulose, 11% Barrier B
Dry Moulded – C	Chemical – Barrier C	0.024	94% Cellulose, 6% Barrier C
Wet Moulded	Unknown	0.021	100% Cellulose
Polypropylene	None	0.022	100% Polypropylene

3.2.2.2 Initial Flowchart

A general flowchart on the production of the trays is shown in Figure 2. Included in the flowchart are the steps required to create and use a food tray, which consist of the raw material cultivation or extraction, the manufacturing of the material to be used in the trays, the production of the trays, the use phase, and waste treatment. The use phase is excluded in this study (indicated by the grey colour) as the food tray is a passive product when in use. More detailed flowcharts for each tray can be seen in Section 3.

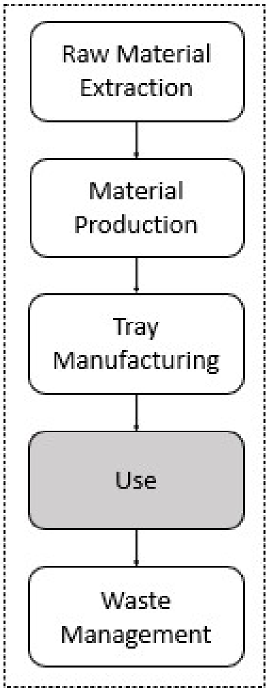

Figure 2 Simplified initial flow chart illustrating the basic steps involved in the life cycle of the products. The dashed line indicates the system boundary, processes beyond which processes are excluded from this study. The grey box indicates the exclusion of the use phase.

As an overview, raw material extraction holds the place for both the plastic tray and moulded fibre trays. For the plastic tray, the polymer used is polypropylene, which must first be extracted as crude oil or natural gas from the earth. For the fibre-based trays, the raw material is softwood for the dry moulded trays and sugarcane for the wet moulded trays, which must be cultivated and harvested. The raw materials must then be processed in order to be used for tray making. The polymer is processed into pellets, and the fibre materials are processed into pulp. The trays are then created using their respective manufacturing processes, used for holding food, and disposed of.

3.2.2.3 System Boundaries

The LCA conducted in this study is cradle-to-grave, meaning it includes all parts of the product life cycle. In relation to natural systems, this study includes the cultivation and harvesting of the fibres required to make the trays and the extraction of the fossil raw materials required for producing polypropylene. The end-of-life process involved with the trays is mechanical recycling, where the materials are broken down into pieces before becoming a new product, and for the portion not recycled, incineration with energy recovery will be used.

Geographically, the trays are produced in different regions, seen in Table 2 along with the location for raw material production. The use phase for each tray is excluded, as it is assumed to be negligible because the packaging is a passive product. This step is relevant for the food in the package rather than the package itself, and as such is allocated to that. The recycling and incineration at the end-of-life is assumed to occur in Europe for all the products.

Table 2 Locations for production of raw materials and trays

Tray Type	Raw Material Production	Tray Production
Dry Moulded	Sweden	Poland
Wet Moulded	China	China
Polypropylene	Belgium	Belgium

As this is a prospective LCA, the time-horizon is set in the future when the dry moulding technology has been introduced in the thermoformed packaging market and has been scaled up to a level comparable to the alternatives. The time period for this is in 2030 based on the planned timeline for the development of Yangi (The Loop Factory, 2020). As the dry moulding technology develops and scales up, the efficiency is expected to increase. The alternative trays are very established processes, and the foreground systems are not expected to change in the given time period.

Within the technical system, the use of capital goods in the process, including the production and maintenance of these goods, are not specifically included. However, the use of datasets from databases can include these. Other aspects outside the scope of the system boundaries include impacts created due to personnel working on the processes.

3.2.3 Inventory Analysis

In order to facilitate the modelling of the processes involved in making trays, openLCA software version1.10.2 and ecoinvent APOS 3.7 have been used (Wernet et al., 2016). OpenLCA is a free, widely used, open-source software which allows for flows, processes, and product systems to be modelled in order to examine different impacts resulting from the product. Ecoinvent provides process data for thousands of products in a wide range of industries, allowing for impacts to be determined as accurately as possible when primary data cannot be used.

In this study, primary data has been gathered from The Loop Factory for the dry moulded packaging. Customer A, which supplies food packaging, is collaborating with The Loop Factory in the development of Yangi, and they have provided data for the plastic packaging. They also sought to provide data for wet moulded packaging, but the primary data was not made available. Where it was not possible to get primary data, literature and ecoinvent database data were used.

3.2.4 Impact Assessment Method and Impact Categories

The impact assessment method used in openLCA was CML 2001, and it is provided by the ecoinvent 3.7 database. It was chosen because the scope of its data is global, which was helpful due to the processes occurring outside of Europe, and it covers a wide range of impact categories, making it applicable to many different systems (Park et al., 2020). Compared to the other available impact assessment methods, CML 2001 was seen to report the most relevant midpoint categories compared to the others available in ecoinvent 3.7.

Multiple impact categories were chosen to report based on their relevance to the different tray processes. They are as follows:

Depletion of abiotic resources relates to the use of non-living resources like crude oil, natural gas, and coal (Baumann & Tillman, 2004). With the use of energy systems powered by fossil fuels and extraction and production of polymer materials appearing in the systems to be compared, this will be a relevant category to investigate.

Global warming potential is a very important category, as it leads to worldwide consequences. Aside from carbon dioxide (CO_2) itself, other gases such as methane and chlorofluorocarbons (CFCs) contribute to global warming as well. These gases have differing potential to contribute to climate change depending on their ability to absorb infrared radiation and the length of time that they remain in the atmosphere (Baumann & Tillman, 2004). Manufacturing processes have great potential to contribute to these emissions, therefore the category is to be included.

Acidification is the result of acidifying pollutants like SO_2 or NO_x, which can appear in weather systems in different forms like acid rain, and cause damage to aquatic and terrestrial ecosystems (Baumann & Tillman, 2004). Emission of these pollutants is connected to systems by the use of combustion processes and the electricity mix in the life cycle of the product.

Eutrophication is the result of excessive nutrients, mainly phosphorous and nitrogen, which leads to changes in biological productivity in vegetation. Fertilizers, sewage effluents, and atmospheric emissions can lead to eutrophication (Baumann & Tillman, 2004). Because three of the food trays are made from plant material, this impact is of interest.

Cumulative energy demand will also be examined for each product. The total use, as well as the sources, renewable and non-renewable will be determined. This is relevant because energy use relates to both the use of resources and creates an impact on the environment, and the systems, being fossil-based for plastic, and fibre-based for the moulded trays will likely result in quite different usage breakdowns.

The toxicity categories, **human toxicity** and **ecotoxicity**, are categories which relate processes to toxic impacts that they can cause on humans and the environment. Human toxicity is of particular interest due to the use of PFAS in the wet moulded product and the link of these chemicals to health problems in humans (Fogg, 2020). PFAs are persistent chemicals, meaning they remain in the body for a very long time, and the accumulation of these chemicals has been linked to health issues (EPA, 2021; Holmquist, 2020). It was sought to include this aspect of the impacts in the LCA, and inventory data on the use of these chemicals and others was searched for. However, the specific inventory on chemicals, particularly the barrier chemicals used in wet moulding which relate to these categories has not been available due to a lack of data, and an impact assessment on toxicity using the available data is not expected to give an accurate picture of the impact. It could be argued that including toxicity in an LCA is only a supporting step in evaluating toxicity, and that fuller understanding of risks would come from additional tools, like a chemical risk assessment (Holmquist, 2020). It was not a part of the scope to include any kind of risk assessment, and as such, toxicity may be better addressed in a study with this as the main area of interest. As a result, toxicity will be left out of this study, though it could be interesting to focus on this aspect in the future.

There is much debate on including **land use** and land use change impact in LCA. Aspects of land use, like occupancy, change in quality, and changes in biodiversity are complicated, with many parts to consider. Due to limited data and knowledge on the complex mechanisms of land use on the environment, this aspect of environmental impacts will not be considered (Baumann & Tillman, 2004).

3.2.5 Allocation

Physical allocation has been used in the case of multi-output processes. The ISO standard prefers the use of physical allocation before others (ISO, 2006b). Despite this, it was initially intended to use economic allocation, as the product value is viewed as the main driving force for running a process (Ardente & Cellura, 2012). However, a lack of cost data made it necessary to use physical mass allocation.

Allocation for the recycling of waste has been done using the 0:100 method, also known as the closed-loop approximation, recyclability substitution, or end-of-life recycling approach (Bhatia et al., 2011). Ekvall et al. (2020) state that this method is used when the properties of the material being recycled are not expected to change in the subsequent product. They also explain that the 0/100 method holds the view that "material lost from the technosphere must be replaced through virgin material production" (p. 31), and this gives an incentive to use products which can be recycled in order to prevent the loss and following replacement of virgin material. Therefore, this method encourages products to be recyclable by allocating the benefits of recycling to the product which provides the materials for recycling after it is used (Ekvall et al., 2020). Frischknecht (2010) explains that this expectation that the material will be recycled is "considered equivalent to the natural capital represented by a credit of avoided environmental burdens" (p. 669), and as a result this is representative of a weak sustainability view, where natural capital can be substituted by man-made capital. In addition to this aspect, the fact that the 0/100 method encourages products to be recyclable but does not encourage the use of recycled materials in the primary product adds to this weak sustainability view.

There are many different end-of-life formulas for allocation, chosen depending on which scenario best fits a product system. Allacker et al. (2017) presents the following equation for the 0/100 method, which credits avoiding production of virgin material, due to the recycled material coming from the primary product:

$$(1)\ E = E_V + R_2(E_{recycled} - E_V^* \frac{Q_S}{Q_P}) + (1 - R_2)E_D$$

Where,

E_V: emissions and resources consumed due to raw materials and manufacturing of virgin material, in units of the respective impact category

R_2: the rate of recycling of the primary product, percentage

$E_{recycled}$: emissions and resources consumed due to recycling, in units of the respective impact category

E_D: emissions and resources consumed due to disposal of materials, in this case, incineration with energy recovery, in units of the respective impact category. The value of ED presented in the Appendix is the combination of the incineration impact and the credit from energy recovery.

E_V^*: emissions and resources consumed due to raw materials and manufacturing of virgin material which is assumed to be substituted by recycling the material from the primary product

$\frac{Q_S}{Q_P}$: a quality correction factor, which takes into account degradation that occurs when a product is recycled

In order to take into account the credit for avoided virgin material production and the change in material quality, Equation (2) will be used in calculating the end-of-life impact.

3.2.6 Assumptions

Assumptions

- The energy system in Europe is expected to change by 2030. Electricity inputs in processes occurring in Europe have been modelled according to the EUCO27 scenario created by the European Commission, seen in which reflects an energy system that fulfils an energy efficiency target of 27% by 2030, which was set by the European Council (Banja & Jégard, 2017). The electricity inputs which have been changed to the EUCO27 electricity mix are those contributing 5% or more to the impacts of the product systems. Heat energy providers which contribute to 5% or more to impacts have been modelled with a Swedish mix in order to simulate this decarbonized system. See Tables B.1 and B.2 in Appendix B.
- The electricity system in China in 2030 has been represented in modelling with an electricity mix based on projections from the U.S. Energy Information Administration (West, 2017). Seen Table B.3 in Appendix B.
- EURO6 vehicles have been chosen for lorry transportation because the study is set in 2030, and this is expected to be the standard for the majority of vehicles used.
- Google Maps and sea-distances.org have been used to determine transportation distances where they were otherwise unspecified, see Appendix B for transportation locations.
- Distance to retail is assumed to be 581 km based on the average distance of road freight transport in the EU in 2018 (Eurostat, 2021b).
- Bagasse pulp is assumed to be produced by Kraft pulping (Rainey & Covey, 2016).
- Wet moulded packaging is known to require chemical addition to create barrier properties. The inventory from Huo and Saito (2009) showed about 2% of the mass is made of these chemicals, but the specific chemicals were not specified, and they have been left out of the model.
- Energy recovery from incineration is assumed to be in the form of heat and 100% efficient.

3.2.7 Data Quality

The characteristics of the data used in an LCA can greatly affect the final results. The ISO standard lists aspects to be considered, including relevance, reliability, and accessibility (Baumann & Tillman, 2004). Relevance includes aspects of time, geography, and completeness of data, ensuring that sources are applicable for the system being studied. Reliability is about the accuracy and uncertainty in the data. Accessibility concerns reproducibility and consistency, which is related to the level of transparency and data collection and documentation.

This study has utilized information from journal articles, textbooks, relevant authorities on the subjects within the study, product developers and manufacturers, and databases. As the study is being modelled in the future, data for the dry moulded trays has been created using current data and expected developments in the system.

3.2.8 Product Systems

This section presents the flow charts and descriptions of each product system included in the LCA.

3.2.8.1 Dry Moulded Trays

The Loop Factory's dry moulded trays are made with softwood kraft fluff pulp produced in Sweden. This pulp process has been represented using inventory data on BLUE85Z pulp from Södra (Södra, n.d). The process for making pulp begins with the cultivation of softwood, in this case pine and spruce. The trees are cut into logs, debarked, and turned into wood chips to prepare them for pulping (Bajpai, 2010). The chips are then digested with cooking liquor to separate the fibres in the wood (Staffas et al., 2013). This is then washed to remove the cooking liquor from the pulp and screened to remove any wood or fibres which have not been properly pulped (Bajpai, 2010). The pulp is then bleached to increase brightness and further screened before drying (Bajpai, 2010). The fluff pulp that the dry moulded trays are made from are placed on a reel for use in the process.

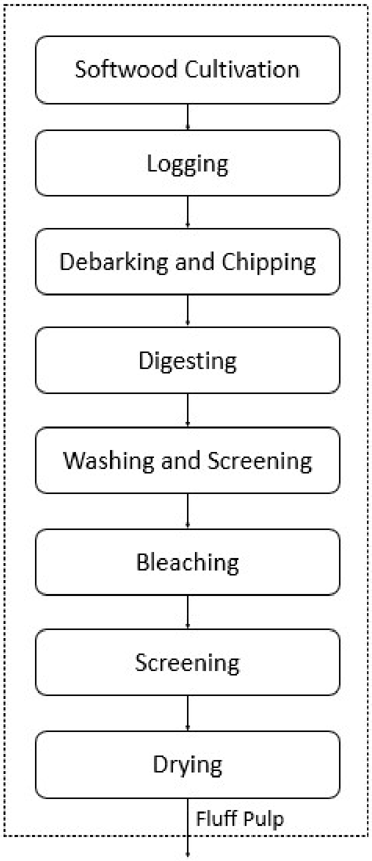

Figure 3 Simplified flowchart depicting the steps involved in the pulping process for softwood fluff pulp (Bajpai, 2010)

The pulp is then transported to Poland, where production is to take place. The fluff pulp is broken down in a hammermill before being airlaid onto a conveyor belt. This fluff sheet is then compressed and die-cuts in the shape of the trays are cut from this sheet. Scrap fluff is sent back to the hammermill in order to be reused. The die-cuts are then pressed with heat in order to shape them into trays. Excess material on the edge of the tray is cut off, then the trays are packed and sent to retail, used, and sent to end-of-life treatment. A flowchart for the process, excluding a barrier is seen in Figure 4. The information for this process has been given by The Loop Factory.

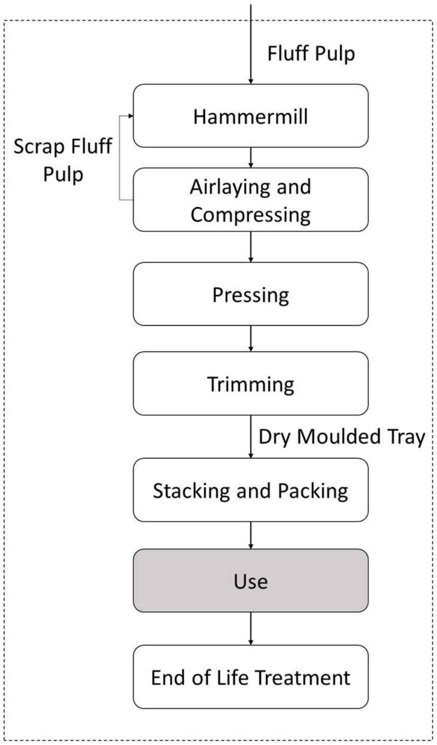

Figure 4 Flowchart for The Loop Factory's dry moulding process using Yangi technology. The grey box indicates the exclusion of the use phase.

In order to be used for food, the trays need to incorporate a barrier to prevent things like oxygen, water, and oils from impacting food or package quality. As a barrier is a critical part of a food tray, the processes for production of the barriers have been included in more detail. These can be in the form of laminate barriers, which are often multilayer sheets made of polymers which combine to provide good barrier properties (Galić, 2015). A laminate is added after pressing the trays into shape, seen in Figure 5. Barriers can also come in the form of a chemical dispersion, often incorporated on the surface of the package (Andersson et al., 2002). In this case, a chemical barrier would be dispersed on the pulp itself before going through the hammermill, see Figure 6.

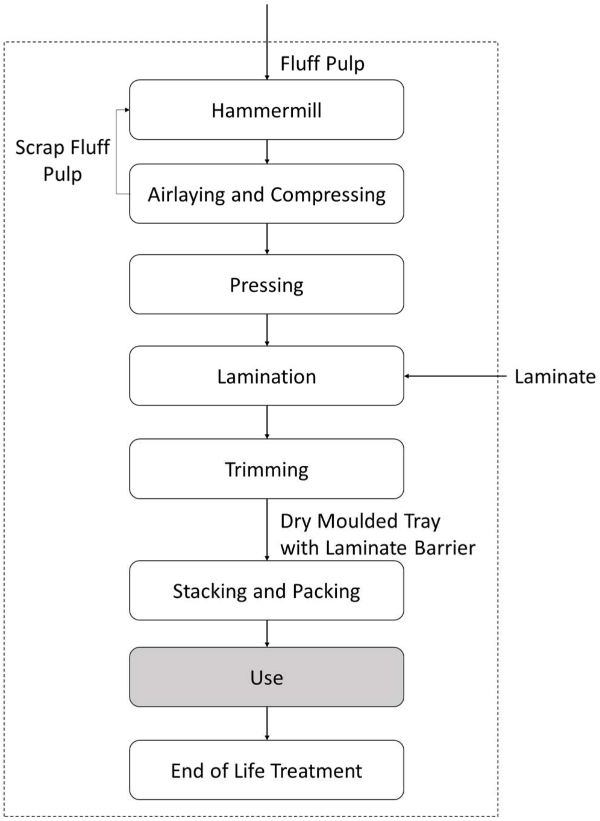

Figure 5 Flowchart for the dry moulding process including the use of a laminate barrier. The grey box indicates the exclusion of the use phase.

Two laminates from different companies have been examined in this assessment, and for confidentiality reasons, they will be known as barriers A and B.

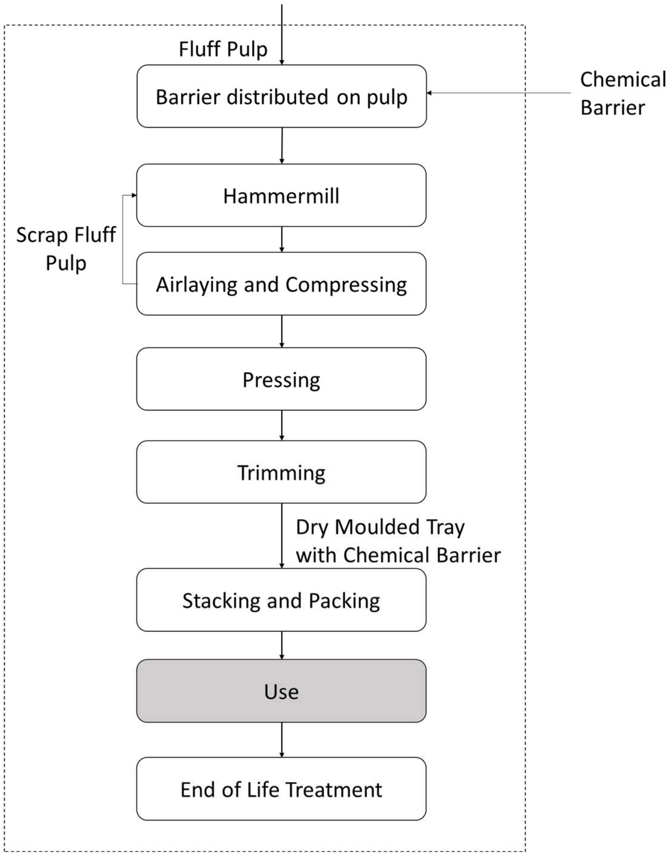

Figure 6 Flowchart for the dry moulding process including the use of a chemical barrier. The grey box indicates the exclusion of the use phase.

A chemical barrier has been included in the LCA, and it will be known as barrier C.

The details of the barriers included in the study, which were given by their producers have been kept confidential and have been placed in the confidential appendix. The laminates used on the dry moulded trays are made up of multiple layers of polymer sheets, which are produced using extrusion methods. A general description of laminate barrier production can be found in Selke and Hernandez (2001). Laminate barrier A is made up of biodegradable plastics, where the resins are extruded and blown in order to form a multilayer film. Laminate barrier B is also a multilayer polymer film produced through multilayer extrusion. It is made from high density polyethylene and a confidential vinyl alcohol polymer. Chemical barrier C is made via chemical mixing in order to create a homogenous dispersion, though the makeup of the barrier is confidential.

3.2.8.2 Wet Moulded Trays

The wet moulded trays are made from cellulose pulp sourced from bagasse, which is a waste of the sugar production process (Mashoko et al., 2010). Sugarcane must first be cultivated before being harvested for sugar production. After the juice is extracted from the sugarcane, what remains is bagasse (Mashoko et al., 2010). To prepare the bagasse for pulping, it must be depithed to remove 30% of the shortest fibres (the “pith”) in order to make a good quality pulp (Rainey & Covey, 2016). Little primary information was received about the details of the bagasse and wet moulding processes, and as such, assumptions about the processes used were made. The bagasse pulp process is assumed to be made using a Kraft pulp process, which is one of the commonly used processes for making bagasse pulp (Rainey & Covey, 2016). After depithing, the bagasse is sent to digestion, where the fibres are broken down (Rainey & Covey, 2016). The pulp is then washed to remove spent cooking liquor and screened before drying, without bleaching in this case (Bajpai, 2010).

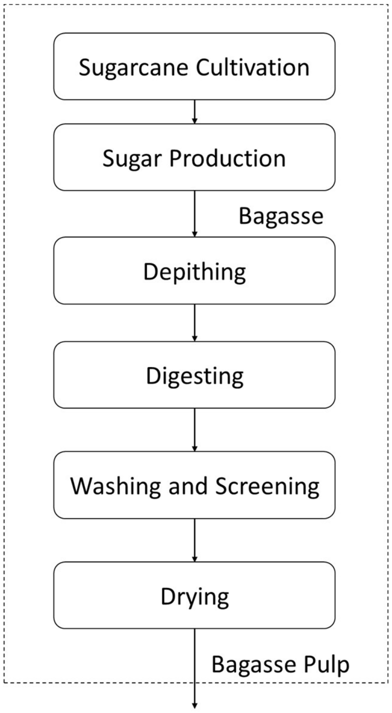

Figure 7 Flowchart for production of bagasse from sugarcane and bagasse pulp process (Bajpai, 2010; Mashoko et al., 2010; Rainey & Covey, 2016).

To use in wet moulding, the bagasse pulp is mixed in a tank with water and any chemical additives required, like PFAS to create the needed barrier properties in order to create a slurry (Didone et al., 2020). The die in the shape of the tray mould is placed into the slurry, and a vacuum sucks the pulp into the mould before pressing with heat and drying in the thermoforming process (Didone et al., 2017). Trimming removes excess material on the trays, and they are packed and sent to storage before being sent to retail. In this case, the bagasse and wet moulding processes occur in China before being sent to Germany for storage before retail throughout Europe.

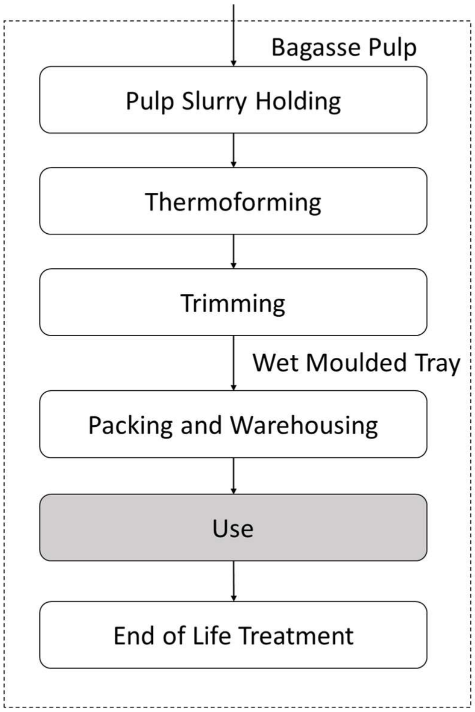

Figure 8 Flowchart of the wet moulding process (Didone et al., 2017). The grey box indicates the exclusion of the use phase.

3.2.8.3 Polypropylene Trays

The raw materials involved in producing polypropylene are crude oil and natural gas, which are extracted from the earth. In order to be used for making PP, these materials need to be further processed. Crude oil must be refined in order to break down into usable fractions, one of which being naptha (Plastics Europe, n.d.). The naptha and gas are further broken down into single components like propylene in the cracking step (Gahleitner & Pualik, 2016). Polymerization takes place either using liquid or gas phase processes, where single propylene monomers are linked to form polymer chains, creating polypropylene resin (Gahleitner & Pualik, 2016).

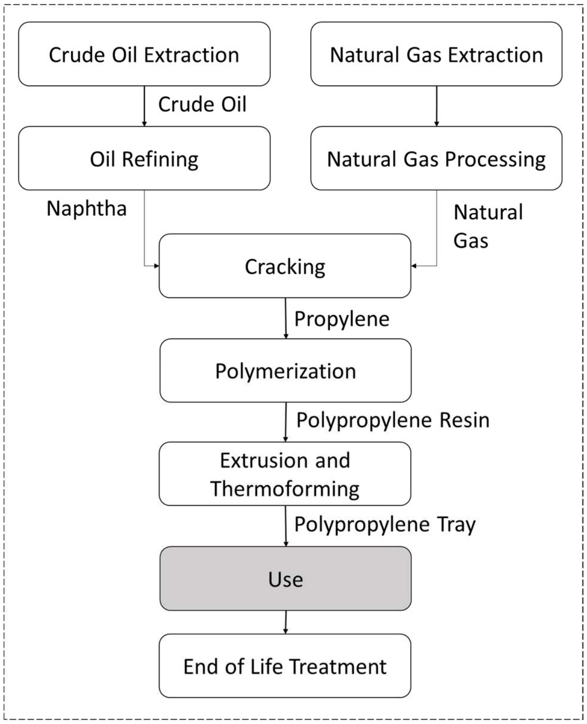

Figure 9 Flowchart for polypropylene trays. The grey box indicates the exclusion of the use phase.

The polypropylene resin is then sent for processing into a tray. The plastic is extruded into a sheet and thermoformed, a technique which heats up the plastic before forming it to a mould shape, in this case a food tray (Breulmann et al., 2016). The trays are then sent to retail and used before end-of-life treatment takes place.

3.2.8.4 End-of-Life Treatment

For all of the food trays, recycling is expected to be used in the end-of-life treatment as this is the push for the future seen in the previously mentioned EU directives. When there is a portion of the trays not being recycled, the end-of-life disposal method is incineration with energy recovery. The energy recovery here is modelled as heat and as being 100% efficient for simplification. Equation (1) will be used to model the emissions in the end-of-life. The Packaging and Packaging Waste directive has set targets for recycling for packaging materials in 2030, including 55% of plastic and 85% of paper and cardboard (Directive 2018/852). These recycling rates will be used in modelling the base case for the end-of-life treatment. Additionally, scenarios of waste management will include 100% recycling and 100% incineration with energy recovery.

Today, polypropylene itself has a tiny recycling rate, around 3% according to Chasan et al. (2019). Additionally, when food grade plastics are recycled, they are likely downgraded in material due to degradation and contamination (Brouwer et al., 2020). Though there are methods being developed to try to solve these recycling problems, it is perhaps unrealistic to expect such high recycling rates to be possible in 2030. However, as future developments are unknown, and analysing on this range of recycling rates will examine what might be possible.

4 Results

4.1 Communication with Customers

It was possible to interview two companies collaborating with The Loop Factory and ask them questions about their packaging sustainability efforts. A discussion was held each with Customer A, a food packaging product supplier, and Customer B, a luxury retail brand. Notes taken during each interview can be found in Appendix A. Those who were interviewed from Customer A were in roles related to sustainability and project management, while those from Customer B were in roles related to sustainable packaging and responsible innovation. Overall, it was clear from the interviews that customers are becoming more aware of environmental issues related to products they buy, and sometimes seek environmental data on those products. Additionally, plastic is of major concern, and this material in particular appears to be under the most scrutiny.

Both companies are facing increased legislation from the EU as well as specific legislation from countries in which they operate. Customer A specifically named the SUP directive and the Packaging and Packaging Waste directive as regulations of concern. It did appear from both customers, that one issue with legislation announcements is clarification of specific requirements. After a regulation is first announced, it appears that there is often much confusion over how it should be applied to the many different businesses affected by it, and clarifying information is often necessary.

The customers both spoke of their desire to reduce use of plastic, as well as analyse end-of-life operations. Customer A mentioned requests from customers, asking for products to be recyclable, and Customer B stated their goal to minimize the overall impact. Additionally, Customer B laid out the principles they are following in their eco-design strategy, including reducing material use, particularly for plastic, promoting sustainable materials, and designing materials and products which can have a second life.

This LCA is analysing multiple materials for making food trays, which is in line with the customer's desires to explore packaging materials outside of plastic. The results of the life cycle impact assessment will include a sensitivity analysis which varies the rate of recycling. There is a push for recyclable materials occurring, though it is important to explore end-of-life options, both because recycling a product does not inherently result in the lowest environmental impact, and consumer behaviour may not follow recycling for waste management, even when it is desired by producers.

4.2 Results of the Life Cycle Assessment

The values for the results can be found in Appendix C. In the graphs the life cycle parts are shown in different grey shades, with the overall total shown represented with a diagonally striped bar. In each graph, the recycling and incineration impacts are shown as negative credits to the system due to the use of Equation (1). The recycling gives a negative credit for avoided production of virgin material. The incineration credit is negative due because the impact from incineration and the credit for avoided heat energy production have been combined.

The results first present a case where both recycling and incineration take place in section 4.2.1, where 85% of paper packaging and 55% of plastic packaging will be recycled in the EU, based on the 2030 goal of the directive on packaging and packaging waste (Directive 2018/852). In the present day, Barrier A is not able to be recycled, though it has been modelled as such due to possible advancements in the future when the study is taking place.

The second part of the results in section 4.2.2 is a sensitivity analysis, where the recycling rate has been varied between 100% and 0%. This analysis shows that, despite what one might assume about using recycling as end-of-life treatment, it does not inherently lead to fewer emissions than incineration, though this depends on how the end of life is calculated.

Finally, sensitivity analysis was completed in section 4.2.3 where the wet moulded trays are modelled to be produced in Europe. The actual wet moulded trays are produced in China, while the rest of the trays in this study are produced in Europe. The comparison between the plastic and dry moulded trays shows the difference between production methods, as the energy systems are the same. However, because of the differences between both packaging technology used and energy systems, the comparison between the wet moulded packaging and the other types does not compare a specific part of the system, but rather the packaging product as a whole. This sensitivity analysis allows for comparison between the production technologies since they will be using the same energy mix.

4.2.1 End-of-Life Recycling and Incineration Case

This section presents the case results for 85% paper and 55% plastic recycling for each of the studied trays.

4.2.1.1 Global Warming Potential

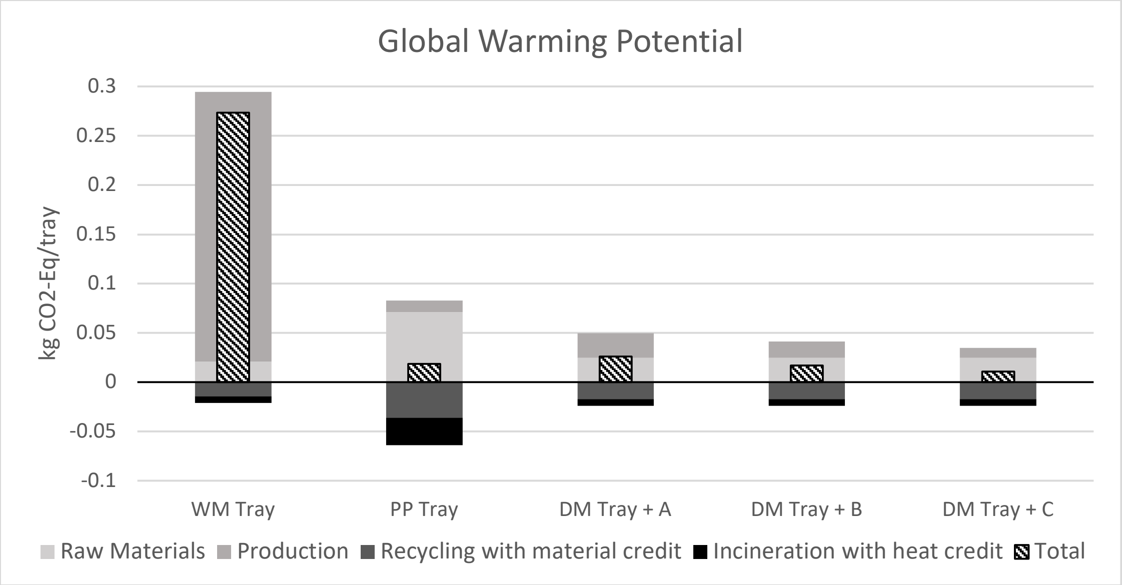

Figure 10 Global warming potential for the food trays

Table 3 Total global warming potential for each tray in the case of 85% paper and 55% plastic recycling

85% Paper/55% Plastic Recycling	Total Global Warming Potential (kg CO_2-Eq)
Wet Moulded Tray	0.274
Polypropylene Tray	0.019
Dry Moulded Tray + A	0.026
Dry Moulded Tray + B	0.017
Dry Moulded Tray + C	0.011

The wet moulded tray, with production in China, is the only production process which directly utilizes coal, the emissions of which largely contribute to the global warming potential. The electricity mixes for each tray, including the European 2030 mix contain some use of coal. Polypropylene raw materials contribute largely due to the use of materials like natural gas and crude oil directly needed to make PP granulate. The plastic tray, due to its larger negative credit from recycling and incineration, performs better than the dry moulded tray with barrier A, but the dry moulded trays with barriers B and C result in the lowest global warming potential.

Due to the method used for end-of-life recycling allocation, the wet moulded trays produced in China result in a much larger impact compared to the other trays. This is because when recycling occurs, a credit is given for avoided production of virgin material. For polypropylene and the dry moulded trays, the majority of the impact generally comes from the raw material production, while the majority of the wet moulded tray impact comes from production of the tray itself. Therefore, avoiding production of virgin material gives a much greater negative emissions credit to the polypropylene and the dry moulded tray, while the wet moulded tray only receives a small credit. This is seen in the other impact categories as well.

4.2.1.2 Acidification Potential

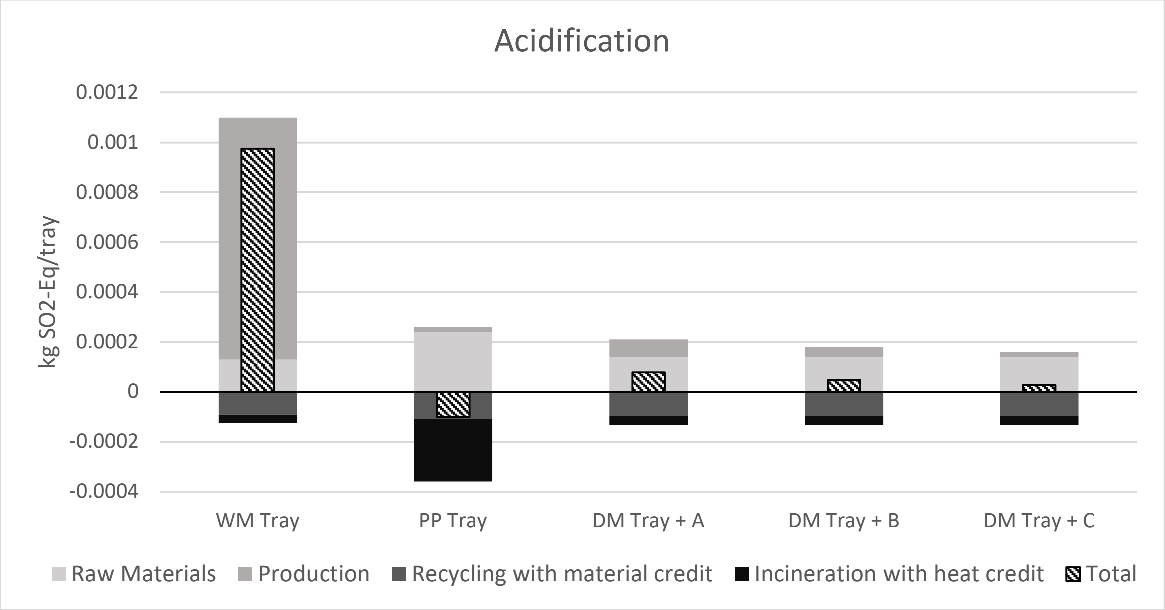

Figure 11 Acidification potential for the food trays

Table 4 Total acidification potential for each tray in the case of 85% paper and 55% plastic recycling

85% Paper/55% Plastic Recycling	Total Acidification (kg SO_2-Eq)
Wet Moulded Tray	9.75E-04
Polypropylene Tray	-9.96E-05
Dry Moulded Tray + A	7.89E-05
Dry Moulded Tray + B	4.75E-05
Dry Moulded Tray + C	2.89E-05

Acidification is based on pollutants like SO_2 or NO_x, among others. For the wet moulded tray, contributions to this category come from the use of coal in the electricity mix and in tray production, as well as in the processes involved in pulp production itself. The data set for the production of wet moulded trays specifically lists emissions of SO_2 and NO_x, which creates a large impact in the production process. For the plastic tray, contributions stem mainly from the polypropylene granulate production process. The dry moulded trays contribute to acidification in the raw material pulp production, the inventory data of which specifically includes SO_2 and NO_x as emissions in much larger quantities than the bagasse pulp production. The large benefit that plastic receives from energy recovery in incineration is in this case able to make the overall emission total negative.

4.2.1.3 Eutrophication Potential

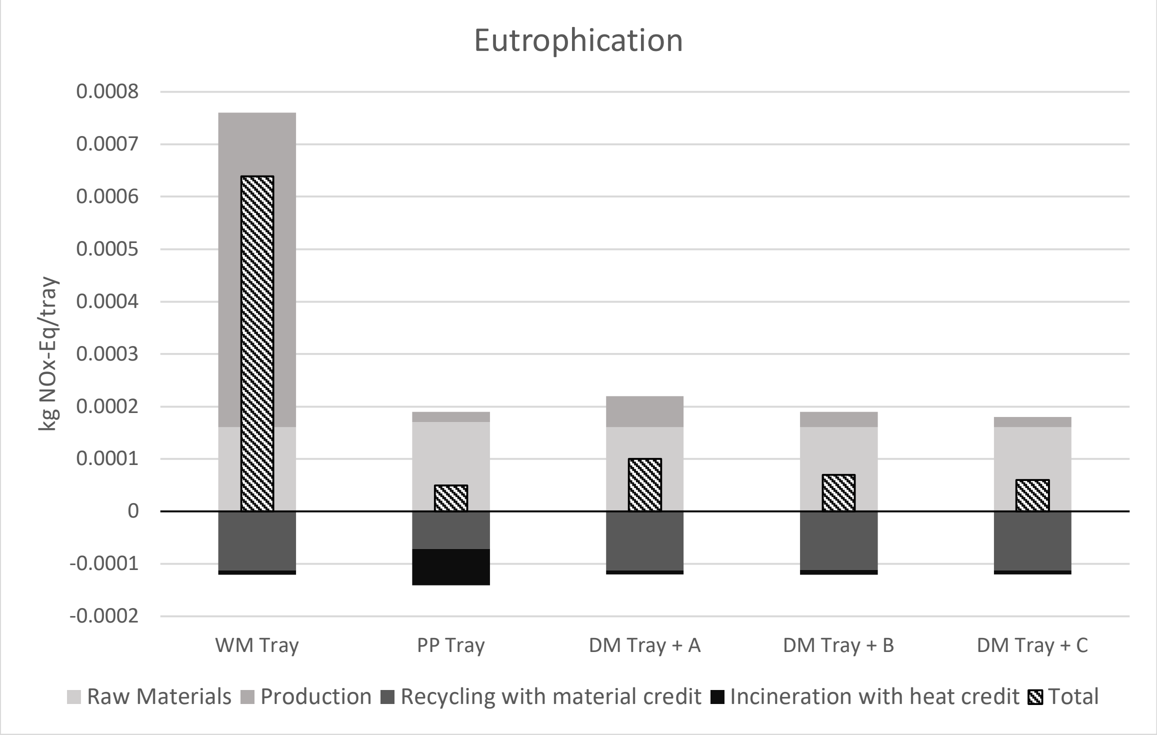

Figure 12 Eutrophication potential for the food trays

Table 5 Total eutrophication potential for each tray in the case of 85% paper and 55% plastic recycling

85% Paper/55% Plastic Recycling	Total Eutrophication (kg NOx-Eq)
Wet Moulded Tray	6.39E-04
Polypropylene Tray	4.94E-05
Dry Moulded Tray + A	9.99E-05
Dry Moulded Tray + B	6.95E-05
Dry Moulded Tray + C	5.99E-05

Eutrophication is associated with the use of nutrients on plant life, like fertilizers containing phosphorous and nitrogen, though atmospheric emissions also contribute. The use of fertilizers is not expected for the softwood, with the impact coming from processes and machinery use associated with wood production. In the case of the wet moulded trays, a large impact comes from the production process, which creates large emissions of NO_x associated with the use of coal for heat in production. Overall, the polypropylene system contributes the least to eutrophication potential. The PP production process does contribute through NOx emissions rather than through use of fertilizers, but overall, the small impact due to tray production combined with the recycling and energy recovery credit in incineration creates the smallest total for polypropylene trays.

4.2.1.4 Abiotic Resource Depletion Potential

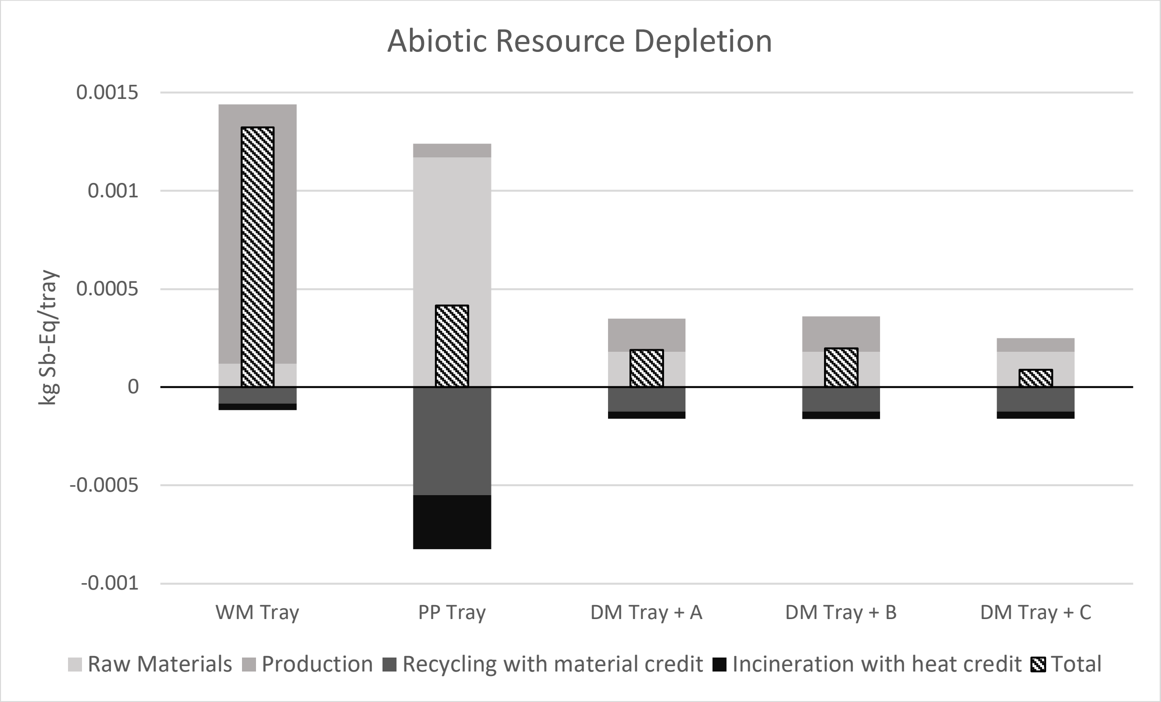

Figure 13 Abiotic resource depletion potential for the food trays

Table 6 Total abiotic resource depletion potential for each tray in the case of 85% paper and 55% plastic recycling

85% Paper/55% Plastic Recycling	Total Abiotic Resource Depletion (kg Sb-Eq)
Wet Moulded Tray	1.32E-03
Polypropylene Tray	4.16E-04
Dry Moulded Tray + A	1.90E-04
Dry Moulded Tray + B	1.98E-04
Dry Moulded Tray + C	8.96E-05

Abiotic resource depletion relates to the use of non-renewable resources, like fossil resources. The production of wet moulded trays includes the use of coal for heat, while raw materials for polypropylene require natural gas and oil, all of which contribute to abiotic resource depletion. For the dry moulded trays, non-renewable resource use appears mainly in the electricity and heat energy mix, as well as in the use of machinery in forestry processes, and diesel in transportation. The large resource use in production of the wet moulded trays results in the largest overall impact, while the dry moulded trays create the lowest impact for abiotic resource use.

4.2.1.5 Cumulative Energy Demand

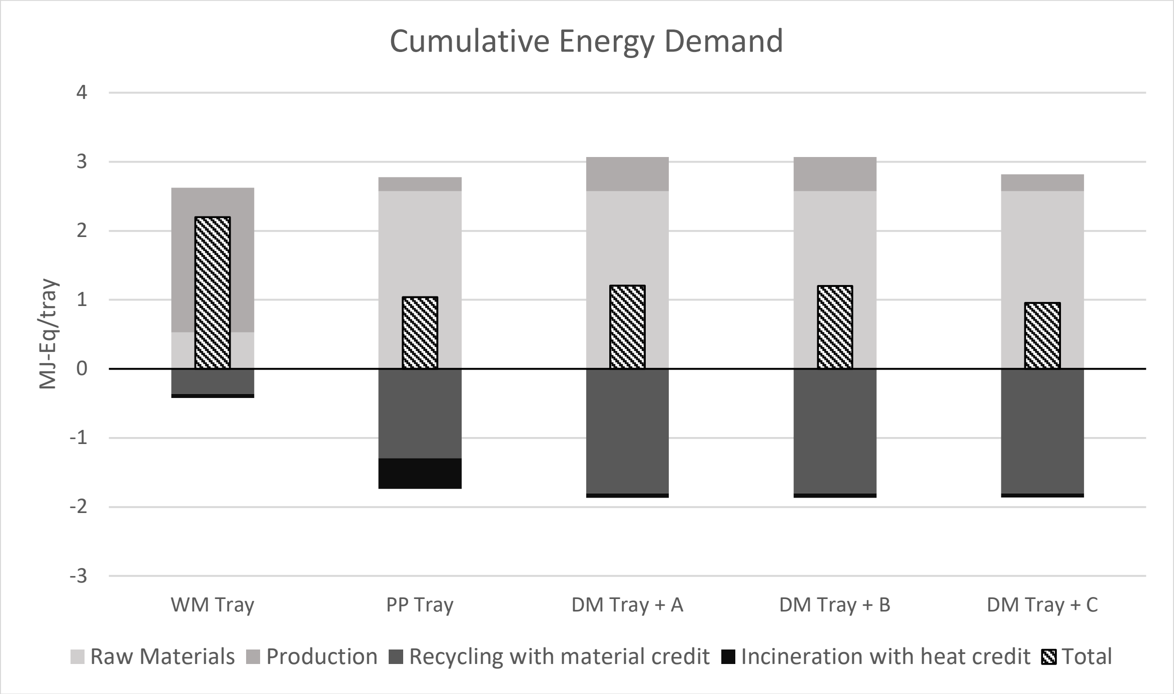

Figure 14 Cumulative energy demand for the food trays

Table 7 Total cumulative energy demand for each tray in the case of 85% paper and 55% plastic recycling

85% Paper/55% Plastic Recycling	Total Cumulative Energy Demand (kg MJ-Eq)
Wet Moulded Tray	2.20
Polypropylene Tray	1.04
Dry Moulded Tray + A	1.21
Dry Moulded Tray + B	1.20
Dry Moulded Tray + C	0.95

The cumulative energy demand presents the overall energy use from cradle-to-grave for each tray. In this case, the wet moulded trays require the most energy, followed by the dry moulded trays with barriers A and B, and then the plastic trays. The dry moulded tray with barrier C creates the lowest energy demand.

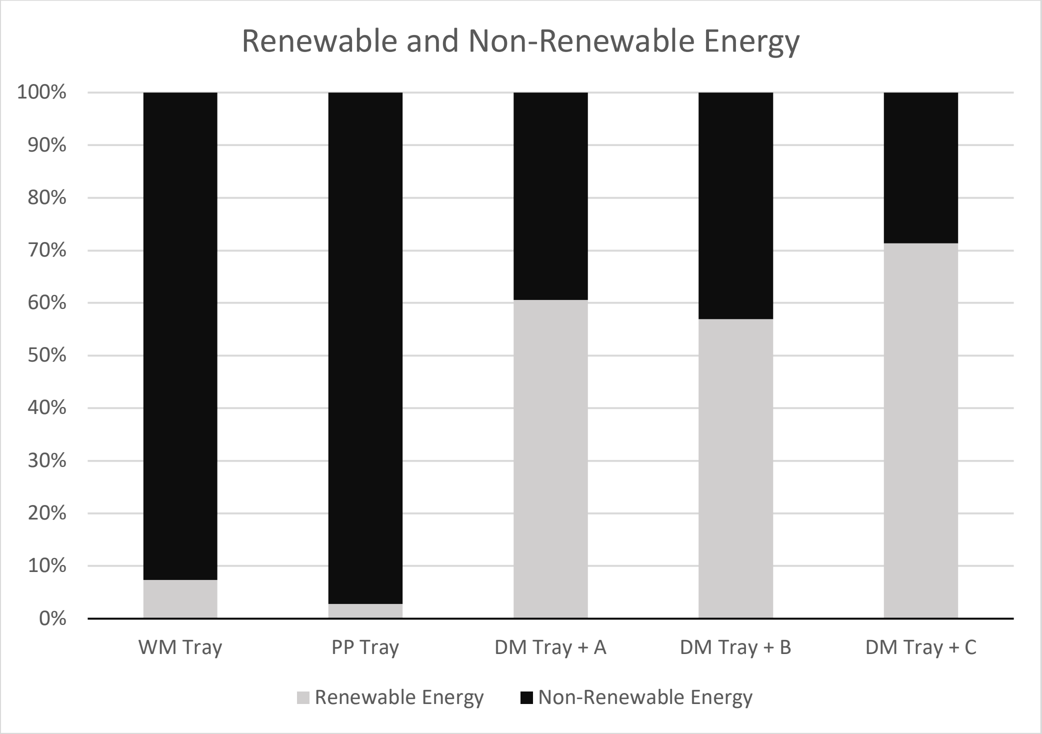

Figure 15 Cumulative energy demand, shown in terms of percentage use of renewable and non-renewable energy

Presented in terms of percentage of energy type used, Figure 15 shows that the wet moulded and polypropylene trays use much more non-renewable energy than the dry moulded trays. The dry moulded trays use more than 50% renewable energy, while the wet moulded and polypropylene trays use more than 90% non-renewable. For the wet moulded trays, the majority of the energy use comes from the production step, which utilizes coal and the Chinese energy mix, which contains greater use of non-renewable energy sources than the European mix. The largest use of energy for the polypropylene trays comes from the raw materials, where crude oil and coal are used in the production of polypropylene granulate. For the dry moulded trays, the majority of the energy use occurs in the pulp process.

4.2.2 Sensitivity Analysis - Comparison of Recycling Rate

The following results show the difference in emissions that occurs for each impact assessment when the rate of recycling changes. Shown in the graphs are a case of 100% recycling, a case of 85% paper and 55% plastic recycling, and a case of 0% recycling. As recycling decreases, the rate of incineration with energy recovery increases.

4.2.2.1 Global Warming Potential

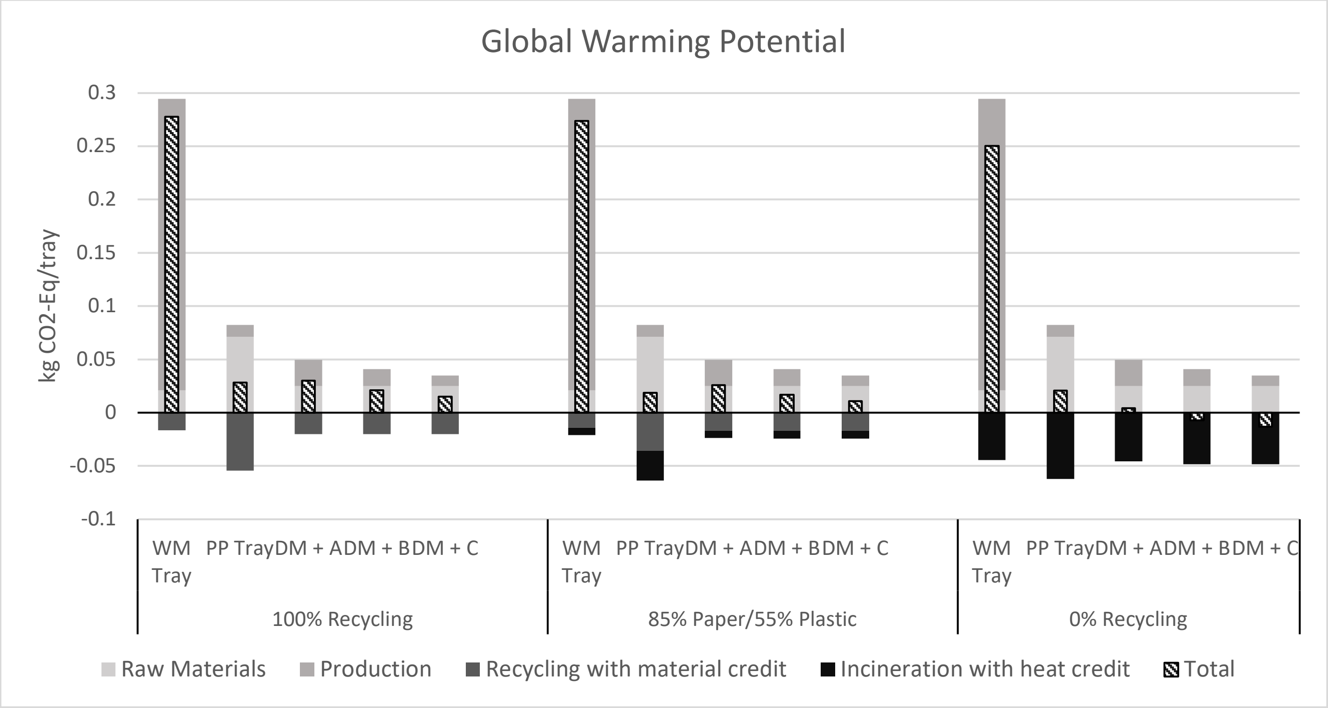

Figure 16 Global warming potential for 100% overall recycling, the base case of 85% paper recycling and 55% plastic recycling, and 0% overall recycling

Table 8 Total global warming potential for each tray and recycling rate

Total Global Warming Potential	100% Recycling (kg CO_2-Eq)	85% Paper/55% Plastic Recycling (kg CO_2-Eq)	0% Recycling (kg CO_2-Eq)
Wet Moulded Tray	0.278	0.274	0.250
Polypropylene Tray	0.028	0.019	0.021
Dry Moulded Tray + A	0.030	0.026	0.004
Dry Moulded Tray + B	0.021	0.017	-0.007
Dry Moulded Tray + C	0.015	0.011	-0.013

The results show that as recycling rate decreases, the benefit from the credit for avoided heat production in incineration results in a decreasing impact for each of the trays, aside from the plastic tray in the 0% recycling case. The smaller impact as recycling rate decreases is due to the credit from incineration being larger than the credit from avoided virgin material in production. The impact from the plastic in the 0% recycling case actually increases because the combined credit from recycling and incineration together in the middle case is larger than the credit from incineration only. The wet moulded tray creates the largest climate impact in each case. In the 100% and 85%/55% cases, the dry moulded tray results in the next largest impact, followed by polypropylene, and finally the dry moulded trays with barriers A and B. For the 0% recycling case, the dry moulded trays create the lowest global warming impact.

4.2.2.2 Acidification Potential

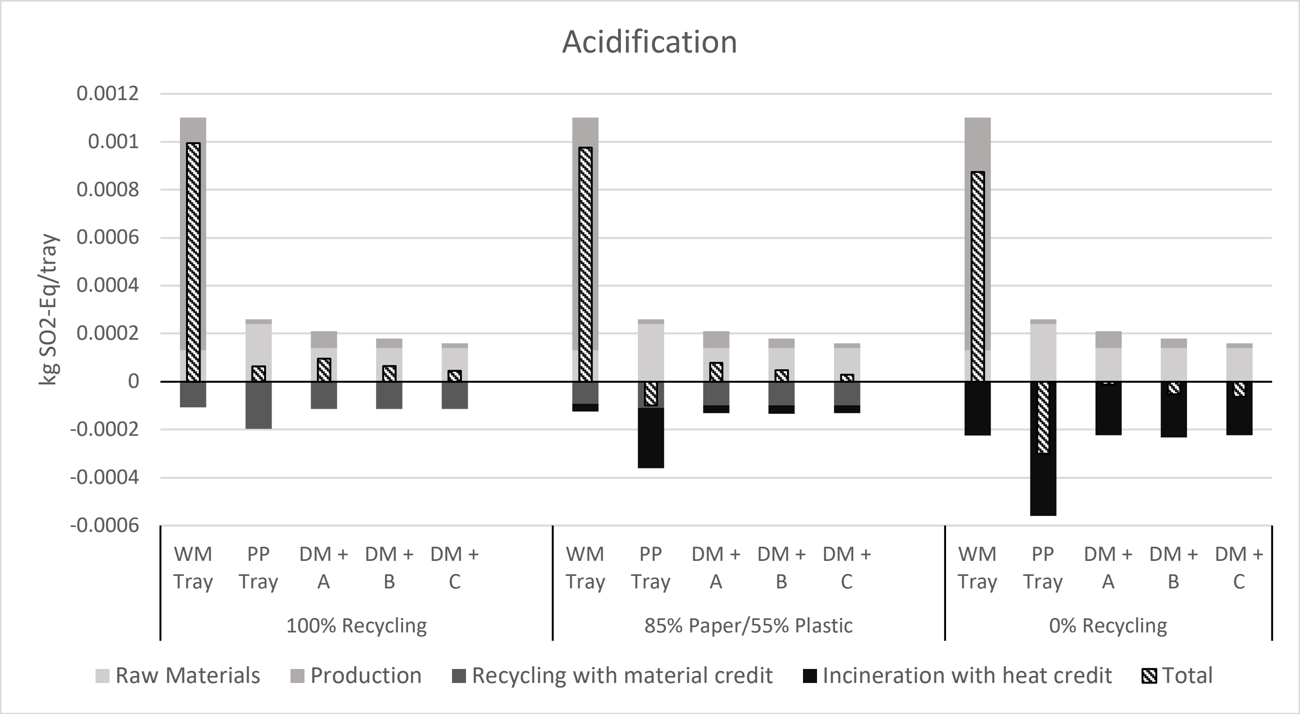

Figure 17 Acidification potential for 100% overall recycling, the base case of 85% paper recycling and 55% plastic recycling, and 0% overall recycling

Table 9 Total acidification potential for each tray and recycling rate

Total Acidification	100% Recycling (kg SO_2-Eq)	85% Paper/55% Plastic Recycling (kg SO_2-Eq)	0% Recycling (kg SO_2-Eq)
Wet Moulded Tray	9.93E-04	9.75E-04	8.75E-04
Polypropylene Tray	6.44E-05	-9.96E-05	-3.00E-04
Dry Moulded Tray + A	9.51E-05	7.89E-05	-1.30E-05
Dry Moulded Tray + B	6.52E-05	4.75E-05	-5.26E-05
Dry Moulded Tray + C	4.51E-05	2.89E-05	-6.29E-05

For acidification, decreases in recycling rate result in similar decreases in impact. This is due to the amount of avoided acidifying pollutants created from energy recovery in incineration being greater than that of avoided virgin material. Wet moulding creates the largest impact in all cases. In the 100% recycling case, the dry moulded trays with barriers A and B result in the next largest impact, followed by polypropylene, and finally the dry moulded tray with barrier C with the lowest impact. For the middle and 0% recycling cases, the large benefit that polypropylene receives from incineration results in the lowest impact due to acidification.

4.2.2.3 Eutrophication Potential

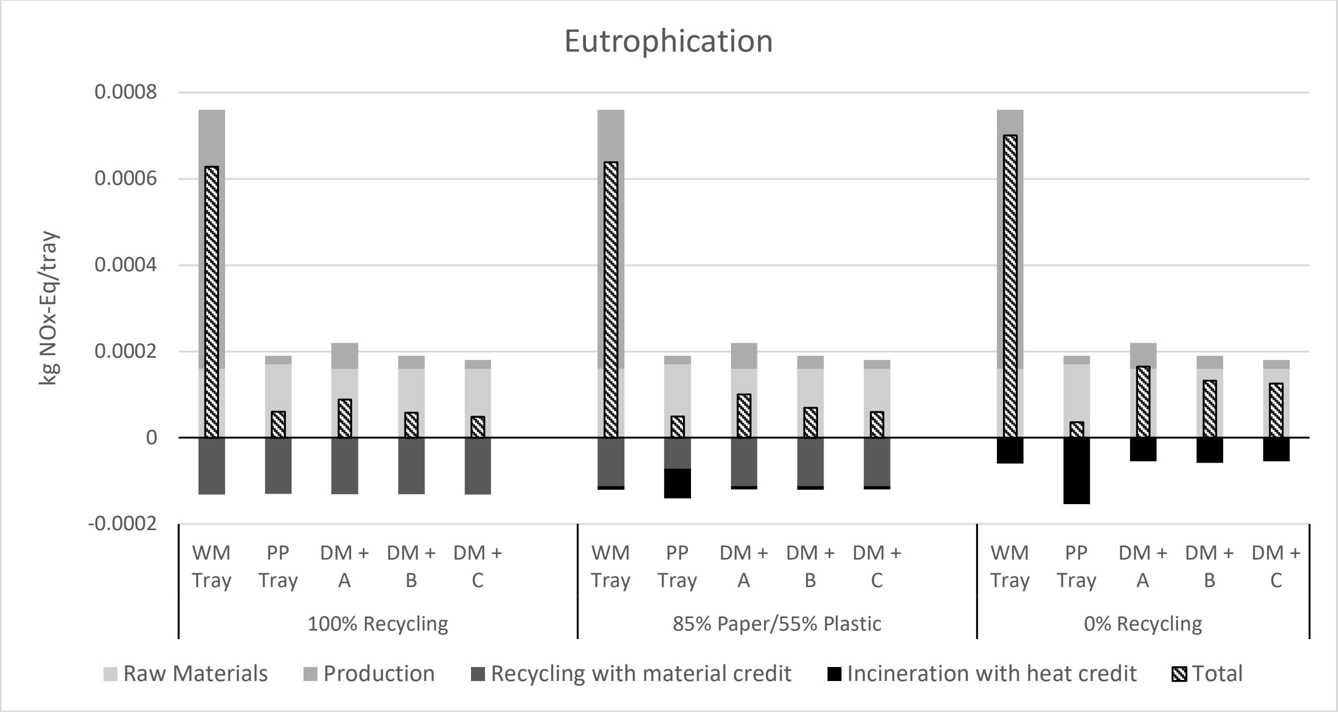

Figure 18 Eutrophication potential for 100% overall recycling, the base case of 85% paper recycling and 55% plastic recycling, and 0% overall recycling

Table 10 Total eutrophication potential for each tray and recycling rate

Total Eutrophication	100% Recycling (kg NOx-Eq)	85% Paper/55% Plastic Recycling (kg NOx-Eq)	0% Recycling (kg NOx-Eq)
Wet Moulded Tray	6.28E-04	6.39E-04	7.01E-04
Polypropylene Tray	6.02E-05	4.94E-05	3.62E-05
Dry Moulded Tray + A	8.84E-05	9.99E-05	1.65E-04
Dry Moulded Tray + B	5.84E-05	6.95E-05	1.32E-04
Dry Moulded Tray + C	4.84E-05	5.99E-05	1.26E-04

As recycling rate decreases, the impact for eutrophication increases for all of the fibre-based trays. Therefore, the avoided emissions of eutrophication causing pollutants in virgin pulp production when the fibre trays are recycled is greater than the emissions avoided for energy recovery in incineration. The impact due to the polypropylene tray slightly decreases as the rate of recycling decreases. This is because the avoided production of polypropylene granulate through recycling is less beneficial than the avoided production of heat through incineration. In the 100% recycling case, the dry moulded trays with barriers A and B create the lowest overall eutrophication impact. In the middle and 0% recycling cases, the polypropylene trays result in the lowest impact.

4.2.2.4 Abiotic Resource Depletion Potential

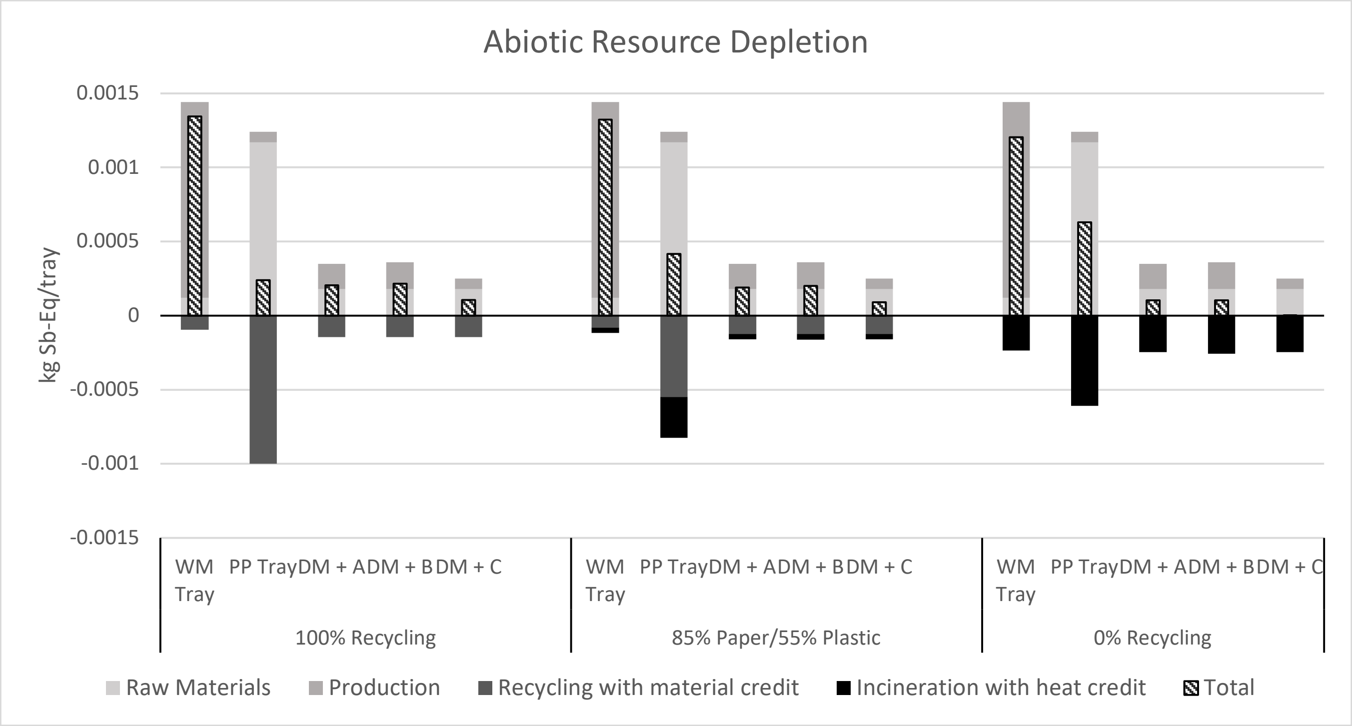

Figure 19 Abiotic resource depletion potential for 100% overall recycling, the base case of 85% paper recycling and 55% plastic recycling, and 0% overall recycling

Table 11 Total abiotic resource depletion potential for each tray and recycling rate

Total Abiotic Resource Depletion	100% Recycling (kg Sb-Eq)	85% Paper/55% Plastic Recycling (kg Sb-Eq)	0% Recycling (kg Sb-Eq)
Wet Moulded Tray	1.34E-03	1.32E-03	1.20E-03
Polypropylene Tray	2.40E-04	4.16E-04	6.30E-04
Dry Moulded Tray + A	2.05E-04	1.90E-04	1.02E-04
Dry Moulded Tray + B	2.15E-04	1.98E-04	1.02E-04
Dry Moulded Tray + C	1.05E-04	8.96E-05	2.18E-06

With decreasing recycling rate, all of the fibre trays decrease in abiotic resource use, while the polypropylene trays increase. This is once again due to the difference in credit possible for incineration and recycling. For the fibre trays, the benefit of avoided pulp production is smaller than the benefit of avoided heat production when it comes to abiotic resource depletion. For polypropylene, raw material production requires a large amount of abiotic resources, and the avoided production of this for recycling results in a larger credit than the avoided credit of heat production in incineration. In all cases, the wet moulded trays result in the largest abiotic resource depletion, followed by polypropylene trays, and finally dry moulded trays with the lowest depletion.

4.2.2.5 Cumulative Energy Demand

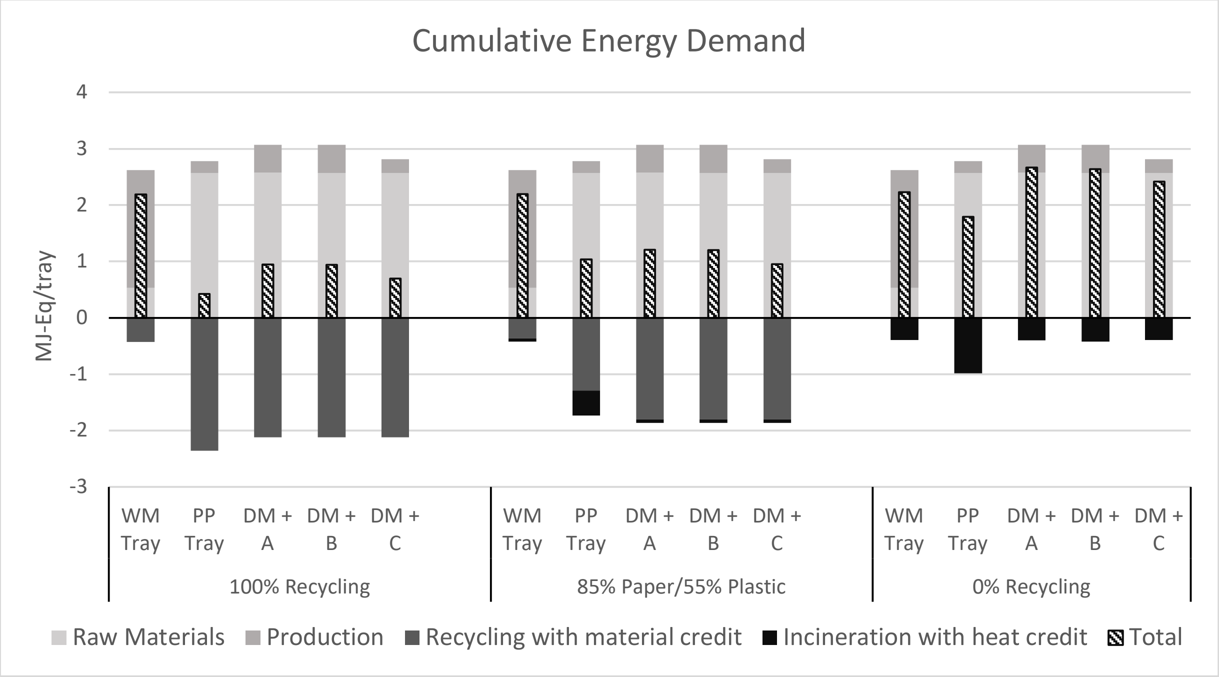

Figure 20 Cumulative energy demand for 100% overall recycling, the base case of 85% paper recycling and 55% plastic recycling, and 0% overall recycling

Table 12 Total cumulative energy demand for each tray and recycling rate

Total Cumulative Energy Demand	100% Recycling (kg MJ-Eq)	85% Paper/55% Plastic Recycling (kg MJ-Eq)	0% Recycling (kg MJ-Eq)
Wet Moulded Tray	2.19	2.20	2.23
Polypropylene Tray	0.42	1.04	1.79
Dry Moulded Tray + A	0.95	1.21	2.67
Dry Moulded Tray + B	0.95	1.20	2.64
Dry Moulded Tray + C	0.70	0.95	2.42

As recycling rate decreases, the total cumulative energy demand increases for each tray. The wet moulded trays do not change much with the change in recycling rate because the credit for avoided bagasse pulp is very similar to the credit for avoided heat production. The other trays are seen to change more because the credit for avoided energy demand in virgin material production in recycling is much greater than the credit for avoided energy from heat production in incineration. For the 100% and 85% paper/55% plastic recycling cases, the wet moulded trays require the most energy, while in the 0% recycling case, the dry moulded trays create the largest impact.

4.2.3 Sensitivity Analysis - European Wet Moulding

In order to make a better comparison between wet and dry moulding tray production, a scenario was completed where the wet moulding was modelled in Europe using softwood kraft pulp rather than bagasse. In this way, the wet moulded and dry moulded trays occur using the same European energy system, with the comparison being solely between the methods used to produce the trays. For the wet moulded tray production process, the same inventory as the Chinese production has been used, while replacing the electricity with the european mix. In the Chinese system, coal is input to the system to be used for heat, while in the European system, this has been replaced with natural gas, which is expected to be the largest used energy carrier for heating and cooling in the EU in 2030 (Fraunhofer Institute for Systems and Innovation Research, 2017). An investigation of other possible heat sources, such as biofuel, could be an interesting area to look into in the future. The european wet moulded tray also includes the addition of barrier C. This is because in reality, the wet moulded trays require a barrier in order to protect their contents just like the dry moulded trays. The process for the raw materials of wet and dry moulded trays is the exactly the same, aside from the mass of the trays, resulting in a lower impact for the raw materials for the wet moulded trays in each case. The presented products were modelled using the middle case of an 85% paper and 55% plastic recycling rate. The label WM-CN represents the wet moulded trays produced in China, while WM-EU represents the wet moulded trays produced in Europe.

4.2.3.1 Global Warming Potential

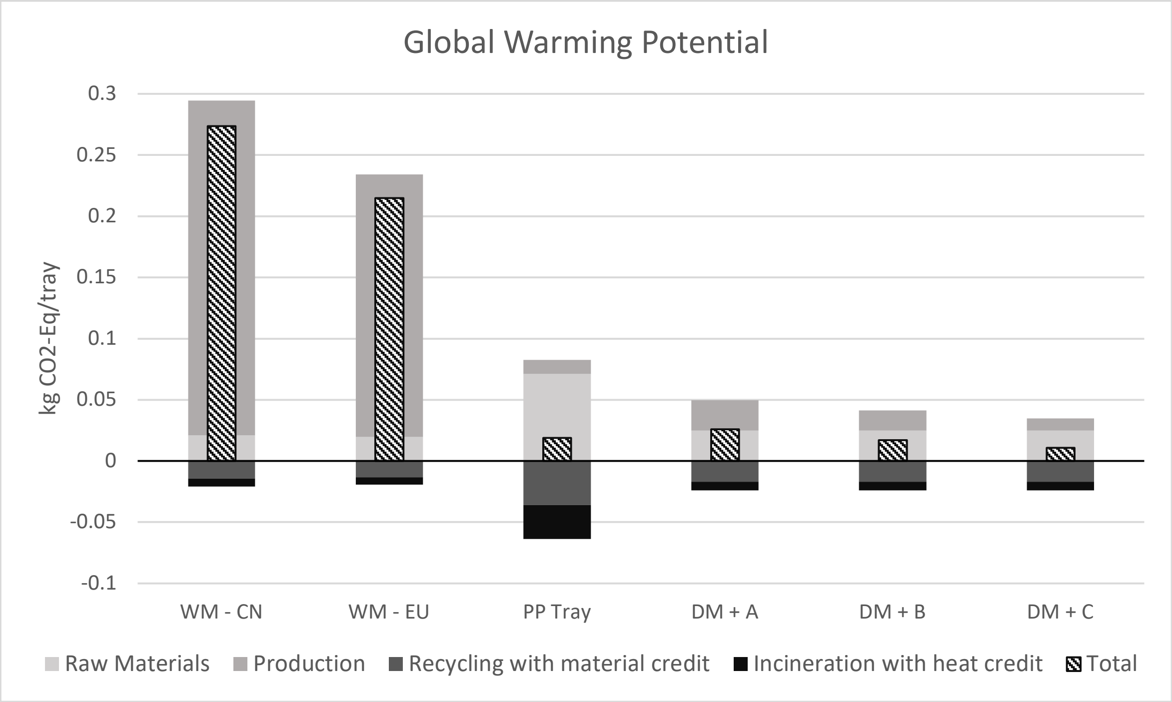

Figure 21 Global warming potential for the food trays, including a wet moulded tray produced in Europe

Table 13 Total global warming potential including the European wet moulded tray

85% Paper/55% Plastic Recycling	Total Global Warming Potential (kg CO_2-Eq)
Wet Moulded - CN	0.274
Wet Moulded - EU	0.215
Polypropylene Tray	0.019
Dry Moulded Tray + A	0.026
Dry Moulded Tray + B	0.017
Dry Moulded Tray + C	0.011

Starting with raw materials of the two wet moulded trays, due to the change in pulp process from bagasse to softwood, it is not possible to compare definitively the differences in performance. When it comes to European wet moulding and dry moulding however, the same pulp process is used for the raw materials, and the lower mass required for wet moulded trays leads to a lower raw material impact.

Comparing the wet moulded trays made in China to the ones made in Europe, the impact from production is lower due to the change in heat source from coal to natural gas and the change in energy mix. Looking at wet and dry moulding in Europe, the results show that the production process of dry moulding results in a much lower global warming impact compared to the European wet moulded trays. The wet moulded trays use natural gas for heat production, causing emissions which contribute greater to the greater global warming impact. This case creates the same result as that of Figure 10, with the addition of the European wet moulded tray, which creates the second largest global warming impact.

4.2.3.2 Acidification Potential

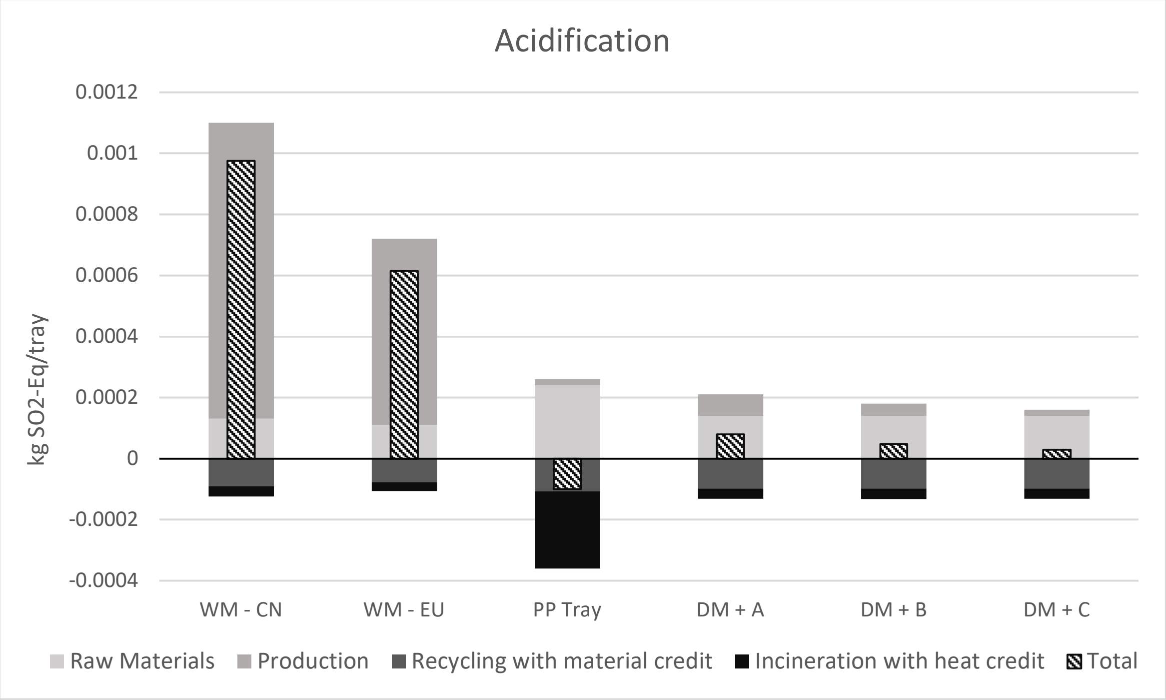

Figure 22 Acidification potential for the food trays, including a wet moulded tray produced in Europe

Table 14 Total acidification potential including the European wet moulded tray

85% Paper/55% Plastic Recycling	Total Acidification (kg SO_2-Eq)
Wet Moulded - CN	9.75E-04
Wet Moulded - EU	6.14E-04
Polypropylene Tray	-9.96E-05
Dry Moulded Tray + A	7.89E-05
Dry Moulded Tray + B	4.75E-05
Dry Moulded Tray + C	2.89E-05

Examining the production of the two wet moulded trays, the change in acidification impact comes largely from the change in heat source from coal to natural gas. Looking at the European wet and dry moulded trays, the wet moulding process leads to a larger acidification impact over dry moulding, with the greatest impact coming from the natural gas used. Overall, the dry moulded trays result in a lower impact compared to wet moulding, with the polypropylene trays creating the lowest total acidification impact, similar to the results in section 4.2.1.2.

4.2.3.3 Eutrophication Potential

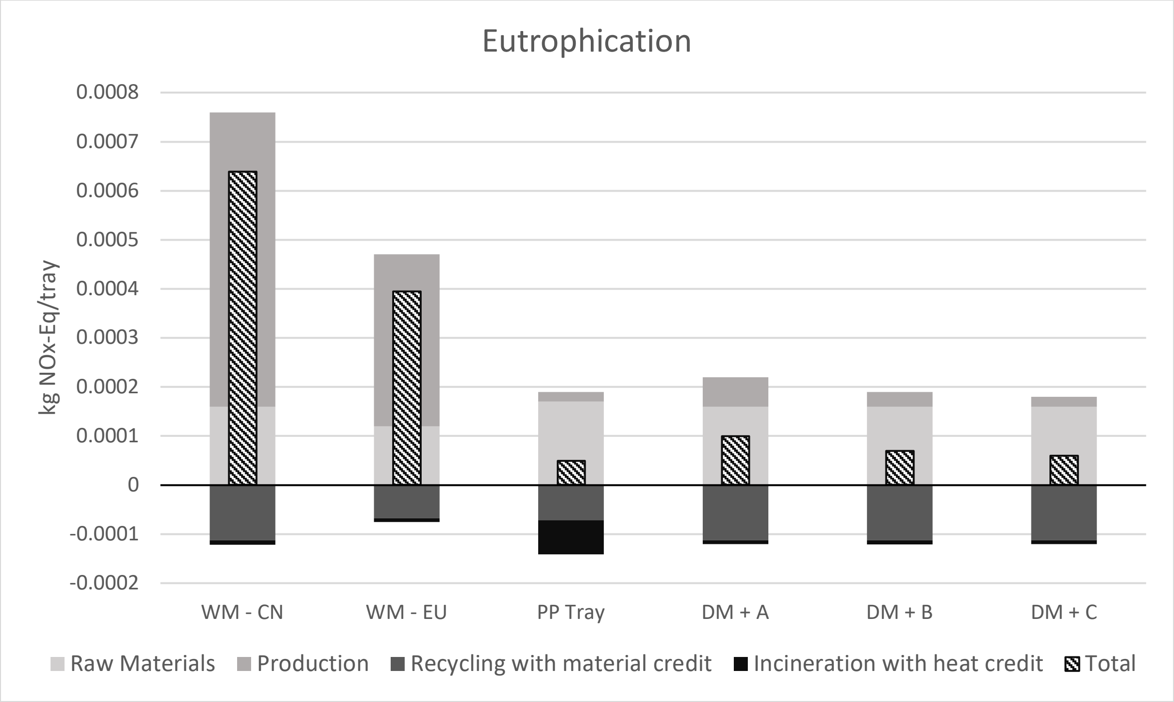

Figure 23 Eutrophication potential for the food trays, including a wet moulded tray produced in Europe

Table 15 Total eutrophication potential including the European wet moulded tray

85% Paper/55% Plastic Recycling	Total Eutrophication (kg NOx-Eq)
Wet Moulded - CN	6.39E-04
Wet Moulded - EU	3.95E-04
Polypropylene Tray	4.94E-05
Dry Moulded Tray + A	9.99E-05
Dry Moulded Tray + B	6.95E-05
Dry Moulded Tray + C	5.99E-05

For the eutrophication potential, the difference in production impact of the European and Chinese wet moulding trays is caused mainly by the change in heat source from coal to natural gas. The production impact of European wet moulding is larger than dry moulding, largely due to emissions created in wet moulded tray production because of natural gas use. In total, the dry moulded trays produce a smaller eutrophication impact than wet moulded, though, as was seen in section 4.2.1.3, the polypropylene trays overall still result in the smallest eutrophication impact.

4.2.3.4 Abiotic Resource Depletion Potential

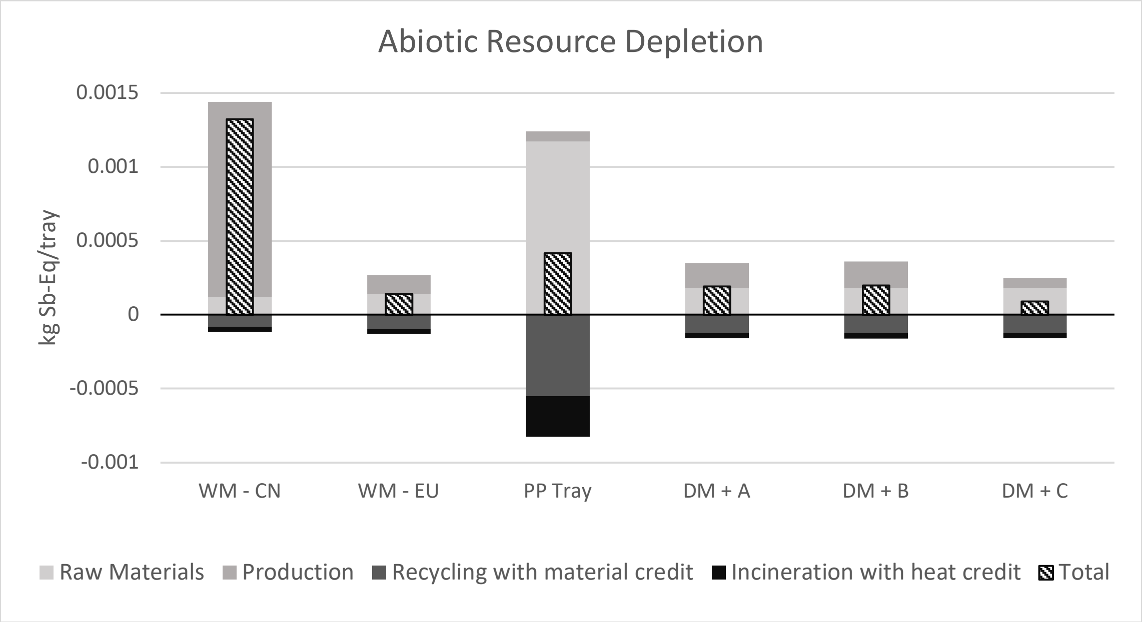

Figure 24 Abiotic resource depletion potential for the food trays, including a wet moulded tray produced in Europe

Table 16 Total abiotic resource depletion potential including the European wet moulded tray

85% Paper/55% Plastic Recycling	Total Abiotic Resource Depletion (kg Sb-Eq)
Wet Moulded - CN	1.32E-03
Wet Moulded - EU	1.42E-04
Polypropylene Tray	4.16E-04
Dry Moulded Tray + A	1.90E-04
Dry Moulded Tray + B	1.98E-04
Dry Moulded Tray + C	8.96E-05

There is a vast difference in the production impact of the wet moulded trays. The inclusion of coal in the Chinese wet moulded inventory causes the majority of the abiotic resource depletion. The natural gas used in the European production does not cause the largest impact to resource depletion for the European wet moulded trays, rather the electricity mix does. When creating the European inventory, the amount of natural gas input into the production process was based on creating the same amount of heat as the coal would for the Chinese production. This was because these inputs are not a physical part of the trays but rather used for their heat energy. When creating the same amount of heat energy, less natural gas is needed compared to coal, resulting in the larger resource impact for coal.

For the European production of wet and dry moulded trays, the wet moulded tray creates less of a resource depletion impact than the dry moulded tray with barriers A and B, while the dry moulded tray with barrier C creates the least impact. In this case, the laminate barriers cause a greater use of abiotic resources, leading to a larger impact for production. Overall, the dry moulded tray with barrier C creates the lowest impact due to resource depletion, followed by the European wet moulded tray, then the other dry moulded trays.

4.2.3.5 Cumulative Energy Demand

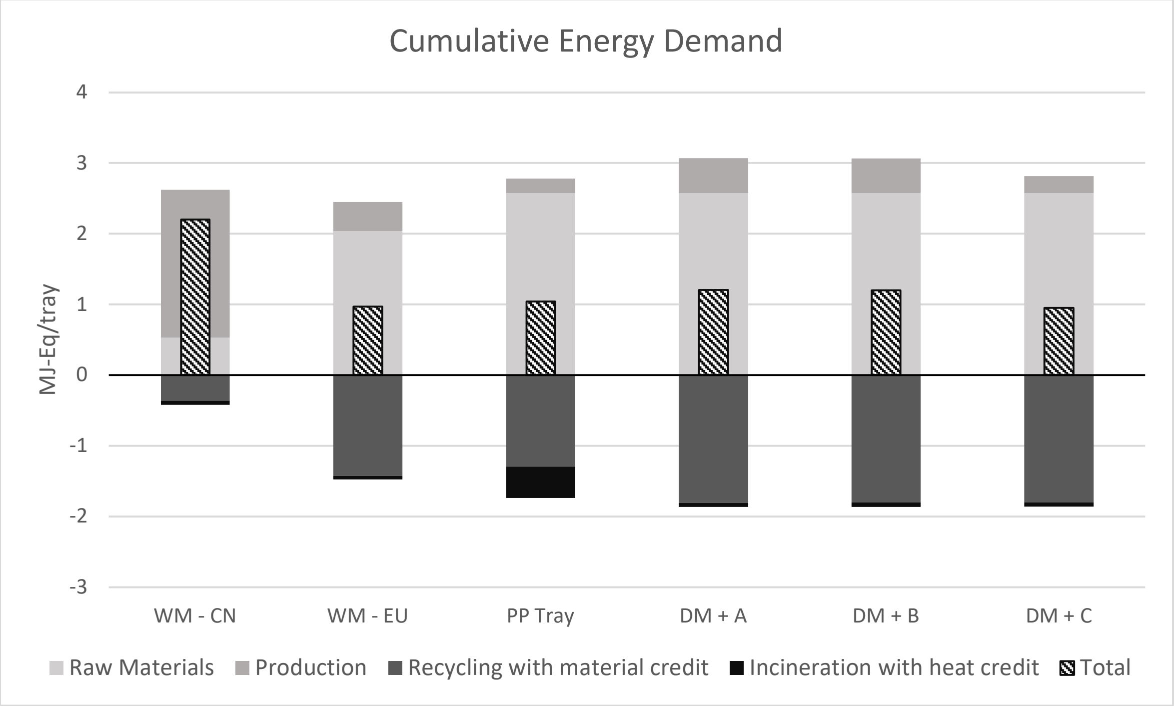

Figure 25 Cumulative energy demand for the food trays, including a wet moulded tray produced in Europe

Table 17 Total cumulative energy demand including the European wet moulded tray

85% Paper/55% Plastic Recycling	Total Cumulative Energy Demand (kg MJ-Eq)
Wet Moulded - CN	2.20
Wet Moulded - EU	0.97
Polypropylene Tray	1.04
Dry Moulded Tray + A	1.21
Dry Moulded Tray + B	1.20
Dry Moulded Tray + C	0.95

Comparing the Chinese wet moulding to European, it is not possible to say definitively that the raw material pulp process increases in impact due to the change in energy mix because the pulp process inventory has changed to match dry moulding. It can be seen that the European wet moulding raw materials result in creates a smaller impact compared to dry moulding, and because they are the same inventory this smaller result is credited to the fact that the amount of pulp used for a wet moulded tray is smaller than for dry moulding and therefore requires less energy to produce.

Looking at the production of the two wet moulded trays, the difference seen in production energy demand is due in large part to the change in heat source, as well as the change to a European energy mix. Comparing the European wet moulded and dry moulded tray production, the wet moulded tray, which includes barrier C, demands less energy than the dry moulded tray with barriers A and B, though it does require more energy than the dry moulded tray with barrier C. This illustrates the significance of barrier choice on production energy. Overall like in Figure 14, when end-of-life treatment is included, the credit given from avoided virgin material production in recycling and avoided heat production in incineration leads to the greatest impact for wet moulded trays in China, followed by the dry moulded trays with barriers A and B and then polypropylene. The wet moulded trays produced in Europe manage to result in the second lowest energy demand, with the dry moulded tray with barrier C being the lowest.

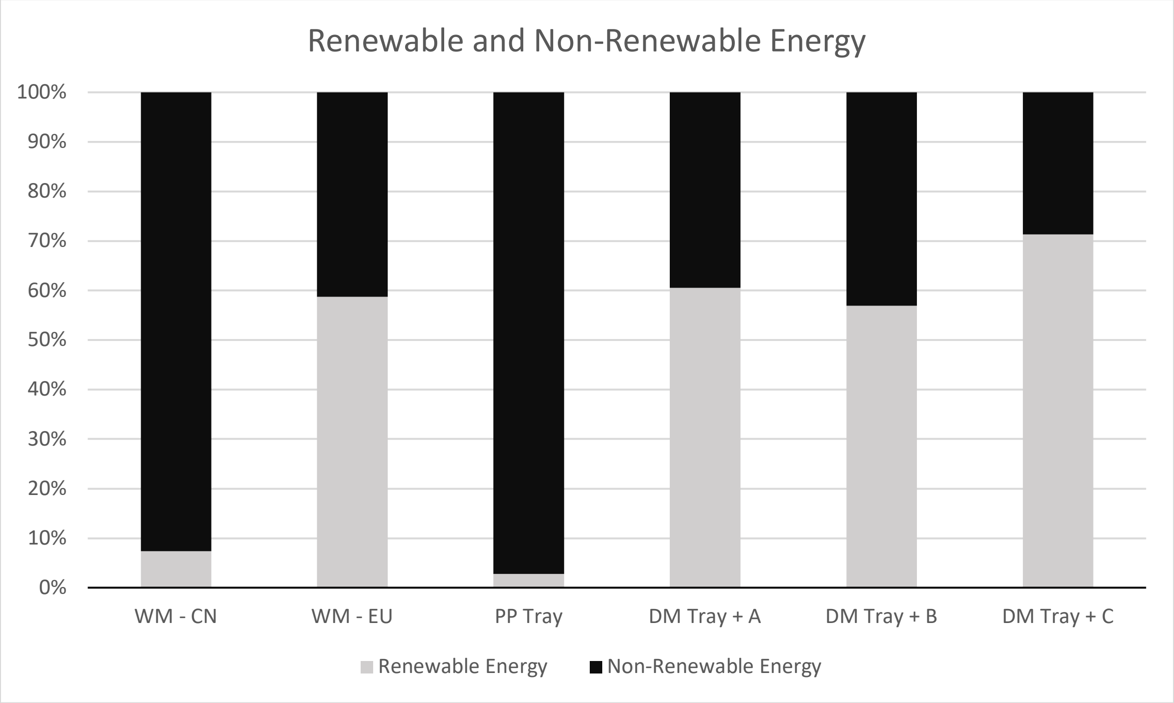

Figure 26 Cumulative energy demand, shown in terms of percentage use of renewable and non-renewable energy

Figure 26 shows the percentage use of energy type used for each tray. Adding the European wet moulded trays drastically changes the wet moulding energy type compared to the trays produced in China. When the wet moulded trays are produced in Europe, the majority of the energy demand comes from the raw material pulp production, which requires mainly renewable energy. Despite the different production methods of wet and dry moulding, overall, the types of energy used when both trays are made in Europe are nearly the same.

5 Discussion

Throughout this study, many choices needed to be made in order to complete the modelling for the studied food trays. Completed at an early point in the study, the interviews guided some of these choices. There was a definite emphasis on recycling and reducing overall environmental impact, and as a result it was important to show the variation possible in the end-of-life and examine how this affected the results. It was very interesting to discuss the different factors influencing sustainability decisions in each company. It would have been interesting to interview more companies to examine packaging sustainability demands and efforts in other sectors. The results of the recycling rate sensitivity analysis could be useful for deciding on tray type if a certain end-of-life treatment is desired. Additionally, knowing the difference in impact with different end-of-life treatments is useful for promoting the lowest impact option.

As this study was set in 2030, it was attempted as much as possible to model the systems using likely developments in this year, as with the European and Chinese energy mixes. It may be seen as unrealistic to include polypropylene in the recycling sensitivity analysis, when in the present day, the recycling rate is so low (Chasan et al., 2019) as well as barrier A, which is currently not recyclable. This LCA looks to the future, and it was seen to be worth exploring what may be possible in the future. Developments may occur which allow for greater polymer recycling. It could also be that greater bans occur for different materials like plastic and reduce its use entirely. There are any number of possible scenarios that could occur, but due to time constraints, it was not possible to explore these. It would be interesting in the future to explore more of these possibilities.

Reviewing the overall results, the dry moulded trays with barriers B and C perform favourably in terms of global warming potential and all of the dry moulded trays perform well in the abiotic resource depletion in the recycling rate sensitivity analysis. The plastic trays perform well for eutrophication and acidification. Overall, the Chinese wet moulded trays perform the worst for global warming, acidification, eutrophication, and abiotic resource depletion due to a large impact in production.

A big reason for the large impact due to production of wet moulded trays had to do with the fact that the trays were made in China, where the energy mix contains a larger portion of non-renewable resources like coal, which leads to larger emissions in general. Both the wet moulded and polypropylene trays are actually produced by Customer A, so it was considered important to include them using as much of the real-life parameters of their production as possible, including their geographic location. However, comparing the wet moulded trays produced in China to the rest of the trays produced in Europe must be done knowing that is it not possible to make specific claims about the specific tray production technologies because both the packaging method and the energy mix are changed. Because of this, it was important to complete a better comparison using the wet moulded trays. The European wet moulded production system compared to dry moulded made it possible to know that the comparison was between the two packaging methods.

The results of the European sensitivity analysis showed that the wet moulded tray produced in Europe resulted in a smaller impact for each impact category compared to its Chinese counterpart. The change in energy mix and heat supply were large contributors to this. Other than the impact improvement over the Chinese wet moulded trays, the results of global warming potential, acidification, and eutrophication did not change. However, the European wet moulded tray produced favourable results when it came to abiotic resource potential and cumulative energy demand, where it performed second best behind the dry moulded tray with barrier C.

The two energy mixes, Chinese and European were created using predictions about energy use in 2030 in the EU and China. The EU energy mix has been taken from the EUCO27 scenario from Banja & Jégard (2017), while the Chinese 2030 electricity mix has been taken from West (2017). These mixes are sourced from predictions, and though they have been created with governmental goals in mind, it is not possible to know exactly what the future will look like, and how product systems may change.

Considering the results of the barriers used on the dry moulded trays, barrier C consistently performs the best in terms of producing the smallest impact, regardless of impact category or recycling rate. This barrier is the lowest mass of the three, and though all of the barriers contain materials sourced from fossil resources, the differences in mass used and production processes leads to the lowest impact for barrier C. It could be interesting for future work to examine the barriers more specifically and include other possible barriers in the analysis.

Aside from recycling rate and geographical boundaries, another decision which impacted the results was the choice of allocation method. Using physical allocation for processes with multiple outputs resulted in a lower impact for the bagasse pulp due to bagasse being one of multiple products in the sugar production system and receiving only 55% of the impact as a result. A different choice of allocation method, such as economic or a physical aspect other than mass could greatly change the results. Aside from the physical allocation, the end-of-life allocation can greatly affect the results. There are different equations which place the impact from recycling on either the primary product, the secondary product, or a mix of those (Ekvall et al., 2020). There are guidelines on when each equation is most appropriate, but it can be possible to argue for multiple methods of allocation for a product system depending on how the materials are used and how the product system is set up (Bhatia et al., 20211).

As was mentioned briefly in the Methodology, the toxicity impact categories as well as land use have not been addressed in this LCA. It is important to remember that, though it was not able to be included here, the wet moulded trays require barrier chemicals which usually includes PFAS. These chemicals provide good protection from water and oil, but have been linked to health issues (Holmquist, 2020). Additionally, including land use would provide insight on the impact of the trays on land, particularly the fibre-based trays. A fuller, more complete view of the packaging technologies would include assessment of these categories, and this is recommended for future work.

The different products were modelled with a varying amount of primary data. The system modelled with the most primary data is the dry moulded process, as this is the process that The Loop Factory directly works with. It was also possible to get data on the barrier production from the companies producing them due to their relationships with The Loop Factory. The pulp data from Södra is not exactly the same as the fluff pulp that The Loop Factory uses, but it was decided that this was a good approximation of the pulp. The polypropylene tray system was based largely on ecoinvent processes. Inventory data on the PP tray production process was received from the tray producer, with the rest of the modelling data coming from ecoinvent. For the wet moulded trays, the production system was modelled without primary data in the inventory. Inventory data on bagasse production from sugar was taken from Mashoko et al. (2010), and wet moulded tray production was taken from Huo and Saito (2009). It was not possible to find data on the inventory of bagasse pulp, and as a result, a sulphate pulp process from ecoinvent was used, replacing bagasse for softwood in the inventory. Using data from ecoinvent does not mean that the product system is inaccurate, though using primary data is the best way to know that the system is as close to reality as possible, and it could be interesting to see the results with data from bagasse pulp and wet moulded package producers.

This life cycle assessment sought to expand knowledge of environmental performance for dry moulded packaging and alternatives when used for takeaway food packaging. Though past research seen did not include dry moulded packaging specifically, results which were presented by Schenker et al. (2021) showed a lower climate change impact for cellulose fibre packaging compared to plastic. This was seen for the case of dry moulded trays, but not for wet moulded trays, which resulted in a larger impact than the polypropylene tray, see Figure 21. This may be due to the inventory data. The moulded pulp product production inventory used by Schenker et al. (2021) was taken from primary data which was kept confidential. The importance of further research examining that there are not issues occurring in end-of-life treatment when barriers are used with fibre packaging was also mentioned. The results of this study do not include an aspect of how the inclusion of barriers may affect the end-of-life treatment, as recycling is expected to be possible for the fibre trays, aside from for barrier A in the present day. Further research on barrier performance and the compromises necessary to achieve acceptable protection of packaging contents will be necessary in the future. This study does fill in the previously empty research space of environmental impacts of takeaway packaging including dry moulded packaging. Further research in this space, including different modelling choices and applications of dry moulding, will strengthen this research area.

With all of these different choices which have been made, it is possible that another LCA practitioner completing this study would produce different results. However, the results of this study have been based on decisions which have been backed up by data and practicality, fuelled by curiosity, and seeks to be as accurate as possible in the time frame that the thesis provided.

6 Conclusions

The two aims of this study include to examine the drivers of sustainable packaging for customers of The Loop Factory and to evaluate the environmental impact of their dry moulding technology through life cycle assessment when used as a food tray. Through interviews with two of the companies collaborating with The Loop Factory, it was possible to get a better idea of their goals and how The Loop Factory can help them get there. The interviews informed the cases that were examined, particularly with regard to the end-of-life waste treatment cases.

This cradle-to-grave prospective life cycle assessment evaluated environmental impacts of the food tray made with Yangi dry moulding technology compared to wet moulded and polypropylene trays. This comparison revealed the nuance required when evaluating options in terms of sustainability, and how modelling choices affect final results. In the recycling rate sensitivity analysis, the LCA revealed a favourable performance for dry moulding with barriers B and C in terms of having the lowest impact for global warming potential and all of the dry moulded trays in the 0% recycling case. Throughout the results, the choice of barrier was seen to affect the results, with barrier A consistently creating the largest impact of the barriers. In the recycling rate sensitivity study, the cases of 85% paper/55% plastic recycling and 0% recycling for acidification and eutrophication, plastic resulted in the lowest impact. The plastic tray also performed well in terms of energy demand. It must be remembered that the comparison was completed using two different energy mixes, where the wet moulded trays were produced in China, while the rest were made in Europe, and this causes issues when trying to draw definitive conclusions about wet moulding vs. the other methods. Comparison may be made between the overall tray products and parts of the life cycle, but it is not sound to make comparisons about the specific production processes when both the technology and energy mix differ. The European mix allowed for comparison between the two wet moulding systems, looking at how the energy mixes affect the performance, as well as for comparison between the tray production methods occurring in Europe. Despite the reduction in impact compared to the wet moulded trays produced in China, the European production of wet moulded trays was not seen to change the results for the cases of global warming potential, acidification potential, and eutrophication potential.

Climate impact, resource use, and energy use are commonly seen advertised as selling points for products, while acidification and eutrophication are not commonly seen in everyday life. It also must be remembered that legislation is pushing for reduction of single use plastics and higher recycling rates. Depending on the tray options, the waste management methods, the production system, impacts of concern, and customer and legislative demands, the right choice of tray will be up to the user, but the dry moulded trays check many of the boxes.

7 Future Work

- An analysis focused on ecotoxicity and human toxicity. This is of particular interest due to the use of PFAS in wet moulding.
- An analysis of different future energy mix scenarios and the effect on the product systems
- An analysis of other waste management methods, such as anaerobic digestion
- An analysis which includes other allocation methods, both for multi-output processes and recycling
- Further analysis of barriers on dry moulded packaging, and the compromise between benefits like barrier performance and end-of-life treatment possible

References

Allacker, K., Mathieux, F., Pennington, D., & Pant, R. (2017). The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *International Journal of Life Cycle Assessment,* 22, 1441-1458. https://doi.org/10.1007/s11367-016-1244-0

Andersson, C., Ernstsson M., & Järnström, L. (2002). Barrier properties and heat sealability/failure mechanisms of dispersion-coated paperboard. *Packaging Technology and Science, 15*(4), 209-224. https://doi.org/10.1002/pts.590

Ardente, F., & Cellura, M. (20129. Economic allocation in life cycle assessment. *Journal of Industrial Ecology, 16*(3), 387-398. https://doi.org/10.1111/j.1530-9290.2011.00434.x

Arvidsson, R., Tillman, A. M., Sandén, B. A., Janssen, M., Nordelöf, A., Kushnir, D., & Molander, S. (2018). Environmental assessment of emerging technologies recommendations for prospective LCA. *Journal of Industrial Ecology, 22*(6), 1286-1294. https://doi.org/10.1111/jiec.12690

Bajpai, P. (2010). Overview of pulp and papermaking processes. In *Environmentally friendly production of pulp and paper* (pp. 8-45). John Wiley & Sons, Incorporated. https://ebookcentral.proquest.com/lib/chalmers/reader.action?docID=675063&ppg=3

Banja, M., & Jégard, M. (2017). Renewable technologies in the EU electricity sector: trends and projections -Analysis in the framework of the EU 2030 climate and energy strategy. Luxembourg: Publications Office of the European Union. 10.2760/733769

Baumann, H., & Tillman, A. M. (2004). *The hitch hiker's guide to LCA: An orientation in life cycle assessment methodology and application*. Studentlitteratur.

Berk, Z. (2018). Food packaging. *In Food process engineering and technology* (3rd ed.). (pp. 625-642). Elsevier Science & Technology.

Bhatia, P., Cummis, C., Draucker, L., Rich, D., Lahd, H., & Brown, A. (2011). *Product Life Cycle Accounting and Reporting Standard.* https://www.wri.org/research/greenhouse-gas-protocol-product-life-cycle-accounting-and-reporting-standard#:~:text=The%20GHG%20Protocol%20Product%20Life,associated%20with%20a%20specific%20product.

Breulmann, M., Künkel, A., Philipp, S. Reimer, V., Siegenthaler, K.O., Skupin, G., & Yamamoto, M. (2016). Polymer, Biodegradable. In Wiley-VCH (Ed.), *Ullmann's polymers and plastics – products and processes, 4 volume set* (pp. 1232-1259). John Wiley & Sons.

British Standards Institution. (2011). Specification for the assessment of the lifecycle greenhouse gas emissions of goods and services (PAS 2050:2011). https://shop.bsigroup.com/upload/shop/download/pas/pas2050.pdf

Brouwer, M.T., Thoden van Velzen, E.U., Ragaert, K., ten Klooster, R. (2020). Technical limits in circularity for plastic packages. *Sustainability, 12*(23), 10021. https://doi.org/10.3390/su122310021

Buyle, M., Audenaert, A., Billen, P., Boonen, K., & Van Passel, S. (2019). The future of ex-ante LCA? Lessons learned and practical recommendations. *Sustainability, 11*(19), 5456. https://doi.org/10.3390/su11195456

Chasan, E. (2019). *There's finally a way to recycle the plastic in shampoo and yogurt packaging.* Bloomberg Businessweek. https://www.bloomberg.com/news/features/2019-09-25/polypropylene-plastic-can-finally-be-recycled

Collingridge, D. (1980). *The social control of technology*. Frances Pinter.

Copello de Souza, L. (2019). *Unfolding the single-use plastics directive: Policy briefing*. Zero Waste Europe. https://rethinkplasticalliance.eu/wp-content/uploads/2019/05/ZWE_Unfolding-the-SUP-directive.pdf

Cucurachi, S., van der Giesen, C., & Guinée, J. (2018). Ex-ante LCA of emerging technologies. *Procedia CIRP*, *69*, 463-468. https://doi.org/10.1016/j.procir.2017.11.005

Didone, M., Saxena, P., Meijer, E. B., Tosello, G., Bissacco, G., McAloone, T. C., Pigosso, D. C. A., & Howard, T. J. (2017). Moulded Pulp Manufacturing: Overview and Prospects for the Process Technology. *Packaging Technology and Science, 30*(6), 231-249. https://doi.org/10.1002/pts.2289

Directive 94/62/EC. *Packaging and packaging waste*. European Parliament, Council of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A01994L0062-20180704

Directive 2018/852. *Amending directive 94/62/EC on packaging and packaging waste.* European Parliament, Council of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1551965345008&uri=CELEX:32018L0852

Directive 2019/904. *The reduction of the impact of certain plastic products on the environment.* European Parliament, Council of the European Union. http://data.europa.eu/eli/dir/2019/904/oj

Ekvall, T., Björklund, A., Sandin, G., Jelse, K., Lagergren, J., Rydberg, M. (2020). *Modeling recycling in life cycle assessment*. Swedish Life Cycle Center. https://www.lifecyclecenter.se/publications/modeling-of-recycling-in-life-cycle-assessment/

Ellen MacArthur Foundation (2016). *The New Plastics Economy — Rethinking the future of plastics*. http://www.ellenmacarthurfoundation.org/publications

Eurostat. (2021a). Recycling rate of packaging waste by type of packaging. [Data File]. https://ec.europa.eu/eurostat/databrowser/view/cei_wm020/default/table?lang=en

Eurostat. (2021b). Road freight transport by journey characteristics. https://ec.europa.eu/eurostat/statistics-explained/index.php/Road_freight_transport_by_journey_characteristics#Average_distance_travelled

Feber, D., Nordigården, D., Granskog, A., Ponkshe S., Berg, P. (2020). *The drive toward sustainability in packaging – beyond the quick wins.* McKinsey & Company. https://www.mckinsey.com/industries/paper-forest-products-and-packaging/our-insights/the-drive-toward-sustainability-in-packaging-beyond-the-quick-wins#

Fogg, J. (2020, September 21). *When recyclability isn't enough.* Packaging Strategies. https://www.packagingstrategies.com/articles/95676-when-recyclability-isnt-enough

Fraunhofer Institute for Systems and Innovation Research (ISI), Fraunhofer Institute for Solar Energy Systems (ISE), Institute for Resource Efficiency and Energy Strategies GmbH (IREES), Observ'ER, TU Wien – Energy Economics Group (EEG), & TEP Energy GmbH (TEP). (2017). *Mapping and analyses of the current and future (2020-2030) heating/cooling fuel deployment (fossil/renewables)*. European Commission. https://ec.europa.eu/energy/sites/ener/files/documents/mapping-hc-final_report-wp3-wp4.pdf

Gahleitner, M. & Pualik, C. (2016). Propylene. In Wiley-VCH (Ed.), *Ullmann's polymers and plastics – products and processes, 4 volume set* (pp. 937-979). John Wiley & Sons.

Galić, K. (2015). *Barrier packaging materials*. New Food. https://www.newfoodmagazine.com/article/16971/barrier-packaging-materials/

Gallego-Schmid, A., Mendoza, J.M.F., Azapagic, A. (2019). Environmental impacts of takeaway food containers. *Journal of Cleaner Production, 211*, 417-427. https://doi.org/10.1016/j.jclepro.2018.11.220

Hermansson, F. (2013). *Environmental Evaluation of Bio-Composites Using LCA*. [Master's Thesis, Chalmers University of Technology]. Chalmers Open Digital Repository.

Holmquist, H. (2020). *Chemical substitution with a life cycle perspective: The case of per- and polyfluoroalkyl substances in durable water repellents*. [Doctoral Thesis, Chalmers University of Technology]. Research.chalmers.se

Huo, L. & Saito, K. (2009). Multidimensional life cycle assessment on various moulded pulp production systems. *Packaging Technology and Science, 22*(5), 261-273. https://doi.org/10.1002/pts.852

International Organization for Standardization. (2006a). *Environmental management – Life cycle assessment – Principles and framework* (ISO Standard No. 14040:2006). http://www.cscses.com/uploads/2016328/20160328110518251825.pdf

International Organization for Standardization. (2006b). *Environmental management – Life cycle assessment – Requirements and guidelines* (ISO Standard No. 14044:2006). https://www-sis-se.eu1.proxy.openathens.net/api/document/get/46898

Mashoko, L., Mbohwa, C., Thomas, V.M. (2010). LCA of the South African sugar industry. *Journal of Environmental Planning and Management, 53*(6), 793-807. https://doi.org/10.1080/09640568.2010.488120

Material Economics. (2018). *Sustainable packaging – the role of materials substitution.* https://materialeconomics.com/publications/sustainable-packaging

Nikodinovic-Runic, J., Guzik, M., Kenny, S.T., Babu, R., Werker, A., O'Connor, K.E. (2013). Carbon-rich wastes as feedstocks for biodegradable polymer (polyhydroxyalkanoate) production using bacteria. *Advances in Applied Microbiology, 84*, 139-200. https://doi.org/10.1016/B978-0-12-407673-0.00004-7

Park, W., Kim, R., Roh, S., & Ban, H. (2020). Analysis of major environmental impact categories of road construction materials. *Sustainability, 12*(17), 6951. https://doi.org/10.3390/su12176951

Plastics Europe (n.d.) *How plastics are made.* https://www.plasticseurope.org/en/about-plastics/what-are-plastics/how-plastics-are-made

Plastics Europe (2019*). Plastics – The facts 2020.* https://www.plasticseurope.org/en/resources/publications/4312-plastics-facts-2020

PulPac (2021). *Technology*. https://www.pulpac.com/technology/

Sangroniz, A., Zhu, J.B., Tang, X., Etxeberria, A., Chen, E.Y.X., & Sardon, H. (2019). Packaging materials with desired mechanical properties and full chemical recyclability. *Nature Communications*, 10(3559). https://doi.org/10.1038/s41467-019-11525-x

Schenker, U., Chardot, J., Missoum, K., Vishtal, A., & Bras, J. (2021). Short communication on the role of cellulosic fibre-based packaging in reduction of climate change impacts. *Carbohydrate Polymers, 254*, 117248. https://doi.org/10.1016/j.carbpol.2020.117248

Selke, S.E., & Hernandez, R.J. (2001). Packaging: Polymers in flexible packaging. In Buschow, K.H.J., Cahn, R.W., Flemings, M.C., Ilschner, B. Kramer, E.J., Mahajan, S., & Veyssière, P. (Eds.), *Encyclopedia of materials: Science and technology.* (2nd ed., pp. 6652-6656). Elsevier. https://doi.org/10.1016/B0-08-043152-6/01176-1

Staffas, L., Tufvesson, L., Svenfelt, Å., Åstrom, S., Torén, J., & Arushanyan, Y. (2013). *Alternative sources for products competing with forest based biofuel – A pre-study*. Report No 2013:9, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. www.f3centre.se

Södra (n.d.). *Environmental Data.* https://www.sodra.com/sv/se/massa/massa-och-hallbarhet/environmental-data/

The Loop Factory. (2020) *Enabling manufacturing technology for fibre-based packaging solutions*. Unpublished Manuscript.

Throne, J. (2017). Thermoforming. In M. Kutz (Ed.) *Applied Plastics Engineering Handbook* (2nd ed.). (pp. 245-275) https://doi.org/10.1016/B978-0-323-39040-8.00016-X

United States Environmental Protection Agency. (2021, April 6). *Basic Information on PFAS*. https://www.epa.gov/pfas/basic-information-pfas#:~:text=periods%20of%20time.-,There%20is%20evidence%20that%20exposure%20to%20PFAS%20can%20lead%20to,immunological%20effects%20in%20laboratory%20animals.&text=cancer%20(for%20PFOA)%2C%20and

West, B. (2017, September 27). *Chinese coal-fired electricity generation expected to flatten as mix shifts to renewables*. United States Energy Information Administration (EIA). https://www.eia.gov/todayinenergy/detail.php?id=33092

Wagner, J. R. (2009). Nonwovens. In K. L. Yam (Ed.), *The Wiley Encyclopedia of Packaging* (3rd ed.). (pp. 672–674). John Wiley & Sons.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment, 21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Appendix

Appendix A – Customer Interviews

The following tables are summaries of the interview notes taken with Customer A and B. These discussions sought to determine where the push for sustainability in packaging is coming from for each company, and what their plans to address these pushes are.

Table A.1 Summary of discussion with Customer A.

	Customer A - food packaging product supplier
What are drivers for your sustainability needs?	There is an increase in general awareness from customers about sustainability, especially single use materials and single use plastic in particular. An increase in awareness of limitations at the end-of-life and how different materials can be managed is occurring as well.
What are customers asking for? Have you noticed a change in their requests as new legislation is approved?	Customers are often interested in seeing reports like carbon footprint and water consumption of products compared to others.
What regulations have you found to be most impactful in your sustainability efforts, and how have they influenced the direction of your environmental efforts? (SUP Directive, EU Packaging and Packaging Waste)	- Single Use Plastics directive: There is still a wait on guidelines clarifying further which materials and products in particular are to be banned and whether materials like cellulose are to be exempt. - Packaging and Packaging Waste directive: Producer responsibility is becoming more strict - Expected food safety legislation: PFAs are used in wet moulding, and there is anticipation that a ban will be coming, partly due to the fact that there is already a ban in Denmark. Customer A is looking into this and looking for alternatives due to their own interest, as well ask customers who have asked about it.
What direction do you see your efforts going in the future in terms of your packaging?	There are plans to reduce plastic use, including barriers for trays due to the push from regulation. Proposed regulations include taxing trays containing plastic, and consumption reduction targets from the Single Use Plastic directive, so there is financial incentive to replace these materials. The end-of-life infrastructure is being scrutinized due to demand from customers that product be recyclable.

Table A.2 Summary of discussion with Customer B.

	Customer B - luxury retail brand
What are drivers for your sustainability needs?	-They began analysing their packaging portfolio with the aim to set an eco-design strategy. They want to be "at the top" in terms of their eco-design ambition and connect it to luxury packaging. -Changing regulations around the world are creating a push to do better in aspects like recyclability. Customer B follows key principles: - Reduce material use with reduction targets, especially for plastic - Design materials and products which can have a second life - Promote the use of sustainable materials - Removing plastics or controversial materials where possible, otherwise switch to non-plastic material
What are customers asking for? Have you noticed a change in their requests as new legislation is approved?	Customer requests regarding sustainability efforts depends on where they are located. In Europe in particular, plastic use is a major concern for their customers.
What regulations have you found to be most impactful in your sustainability efforts, and how have they influenced the direction of your environmental efforts? (SUP Directive, EU Packaging and Packaging Waste)	- Regulations are coming from Europe as a whole, and in the country where Customer B's headquarters are located. There are announcements for different regulations, which they are waiting to get clarifying information on how to apply the regulations within their business. - Customer B is also facing restrictions on the design of products in Asia, which includes how products can be packed for online sales, volume constraints, and certain blacklisted materials.
What direction do you see your efforts going in the future in terms of your packaging?	Customer B has completed examinations of thousands of components in their packaging. They have found plastic to be the most scrutinized, though this is one of the less used packaging materials. When it comes to plastic in particular, the end-of-life and ensuring minimized environmental concern is of great interest. They want to promote recycled and biobased materials, after ensuring that the environmental impact is actually better than a fossil-based or virgin material.

Appendix B – Life Cycle Inventory Modelling

B.1 Energy System

Because the LCA is set to be in 2030, the electricity systems were set up as much as possible to represent what is predicted to occur in the future. The sources and breakdown of the electricity for the European mix were taken from predictions of the EUCO27 Scenario from Banja & Jégard (2017), which is designed to meet the policy goals of the 2030 energy targets set by the European Council. Table B.1 lists the inventory and providers used in openLCA to make the mix. The providers used are Swedish, as it was required to choose a country for the provider, and this was expected to simulate a low carbon system. Where EUCO is listed in the providers, the electricity or heat has been replaced with the 2030 mix.

Table B.1 Inventory flows, amounts, and ecoinvent providers used for the European electricity mix

Source	Flow	Amount (MWh)	Provider
		Inputs	
Nuclear	electricity, high voltage	0.22	electricity production, nuclear, pressure water reactor | electricity, high voltage | APOS, U - SE
Wind	electricity, high voltage	0.197	electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | APOS, U - SE
Gas	electricity, high voltage	0.161	heat and power co-generation, natural gas, conventional power plant, 100MW electrical | electricity, high voltage | APOS, U - SE
Solids	electricity, high voltage	0.138	heat and power co-generation, hard coal | electricity, high voltage | APOS, U - SE
Hydropower	electricity, high voltage	0.108	electricity production, hydro, run-of-river | electricity, high voltage | APOS, U - SE
Solar	electricity, high voltage	0.086	electricity production, solar thermal parabolic trough, 50 MW | electricity, high voltage | APOS, U - RoW
Biomass	electricity, high voltage	0.085	heat and power co-generation, biogas, gas engine | electricity, high voltage | APOS, U - SE
Oil	electricity, high voltage	0.005	electricity production, oil | electricity, high voltage | APOS, U - SE
		Outputs	
-	EUCO27 Electricity Mix	1.0	-

It was also necessary to create a heat energy mix for the production of steam used in processes. This mix was created using Patronen et al. (2017) and is based on the Swedish heating and cooling energy carrier mix.

Table B.2 Inventory flows, amounts, and ecoinvent providers used for the European electricity mix

Flow	Amount (MWh)	Provider
	Inputs	
heat, central or small-scale, other than natural gas	8.2	heat production, at heat pump 30kW, allocation exergy | heat, central or small-scale, other than natural gas | APOS, U - Europe without Switzerland
heat, district or industrial, natural gas	12.3	heat and power co-generation, natural gas, conventional power plant, 100MW electrical | heat, district or industrial, natural gas | APOS, U - SE
heat, district or industrial, other than natural gas	112.5	heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | heat, district or industrial, other than natural gas | APOS, U - SE
heat, district or industrial, other than natural gas	28.6	heat and power co-generation, hard coal | heat, district or industrial, other than natural gas | APOS, U - SE

heat, district or industrial, other than natural gas	18.4	heat and power co-generation, oil | heat, district or industrial, other than natural gas | APOS, U - SE
Outputs		
Heat Energy Mix	180.0	-

The source for the Chinese electricity system in 2030 comes from West (2017).

Table B.3 Inventory flows, amounts, and ecoinvent providers used for the Chinese electricity mix

Source	Flow	Amount (MWh)	Provider
Inputs			
Nuclear	electricity, high voltage	0.038	electricity production, nuclear, pressure water reactor | electricity, high voltage | APOS, U - CN-GD
Coal	electricity, high voltage	0.433	electricity production, hard coal | electricity, high voltage | APOS, U - CN-GX
Wind	electricity, high voltage	0.144	electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | APOS, U - CN-GX
Hydropower	electricity, high voltage	0.192	electricity production, hydro, pumped storage | electricity, high voltage | APOS, U - CN-GD
Biomass	electricity, high voltage	0.019	heat and power co-generation, biogas, gas engine | electricity, high voltage | APOS, U - RoW
Solar	electricity, high voltage	0.077	electricity production, solar thermal parabolic trough, 50 MW | electricity, high voltage | APOS, U - RoW
Natural Gas	electricity, high voltage	0.096	electricity production, natural gas, conventional power plant | electricity, high voltage | APOS, U - CN-GX
Outputs			
-	China 2030 Electricity Mix	1.0	-

B.2 Transportation

Transportation takes place between steps which are known to take materials from one point to another. The distance to retail for all of the trays is considered to be 581 km based on Eurostat (2021b). The other transportation steps are:

Table B.4 Transportation locations for transportation steps in openLCA.

Material Transported	Starting Point	Ending Point
Softwood Pulp	Skutskär, Sweden	Poznan, Poland
Barrier A	Confidential	Poznan, Poland
Barrier B	Confidential	Poznan, Poland
Barrier C	Confidential	Poznan, Poland
Bagasse Pulp	Guangxi, China	Nanning, Guangxi, China
WM Tray	Nanning, Guangxi, China	Munich, Germany

Google maps was used to determine the land distance between locations. Where sea travel was necessary, land transport was assumed to go to the nearest port and sea transport was assumed to send the materials to the port closest to the ending point, where land transport was used to take the material to its final location. Sea-distances.org was used to determine distance between ports. For the case of the bagasse pulp, a specific location was not known for the starting point, and 105 km was assumed, based on the distance travelled on land by Södra’s pulp. For the modelling of transportation in openLCA, Table B.5 lists the type of transportation used on land and sea. The same flows were used each time land and sea transportation occurred.

Table B.5 Transportation flows and providers used for land and sea

Flow	Provider
transport, freight, lorry 16-32 metric ton, EURO6	market for transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U - RER
transport, freight, sea, bulk carrier for dry goods	market for transport, freight, sea, bulk carrier for dry goods | transport, freight, sea, bulk carrier for dry goods | APOS, U - GLO

B.3 Process Inventory

The data for the pulp mill was taken from Södra (n.d) and Södra (2020) and for input of chemicals, Culbertson et al. (2016). The pulp product modelled was Blue 85Z in 2020. First material was transported to the pulp mill in Table B.4, and the pulp inventory is seen in Table B.5. These inventories are the same for each dry moulded tray. The inventories for the barriers and dry moulded tray production have been kept confidential.

Table B.6 Inventory flows, amounts, and ecoinvent providers used for the material input into the pulp mill

Material Input to Pulp Mill			
Flow	**Amount**	**Unit**	**Provider**
Inputs			
hydrogen peroxide, without water, in 50% solution state	17	kg	market for hydrogen peroxide, without water, in 50% solution state | hydrogen peroxide, without water, in 50% solution state | APOS, U - RER
methanol	5	kg	market for methanol | methanol | APOS, U - GLO
quicklime, milled, loose	57	kg	market for quicklime, milled, loose | quicklime, milled, loose | APOS, U - RoW
sodium chlorate, powder	51	kg	EUCO market for sodium chlorate, powder | sodium chlorate, powder | APOS, U (copy) - RER
sodium hydroxide, without water, in 50% solution state	26	kg	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | APOS, U - GLO
sulfuric acid	31	kg	market for sulfuric acid | sulfuric acid | APOS, U - RER
transport, freight train	187*208	kg*km	market for transport, freight train | transport, freight train | APOS, U - Europe without Switzerland
transport, freight, lorry 16-32 metric ton, EURO6	187*270	kg*km	market for transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U - RER
transport, freight, lorry 16-32 metric ton, EURO6	3259*105	kg*km	market for transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U - RER
transport, freight, sea, bulk carrier for dry goods	187*420	kg*km	market for transport, freight, sea, bulk carrier for dry goods | transport, freight, sea, bulk carrier for dry goods | APOS, U - GLO
transport, freight, sea, bulk carrier for dry goods	3259*34	kg*km	market for transport, freight, sea, bulk carrier for dry goods | transport, freight, sea, bulk carrier for dry goods | APOS, U - GLO
wood chips, wet, measured as dry mass	2543	kg	softwood forestry, spruce, sustainable forest management | wood chips, wet, measured as dry mass | APOS, U - SE
wood chips, wet, measured as dry mass	496	kg	softwood forestry, pine, sustainable forest management | wood chips, wet, measured as dry mass | APOS, U - SE
Outputs			
Material Input	3446	kg	-

Table B.7 Inventory flows, amounts, and ecoinvent providers used for the kraft pulp mill

Kraft Pulp Mill			
Flow	**Amount**	**Unit**	**Provider**
Inputs			
electricity, high voltage	1047	kWh	EUCO sulfate pulp production, from softwood, bleached | electricity, high voltage | APOS, U (copy) - RER
EUCO27 Electricity Mix	7	kWh	1 EUCO27 Electricity Generation
heat, from steam, in chemical industry	2960	kWh	EUCO market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | APOS, U (copy) - RER
Material Input	3446	kg	1A Material Input Transport to Pulp Mill
tap water	58825.95	kg	market for tap water | tap water | APOS, U - Europe without Switzerland
Outputs			
Softwood Kraft Pulp	**1**	**t**	
Biomethanol	4.29E-04	t	
BOD5, Biological Oxygen Demand	0.15	kg	
Carbon dioxide, biogenic	2350	kg	
Carbon dioxide, fossil	10	kg	
COD, Chemical Oxygen Demand	7.9	kg	
Dust, unspecified	0.16	kg	
electricity, high voltage	333	kWh	
EUCO27 Electricity Mix	0	MJ	
Lime Sludge	0.035	t	
Nitrogen oxides	1.2	kg	
Nitrogen, total	0.058	kg	
Phosphorus, total	0.004	kg	
Sulfur	0.19	kg	
Sulfur dioxide	0.38	kg	
Tall Oil	0.019	t	
TOC, Total Organic Carbon	2.6	kg	
Turpentine	9.12E-04	t	
Waste Flow	18	kg	

The inventory for bagasse production was taken from Mashoko et al. (2010), where it is a byproduct of the sugar production process.

Table B.8 Inventory flows, amounts, and ecoinvent providers used for bagasse production from sugar, taken from Mashoko et al. (2010)

Flow	Amount	Unit	Provider
Bagasse Production from Sugar			
Inputs			
China 2030 Electricity Mix	296.1	kWh	China 2030 Electricity Generation
hard coal	0.071	t	market for hard coal | hard coal | APOS, S - CN
steam, in chemical industry	4.4	t	steam production, in chemical industry | steam, in chemical industry | APOS, U - RoW
sugarcane	8.46	t	market for sugarcane | sugarcane | APOS, U - RoW
tap water	5.062	t	market for tap water | tap water | APOS, U - RoW
Outputs			
Bagasse	**2.4**	**t**	
BOD5, Biological Oxygen Demand	6.6	kg	
Carbon dioxide, fossil	196	kg	
COD, Chemical Oxygen Demand	19	kg	
filter cake, from sugarcane juice filtration	0.56	t	
Iron	0.00126	kg	
Methane	7.5	kg	
molasses, from sugar beet	0.38	t	
Nitrate	12	kg	
Nitrogen dioxide	7.5	kg	
NMVOC, non-methane volatile organic compounds, unspecified origin	0.07	kg	
Phosphate	0.15	kg	
sugar, from sugarcane	1	t	
Sulfur dioxide	2.18	kg	
Suspended solids, unspecified	0.05	kg	

The inventory for wet moulded trays in China is taken from Huo and Saito (2009) and seen in Table B.10. For modelling bagasse pulp from bagasse, sulfate pulp production process in ecoinvent was used. The wood inputs and outputs as well as electricity were replaced with bagasse and the Chinese electricity mix. The amount did not change in the inventory. The processes used and inputs and outputs changed are seen in Table B.9.

Table B.9 Flows replaced in the ecoinvent process for unbleached sulfate pulp in order to represent bagasse pulp

Bagasse Provider	Inputs Flows Replaced	Replacement	Output Flows Replaced	Replacement
sulfate pulp production, from softwood, unbleached | sulfate pulp, unbleached | APOS, U	pulpwood, softwood, measured as solid wood under bark wood chips, dry, measured as dry mass	Bagasse	Sulfate pulp, unbleached	Bagasse Pulp
market for sulfate pulp, unbleached | sulfate pulp, unbleached | APOS, U	Sulfate pulp, unbleached	Bagasse Pulp	Sulfate pulp, unbleached	Bagasse Pulp

Table B.10 Inventory flows, amounts, and ecoinvent providers used for production of wet moulded trays in China, taken from Huo and Saito (2009)

Wet Moulded Tray Production in China			
Flow	**Amount**	**Unit**	**Provider**
Inputs			
Bagasse Pulp, transported	1100	kg	2 Bagasse Pulp Transport
China 2030 Electricity Mix	1947.75	kWh	China 2030 Electricity Generation
hard coal	3000	kg	market for hard coal | hard coal | APOS, U - CN
tap water	8000	kg	market for tap water | tap water | APOS, U - RoW
Outputs			
Carbon dioxide, fossil	9380	kg	
Dust, unspecified	2.57	kg	
Methane, fossil	2.89E-04	kg	
Nitrogen oxides	12.3	kg	
Solid Wastes	52	kg	
Sulfur dioxide	17.3	kg	
Sulfur oxides	2.44E-04	kg	
WM Tray	**1000**	**kg**	

The wet moulded trays made in Europe utilize the same pulp inventory as in Tables B.6 and B.7, using softwood pulp instead of bagasse. The inventory for wet moulded tray production in Europe uses the same inventory as Table B.10, while replacing coal with natural gas, and the Chinese electricity mix with the European one.

Table B.11 Inventory flows, amounts, and ecoinvent providers used for production of wet moulded trays made in Europe.

Wet Moulded Tray Production in Europe Flow	Amount	Unit	Provider
Inputs			
EUCO27 Electricity Mix	1947.75	kWh	1 EUCO27 Electricity Generation
natural gas, liquefied	4.42	m3	market for natural gas, liquefied | natural gas, liquefied | APOS, U - GLO
Softwood Kraft Pulp, transported	1100	kg	3 European WM Pulp Transport
tap water	8000	kg	market for tap water | tap water | APOS, U - Europe without Switzerland
Outputs			
Carbon dioxide, fossil	9380	kg	
Dust, unspecified	2.57	kg	
Methane, fossil	2.89E-04	kg	
Nitrogen oxides	12.3	kg	
Solid Wastes	52	kg	
Sulfur dioxide	17.3	kg	
Sulfur oxides	2.44E-04	kg	
WM Tray	**1000**	**kg**	

Table B.12 Inventory flows, amounts, and ecoinvent providers used for production of polypropylene trays

PP Tray Production Flow	Amount	Unit	Provider
Inputs			
extrusion of plastic sheets and thermoforming, inline	0.031	kg	extrusion of plastic sheets and thermoforming, inline | extrusion of plastic sheets and thermoforming, inline | APOS, U (copy) - FR
PP Granulates, transported	0.031	kg	1 PP Granulate Transport
Outputs			
PP Thermoformed tray	0.022	kg	
PP Trimmed Scrap	0.009	kg	

B.4 Values for Recycling and Incineration

The modelling of the end-of-life has been done using Equation (1), which gives a credit to the system that provides material to be recycled, and therefore gives a negative emission value of recycling to the system. The incineration with energy recovery also results in a negative emission due to heat recovery, which is assumed to avoid production of heat from other sources. For simplification, energy recovery due to incineration has been assumed to be entirely in the form of heat, and 100% efficient.

The heat recovery possible has been based on the lower heating value (LHV) of each tray, which depends on the material it is composed of (Ioelovich, 2018). The lower heating value quantifies the heat energy released in combustion during the incineration process, and the values for each material are taken from Ioelovich (2018). Seen in Table B.13, the energy recovery per tray depends on the mass and the LHV, of which plastic has the highest compared to the other trays. The energy needed for recycling of the trays is taken from Dong et al. (2018) for the pulp trays and Jeswani et al. (2021) for the plastic tray.

Table B.13 Values for recycling and incineration

Product	Material	Lower Heating Value (MJ/kg)	Mass of Tray	Incineration Energy Recovery (MJ/tray)	Recycling Energy (MJ/kg)	Recycling Energy per Tray (MJ/tray)
WM Tray, China	Bagasse	18.1	0.021	0.38	0.27	0.0057
WM Tray, Europe	Softwood	16.1	0.021	0.34	0.27	0.0057
PP Tray	Polypropylene	44.6	0.022	0.96	1.26	0.027
DM Tray + A	Softwood	16.1	0.024	0.39	0.27	0.0069
DM Tray + B	Softwood	16.1	0.026	0.41	0.27	0.0069
DM Tray + C	Softwood	16.1	0.024	0.39	0.27	0.0065

The inventories for recycling and incineration are shown for each tray in the following tables.

Table B.14 Inventory flows, amounts, and ecoinvent providers used for recycling and incineration for the dry moulded tray with barrier A

<table>
<tr><th colspan="4">DM Tray + A End-of-Life Treatment
Recycling</th></tr>
<tr><th>Flow</th><th>Amount</th><th>Unit</th><th>Provider</th></tr>
<tr><th colspan="4">Inputs</th></tr>
<tr><td>DM Tray + A, transported</td><td>0.024</td><td>kg</td><td>7A DM Tray + A Transport</td></tr>
<tr><td>EUCO27 Electricity Mix</td><td>0.0066</td><td>MJ</td><td>1 EUCO27 Electricity Generation</td></tr>
<tr><th colspan="4">Outputs</th></tr>
<tr><td>DM Tray + A, recycled</td><td>0.024</td><td>kg</td><td></td></tr>
<tr><th colspan="4">Incineration</th></tr>
<tr><th>Flow</th><th>Amount</th><th>Unit</th><th>Provider</th></tr>
<tr><th colspan="4">Inputs</th></tr>
<tr><td>DM Tray + A, transported</td><td>0.024</td><td>kg</td><td>7A DM Tray + A Transport</td></tr>
<tr><th colspan="4">Outputs</th></tr>
<tr><td>DM Tray + A, incinerated</td><td>0.024</td><td>kg</td><td></td></tr>
<tr><td>heat, central or small-scale, other than natural gas</td><td>0.39</td><td>MJ</td><td>market for heat, central or small-scale, other than natural gas | heat, central or small-scale, other than natural gas | APOS, U - Europe without Switzerland</td></tr>
<tr><td>waste packaging paper</td><td>0.024</td><td>kg</td><td>EUCO treatment of waste packaging paper, municipal incineration | waste packaging paper | APOS, U (copy) - RoW</td></tr>
</table>

Table B.15 Inventory flows, amounts, and ecoinvent providers used for recycling and incineration for the dry moulded tray with barrier B

DM Tray + B End-of-Life Treatment Recycling			
Flow	**Amount**	**Unit**	**Provider**
Inputs			
DM Tray + B, transported	0.026	kg	7D DM Tray + B Transport
EUCO27 Electricity Mix	0.0069	MJ	1 EUCO27 Electricity Generation
Outputs			
DM Tray + B, recycled	0.026	kg	
Incineration			
Flow	**Amount**	**Unit**	**Provider**
Inputs			
DM Tray + B, transported	0.026	kg	7D DM Tray + B Transport
Outputs			
DM Tray + B, incinerated	0.026	kg	
heat, central or small-scale, other than natural gas	0.41	MJ	market for heat, central or small-scale, other than natural gas | heat, central or small-scale, other than natural gas | APOS, U - Europe without Switzerland
waste packaging paper	0.026	kg	EUCO treatment of waste packaging paper, municipal incineration | waste packaging paper | APOS, U (copy) - RoW

Table B.16 Inventory flows, amounts, and ecoinvent providers used for recycling and incineration for the dry moulded tray with barrier C

DM Tray + C End-of-Life Treatment Recycling			
Flow	**Amount**	**Unit**	**Provider**
Inputs			
DM Tray + C, transported	0.024	kg	6B DM Tray + C Transport
EUCO27 Electricity Mix	0.0065	MJ	1 EUCO27 Electricity Generation
Outputs			
DM Tray + C, recycled	0.024	kg	
Incineration			
Flow	**Amount**	**Unit**	**Provider**
Inputs			
DM Tray + C, transported	0.024	kg	6B DM Tray + C Transport
Outputs			
DM Tray + C, incinerated	0.024	kg	
heat, central or small-scale, other than natural gas	0.39	MJ	market for heat, central or small-scale, other than natural gas | heat, central or small-scale, other than natural gas | APOS, U - Europe without Switzerland
waste packaging paper	0.024	kg	EUCO treatment of waste packaging paper, municipal incineration | waste packaging paper | APOS, U (copy) - RoW

Table B.17 Inventory flows, amounts, and ecoinvent providers used for recycling and incineration for the wet moulded trays in China

WM Trays made in China End-of-Life Treatment Recycling			
Flow	**Amount**	**Unit**	**Provider**
Inputs			
WM Tray, transported	0.021	kg	4 Wet Moulded Tray, Transport
EUCO27 Electricity Mix	0.0057	MJ	1 EUCO27 Electricity Generation
Outputs			
WM Tray, recycled	0.021	kg	
Incineration			
Flow	**Amount**	**Unit**	**Provider**
Inputs			
WM Tray, transported	0.021	kg	4 Wet Moulded Tray, Transport
Outputs			
WM Tray, incinerated	0.021	kg	
heat, central or small-scale, other than natural gas	0.38	MJ	market for heat, central or small-scale, other than natural gas | heat, central or small-scale, other than natural gas | APOS, U - Europe without Switzerland
waste packaging paper	0.021	kg	EUCO treatment of waste packaging paper, municipal incineration | waste packaging paper | APOS, U (copy) - RoW

Table B.18 Inventory flows, amounts, and ecoinvent providers used for recycling and incineration for the wet moulded trays in Europe

WM Trays made in Europe End-of-Life Treatment Recycling			
Flow	**Amount**	**Unit**	**Provider**
Inputs			
WM Tray, transported	0.021	kg	5 European WM Tray, Transport
EUCO27 Electricity Mix	0.0057	MJ	1 EUCO27 Electricity Generation
Outputs			
WM Tray, recycled	0.021	kg	
Incineration			
Flow	**Amount**	**Unit**	**Provider**
Inputs			
WM Tray, transported	0.021	kg	5 European WM Tray, Transport
Outputs			
WM Tray, incinerated	0.021	kg	
heat, central or small-scale, other than natural gas	0.34	MJ	market for heat, central or small-scale, other than natural gas | heat, central or small-scale, other than natural gas | APOS, U - Europe without Switzerland
waste packaging paper	0.021	kg	EUCO treatment of waste packaging paper, municipal incineration | waste packaging paper | APOS, U (copy) - RoW

Table B.19 Inventory flows, amounts, and ecoinvent providers used for recycling and incineration for the polypropylene trays

Polypropylene Trays End-of-Life Treatment Recycling			
Flow	**Amount**	**Unit**	**Provider**
Inputs			
PP Tray, transported	0.022	kg	3 PP Tray, Transported
EUCO27 Electricity Mix	0.027	MJ	1 EUCO27 Electricity Generation
Outputs			
PP Tray, recycled	0.022	kg	
Incineration			
Flow	**Amount**	**Unit**	**Provider**
Inputs			
PP Tray, transported	0.022	kg	3 PP Tray, Transported
Outputs			
PP Tray, incinerated	0.022	kg	
heat, central or small-scale, other than natural gas	0.96	MJ	market for heat, central or small-scale, other than natural gas | heat, central or small-scale, other than natural gas | APOS, U - Europe without Switzerland
waste plastic, mixture	0.022	kg	EUCO treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | APOS, U (copy) - RoW

Appendix C – Life Cycle Impact Assessment

C.1 Impact Assessment Results

Table C.1 Life cycle impact assessment results for global warming potential for each tray and recycling rate

Global Warming Potential (kg CO2-Eq)	Raw Materials	Production	$E_{recycled}$	E_D
WM Tray, China	2,08E-02	2,74E-01	4,80E-04	-4,44E-02
WM Tray, Europe	1,96E-02	2,13E-01	4,80E-04	-4,44E-02
PP Tray	7,10E-02	1,16E-02	1,23E-02	-6,20E-02
DM Tray + A	2,47E-02	2,51E-02	5,50E-04	-4,57E-02
DM Tray + B	2,47E-02	1,64E-02	5,80E-04	-4,82E-02
DM Tray + C	2,47E-02	1,02E-02	5,40E-04	-4,82E-02

Table C.2 Results of Equation 1 for global warming potential for each tray and recycling rate

	100%			85%/55%			0%		
Global Warming Potential (kg CO2-Eq)	**Recycling**	**Incineration**	**Total**	**Recycling**	**Incineration**	**Total**	**Recycling**	**Incineration**	**Total**
WM Tray, China	-1.68E-02	0	2.78E-01	-1.43E-02	-6.66E-03	2.74E-01	0	-4.44E-02	2.50E-01
WM Tray, Europe	-1.58E-02	0	2.19E-01	-1.34E-02	-5.91E-03	2.15E-01	0	-4.44E-02	1.95E-01
PP Tray	-5.45E-02	0	2.81E-02	-3.59E-02	-2.79E-02	1.88E-02	0	-6.20E-02	2.06E-02
DM Tray + A	-2.00E-02	0	2.98E-02	-1.70E-02	-6.86E-03	2.60E-02	0	-4.57E-02	4.10E-03
DM Tray + B	-1.99E-02	0	2.11E-02	-1.69E-02	-7.23E-03	1.69E-02	0	-4.82E-02	-7.13E-03
DM Tray + C	-2.00E-02	0	1.49E-02	-1.70E-02	-7.23E-03	1.07E-02	0	-4.82E-02	-1.33E-02

Table C.3 Life cycle impact assessment results for acidification potential for each tray and recycling rate

Acidification (kg SO2-Eq)	Raw Materials	Production	$E_{recycled}$	E_D
WM Tray, China	1,30E-04	9,70E-04	1,16E-06	-2,25E-04
WM Tray, Europe	1,10E-04	6,10E-04	1,16E-06	-2,25E-04
PP Tray	2,40E-04	2,00E-05	3,00E-05	-5,60E-04
DM Tray + A	1,40E-04	7,00E-05	1,34E-06	-2,23E-04
DM Tray + B	1,40E-04	4,00E-05	1,40E-06	-2,33E-04
DM Tray + C	1,40E-04	2,00E-05	1,32E-06	-2,23E-04

Table C.4 Results of Equation 1 for acidification potential for each tray and recycling rate

	100%			85%/55%			0%		
Acidification (kg SO2-Eq)	**Recycling**	**Incineration**	**Total**	**Recycling**	**Incineration**	**Total**	**Recycling**	**Incineration**	**Total**
WM Tray, China	-1.07E-04	0	9.93E-04	-9.07E-05	-3.38E-05	9.75E-04	0	-2.25E-04	8.75E-04
WM Tray, Europe	-9.01E-05	0	6.30E-04	-7.66E-05	-3.38E-05	6.14E-04	0	-2.25E-04	4.95E-04
PP Tray	-1.96E-04	0	6.44E-05	-1.08E-04	-2.52E-04	-9.96E-05	0	-5.60E-04	-3.00E-04
DM Tray + A	-1.15E-04	0	9.51E-05	-9.76E-05	-3.34E-05	7.89E-05	0	-2.23E-04	-1.30E-05
DM Tray + B	-1.15E-04	0	6.52E-05	-9.76E-05	-3.49E-05	4.75E-05	0	-2.33E-04	-5.26E-05
DM Tray + C	-1.15E-04	0	4.51E-05	-9.76E-05	-3.34E-05	2.89E-05	0	-2.23E-04	-6.29E-05

Table C.5 Life cycle impact assessment results for eutrophication potential for each tray and recycling rate

Eutrophication (kg NOx-Eq)	Raw Materials	Production	$E_{recycled}$	E_D
WM Tray, China	1,60E-04	6,00E-04	1,02E-06	-5,95E-05
WM Tray, Europe	1,20E-04	3,50E-04	1,02E-06	-5,95E-05
PP Tray	1,70E-04	2,00E-05	3,00E-05	-1,54E-04
DM Tray + A	1,60E-04	6,00E-05	1,18E-06	-5,49E-05
DM Tray + B	1,60E-04	3,00E-05	1,23E-06	-5,79E-05
DM Tray + C	1,60E-04	2,00E-05	1,16E-06	-5,44E-05

Table C.6 Results of Equation 1 for eutrophication potential for each tray and recycling rate

	100%			85%/55%			0%		
Eutrophication (kg NOx-Eq)	**Recycling**	**Incineration**	**Total**	**Recycling**	**Incineration**	**Total**	**Recycling**	**Incineration**	**Total**
WM Tray, China	-1.32E-04	0	6.28E-04	-1.12E-04	-8.92E-06	6.39E-04	0	-5.95E-05	7.01E-04
WM Tray, Europe	-7.90E-05	0	3.91E-04	-6.72E-05	-8.92E-06	3.95E-04	0	-5.95E-05	4.11E-04
PP Tray	-1.30E-04	0	6.02E-05	-7.14E-05	-6.92E-05	4.94E-05	0	-1.54E-04	3.62E-05
DM Tray + A	-1.32E-04	0	8.84E-05	-1.12E-04	-8.23E-06	9.99E-05	0	-5.49E-05	1.65E-04
DM Tray + B	-1.32E-04	0	5.84E-05	-1.12E-04	-8.69E-06	6.95E-05	0	-5.79E-05	1.32E-04
DM Tray + C	-1.32E-04	0	4.84E-05	-1.12E-04	-8.16E-06	5.99E-05	0	-5.44E-05	1.26E-04

Table C.7 Life cycle impact assessment results for abiotic resource use for each tray and recycling rate

Abiotic (kg Sb-Eq)	Raw Materials	Production	$E_{recycled}$	E_D
WM Tray, China	1,20E-04	1,32E-03	3,87E-06	-2,37E-04
WM Tray, Europe	1,40E-04	1,20E-04	2,13E-06	-2,37E-04
PP Tray	1,17E-03	7,00E-05	1,00E-04	-6,10E-04
DM Tray + A	1,80E-04	1,70E-04	4,46E-06	-2,48E-04
DM Tray + B	1,80E-04	1,80E-04	4,66E-06	-2,58E-04
DM Tray + C	1,80E-04	7,00E-05	4,39E-06	-2,48E-04

Table C.8 Results of Equation 1 for abiotic resource use for each tray and recycling rate

		100%			85%/55%			0%	
Abiotic (kg Sb-Eq)	**Recycling**	**Incineration**	**Total**	**Recycling**	**Incineration**	**Total**	**Recycling**	**Incineration**	**Total**
WM Tray, China	-9.57E-05	0	1.34E-03	-8.14E-05	-3.56E-05	1.32E-03	0	-2.37E-04	1.20E-03
WM Tray, Europe	-1.12E-04	0	1.58E-04	-9.55E-05	-3.56E-05	1.42E-04	0	-2.37E-04	2.28E-05
PP Tray	-1.00E-03	0	2.40E-04	-5.50E-04	-2.75E-04	4.16E-04	0	-6.10E-04	6.30E-04
DM Tray + A	-1.45E-04	0	2.05E-04	-1.23E-04	-3.72E-05	1.90E-04	0	-2.48E-04	1.02E-04
DM Tray + B	-1.45E-04	0	2.15E-04	-1.23E-04	-3.87E-05	1.98E-04	0	-2.58E-04	1.02E-04
DM Tray + C	-1.45E-04	0	1.05E-04	-1.23E-04	-3.72E-05	8.96E-05	0	-2.48E-04	2.18E-06

Table C.9 Life cycle impact assessment results for non-renewable energy demand for each tray and recycling rate

Non-Renewable Energy (MJ-Eq)	Raw Materials	Production	$E_{recycled}$	E_D
WM Tray, China	2,23E-01	2,02E+00	1,13E-02	-3,81E-01
WM Tray, Europe	3,03E-01	3,31E-01	1,13E-02	-3,81E-01
PP Tray	2,53E+00	1,91E-01	5,37E-02	-9,59E-01
DM Tray + A	3,81E-01	4,11E-01	1,30E-02	-3,91E-01
DM Tray + B	3,81E-01	4,55E-01	1,36E-02	-4,12E-01
DM Tray + C	3,81E-01	2,09E-01	1,28E-02	-3,89E-01

Table C.10 Results of Equation 1 for non-renewable energy demand for each tray and recycling rate

		100%			85%/55%			0%	
Non-Renewable Energy (MJ-Eq)	**Recycling**	**Incineration**	**Total**	**Recycling**	**Incineration**	**Total**	**Recycling**	**Incineration**	**Total**
WM Tray, China	-1.74E-01	0	2.07E+00	-1.48E-01	-5.72E-02	2.04E+00	0	-3.81E-01	1.86E+00
WM Tray, Europe	-0.24019581	0	0.4151142	-0.204166	-0.0507	0.4004436	0	-3.81E-01	2.53E-01
PP Tray	-2.33E+00	0	3.96E-01	-1.28E+00	-4.32E-01	1.01E+00	0	-9.59E-01	1.76E+00
DM Tray + A	-3.03E-01	0	4.88E-01	-2.58E-01	-5.86E-02	4.75E-01	0	-3.91E-01	4.01E-01
DM Tray + B	-3.03E-01	0	5.33E-01	-2.57E-01	-6.18E-02	5.17E-01	0	-4.12E-01	4.24E-01
DM Tray + C	-3.03E-01	0	2.86E-01	-2.58E-01	-5.83E-02	2.74E-01	0	-3.89E-01	2.01E-01

Table C.11 Life cycle impact assessment results for renewable energy demand for each tray and recycling rate

Renewable Energy (MJ-Eq)	Raw Materials	Production	$E_{recycled}$	E_D
WM Tray, China	3,08E-01	7,12E-02	1,98E-03	-1,02E-02
WM Tray, Europe	1,74E+00	5,18E-02	1,98E-03	-1,02E-02
PP Tray	4,01E-02	1,54E-02	9,37E-03	-2,55E-02
DM Tray + A	2,19E+00	8,42E-02	2,27E-03	-1,03E-02
DM Tray + B	2,19E+00	3,74E-02	2,38E-03	-1,09E-02
DM Tray + C	2,19E+00	3,49E-02	2,24E-03	-1,02E-02

Table C.12 Results of Equation 1 for renewable energy demand for each tray and recycling rate

	100%			85%/55%			0%		
Renewable Energy (MJ-Eq)	**Recycling**	**Incineration**	**Total**	**Recycling**	**Incineration**	**Total**	**Recycling**	**Incineration**	**Total**
WM Tray, China	-2.53E-01	0	1.25E-01	-2.15E-01	-1.53E-03	1.62E-01	0	-1.02E-02	3.69E-01
WM Tray, Europe	-1.439564	0	0.355936	-1.223629	-0.001355409	0.5705152	0	-1.02E-02	1.78E+00
PP Tray	-2.83E-02	0	2.72E-02	-1.56E-02	-1.15E-02	2.85E-02	0	-2.55E-02	3.00E-02
DM Tray + A	-1.82E+00	0	4.59E-01	-1.55E+00	-1.54E-03	7.31E-01	0	-1.03E-02	2.27E+00
DM Tray + B	-1.82E+00	0	4.13E-01	-1.55E+00	-1.63E-03	6.84E-01	0	-1.09E-02	2.22E+00
DM Tray + C	-1.82E+00	0	4.10E-01	-1.54E+00	-1.54E-03	6.81E-01	0	-1.02E-02	2.22E+00

C.2 Calculation of End-of-Life Allocation Example

An example of the use of Equation (1) to determine the end of life for global warming potential, using values from the wet moulded tray made in China from the base case in section 4.2.1.1 and Table C.1. The values for the quality correction factor, Qs/Qp were found in Rigamonti et al. (2020). E_V, $E_{recycled}$, and E_D were calculated in openLCA. E_D as listed in the tables, is the combined value of the incineration impact and the energy credit from avoided heat production, which is why the value is negative for each tray. The same method was used for calculating overall emissions for all of the trays at every recycling rate.

$$(1)\ E = E_V + R_2\left(E_{recycled} - E_V^* \frac{Q_S}{Q_P}\right) + (1 - R_2)E_D$$

Table C.13 Values for Qs/Qp taken from Rigamonti et al. (2020)

Tray Type	Qs/Qp
Moulded Pulp	0.83
Polypropylene	0.94

For the wet moulded tray made in China:

$$E_V = Raw\ Materal\ Emissions + Tray\ Production\ Emissions$$

$$E_V = 2.08 * 10^{-2} + 2.74 * 10^{-1} = 0.29\ kg\ CO_2eq$$

$$Raw\ Material\ Emissions = E_V^*$$

$$\frac{Q_S}{Q_P} = 0.83$$

$$R_2 = 85\%$$

Inputting the values from Table C.1 for the wet moulded tray made in China, all are in units of kg CO_2-Eq:

$$(1)\ E = E_V + R_2(E_{recycled} - E_V^* \frac{Q_S}{Q_P}) + (1 - R_2)E_D$$

$$E = 0.29 + 0.85 * (4.80 * 10^{-4} - 2.08 * 10^{-2} * 0.83) + (1 - 0.85) * -4.44 * 10^{-2}$$

$$E = 0.29 + (-1.43 * 10^{-2}) + (-6.66 * 10^{-3}) = 2.74 * 10^{-1}\ kg\ CO_2eq$$

Appendix Citations

Culbertson, C., Treasure, T., Venditti, R., Jameel, H., & Gonzalez, R. (2016). Life cycle assessment of lignin extraction in a softwood kraft pulp mill. *Nordic Pulp and Paper Research Journal, 31*(1), 30–U247.

Dong, P. A. V., Azzaro-Pantel, C., & Cadene, A.-L. (2018). Economic and environmental assessment of recovery and disposal pathways for CFRP waste management. *Resources, Conservation and Recycling, 133*, 63-75. https://doi.org/10.1016/j.resconrec.2018.01.024

Google Maps. (n.d.). https://www.google.se/maps/dir/

Ioelovich, M. (2018). Energy potential of natural, synthetic polymers and waste materials – A review. *Academic Journal of Polymer Science, 1*(1), 9-23. 10.19080/AJOP.2018.01.555553

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. *Science of The Total Environment, 769*, 144483. https://doi.org/10.1016/j.scitotenv.2020.144483

Patronen, J., Kaura, E., & Torvestad, C. (2017). *Nordic heating and cooling: Nordic approach to EU's heating and cooling strategy*. Nordic Council of Ministers. http://norden.diva-portal.org/smash/get/diva2:1098961/FULLTEXT01.pdf.

Rigamonti, L., Taelman, S.E., Huysveld, S., Sfez, S., Ragaert, K., & Dewulf, J. (2020). A step forward in quantifying the substitutability of secondary materials in waste management life cycle assessment studies. *Waste Management, 114*, 331-340. https://doi.org/10.1016/j.wasman.2020.07.015

Sea-distances.org (n.d). https://sea-distances.org/

Södra (2020). *Annual and sustainability report*. https://www.sodra.com/en-gb/gb/sustainability/sustainability-reports/

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