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Paper vs Leaf: Comparative Life Cycle Assessment Of Single-use Plates Made Of Renewable Materials

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Content

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Abstract:

Global plastic pollution of the natural environment is extremely detrimental as it is causing deaths of animal species. More than 80 % of marine litter is made up by plastics and 70 % of those are made up by disposable items. For this reason, the European Parliament has agreed to abolish the top ten single-use plastic items found in the marine environment from the EU market from 2021. Therefore, the fossil-based disposables will need to be substituted by disposables made from renewable materials. It is thus important to investigate the environmental impact of these alternatives through their life cycle in order to support sustainable consumption and production. In this study, environmental impact of disposable plates made from two different renewable materials (paper and leaf) were analysed by means of life cycle assessment (LCA). The aim of the study was to examine the environmental performance of the two plates in the impact category global warming potential (GWP); and reveal the processes with the largest contributions to the overall GWP of each plate. The leaf plate was produced in India and the paper plate in the Nordics, however, both plates were used and disposed of in Uppsala, Sweden. The results showed that the leaf plate has a higher GWP due to its long-distance transport and electricity use derived from fossil fuels. Scenario analysis has proved that its GWP can be reduced when sea transport route is chosen instead of flying and production is increased. When it comes to the paper plate life cycle, the processing stage was identified to contribute the most to the total GWP. It could be further improved by applying a biodegradable layer for its coating. To keep the good performance in GWP the plate should be incinerated with energy recovery. The disposal of the plates has a substantial positive influence on their total carbon footprint as both plates substitute use of fossil fuels. However, the credits allocated for the different waste management options are specific to Uppsala and thus the results of this study should be applied only under similar conditions.

Keywords: Sustainable Development, Life cycle assessment, Disposable plates, Leaf, Paper,

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Summary:

Global plastic pollution of the natural environment is extremely detrimental as it is causing deaths of animal species. More than 80 % of marine litter is made up by plastics and 70 % of those are made up by disposable items. For this reason, the European Parliament has agreed to abolish the top ten single-use plastic items found in the marine environment from the EU market from 2021. Therefore, the fossil-based disposables will need to be substituted by disposables made from renewable materials such as paper, sugar cane, bamboo or leaves. If these materials are to replace fossil-based plastic it is important to study their environmental impact through their whole life cycle, i.e. from the extraction of raw materials used in the production, through processing of the materials, production, use until the disposal of the disposables. In this study, environmental impact of the whole life cycle of disposable plates made from two different renewable materials (paper and leaf) was analysed. The aim of the study was to examine the environmental impact of the two plates on climate change and reveal the processes with the most potential for improvement. The leaf plate was produced in India and the paper plate in the Nordics, however, both plates were used and disposed of in Uppsala, Sweden. The results showed that the leaf plate has a higher impact on climate change due to its long-distance transport and electricity use derived from fossil fuels. However, it can be reduced when sea transport route is chosen instead of flying and production is increased. When it comes to the paper plate life cycle, the processing of raw materials and manufacturing the paper plate were identified to contribute the most to the overall impact of the paper plate on climate change. It could be further improved by using a biodegradable layer as a coating material, which is applied to make the paper plate soak-proof. The best option for the paper plate when it comes to its disposal is incineration with energy recovery. Disposal of the plates has a substantial positive influence on their total carbon footprint as both plates substitute use of fossil fuels. However, this might be true only in the context of Uppsala, where specific technologies and fossil fuels are used for provision of heat and electricity. These conditions might change in a different geographical location. Therefore, the results of this study should be applied only under similar conditions to Uppsala.

Keywords: Sustainable Development, Life cycle assessment, Disposable plates, Leaf, Paper,

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1. Introduction

Global plastic production reached 322 million tonnes in 2015 and is expected to double over the next 20 years (European Commission, 2018). However, our love for plastic has not always been that strong. In 1950 the global production of plastic was around 2 million tonnes (Geyer et al., 2017). Yet, it was around this time when plastic started to be mass-produced and its main market changed from the military to everyday products such as food packaging, cosmetics packaging, textiles and similar (Andrady and Neal, 2009; Geyer et al., 2017; Parker, 2018). The world realised what benefits this versatile material can bring to our lives. From more health and safety in the food industry to energy savings in transport (Andrady and Neal, 2009). Nowadays, around 40 % of plastic produced in the world is applied in packaging, which is used once and then disposed (Geyer et al., 2017).

The rapidly increasing plastic production and use has given rise to the rapidly increasing plastic waste generated. Globally, a mere 9% of all plastic waste generated until 2015 was recycled, 12% was incinerated, and 79% was disposed of in landfills or the natural environment (Geyer et al., 2017).[1] The highest recycling rates are in Europe, where less than 30% of plastic is recycled (European Commission, 2018), followed by China with 25 % of plastic recycled (Geyer et al., 2017). These numbers are still very low and need to be improved, since most of the plastic waste is littered, landfilled or incinerated (Geyer et al., 2017). This gives rise to greenhouse gas (GHG) emissions, thus contributing to anthropogenic climate change (Eriksson and Finnveden, 2009; European Commission, 2018; IPCC, 2014). Most of this plastic is fossil- based as bio-based plastic, derived from e.g. corn, potatoes, sugar cane or sugar beet (IfBB, 2017), currently make up only 1% of the global annual plastic production (European Bioplastics, n.d.).

In addition to GHG emissions generated from the production and waste management of plastic, leakage of plastic rubbish into the oceans causes formidable damages to the environment. It has been estimated that more than 80% of marine litter is made up by plastics (European Commission, 2018). This plastic degrades to small microplastics less than 5 mm in size, which is eaten by marine species and can get into the food chain (European Commission, 2018). Not only is the plastic polluting the marine environment but also causing deaths of marine species (*BBC*, 2018; Borunda, 2019; Parker, 2018). Therefore, the top ten single-use plastic items such as disposable plates, cutlery, straws or cotton buds, making up over 70% of marine litter, are to be banned from the EU market from 2021(*European Parliament News*, 2018).

If the plastic disposables are to be prohibited, however, the current “to-go” culture based on fast and ready-made food and beverages is to prevail, alternatives to fossil-based, single-use items must be developed. The Industry seems to notice the necessity of change and has thus introduced disposables made of renewable materials, e.g. corn, sugar cane, wood, grass, leaves onto the market (Duni, n.d.(a); Leafymade, n.d.; Vegware, n.d.). As Fieschi and Pretato (2018) have shown it is crucial what material disposable tableware is made from since this has substantial impact on the end-of-life choices for the product. Compostable tableware can reduce the overall environmental impact of food waste management as it can be composted together with the food waste. Otherwise fossil-based, non-compostable disposables would need to be incinerated or landfilled, which has a higher carbon, water and resource footprint (Fieschi and Pretato, 2018). However, if bio-based and compostable disposables are to substitute fossil-plastic disposables, they will need to be produced on a much larger scale than at present. Therefore, it is crucial to study the environmental impact of these alternatives through their life cycle in order to support sustainable consumption and production. Sustainable consumption and production is one of the 17 global Sustainable Development Goals. It aims to reduce resource and energy use; degradation and pollution along the whole life cycle of products and services, while increasing quality of life (UN, n.d.).

Previous research in this field seem to target disposable cups rather than plates (Garrido and Alvarez del Castillo, 2007; Häkkinen and Vares, 2010; Van der Harst et al., 2014; Van der Harst and Potting, 2013; Woods and Bakshi, 2014). The goal of these studies was to compare environmental impacts of

[1] These numbers exclude bio-based plastic, produced from renewable biomass sources.

disposable cups made of different materials in order to find the most environmentally friendly one. Most of the studies were comparing bio-based materials with fossil-based materials. In some studies bio-based materials scored better than fossil-based when it comes to global warming potential (Häkkinen and Vares, 2010). Nonetheless, multiple datasets comparisons based on life cycle assessments of disposable cups showed none of the cup materials to be consistently better than the others (Van der Harst and Potting, 2013). However, three processes were identified to have the highest environmental impact: production of the cup's basic material, cup manufacturing, and waste processing (Van der Harst et al., 2014). Garrido and Alvarez del Castillo (2007) studied reusable and single-use cups and concluded that in order for the reusable cup to have a smaller environmental impact than the single-use cup, it needs to be used at least 10 times.

As no specific study on environmental impacts of single-use plates could be found this study intends to address this research gap. The goal of this research was to assess the global warming potential of common and popular alternatives to fossil-based, single-use plates on the market. The results should serve actors in the Industry to make informed decisions on their product life cycle with the aim to decrease their environmental impact. Ultimately, the results should also inform consumers about the environmental impact of these products in order to make choices in line with sustainable consumption.

This study aims to answer the following research questions:

1. What is the environmental performance of single-use plates made from two different renewable materials in the impact category global warming potential?

2. What are the hotspots in the life-cycle, contributing the most to the overall impact and with the largest potential for improvement, of each type of plate?

2. Background

Disposables is a term encompassing consumer products and packaging that are mostly used only once and then thrown away (Allaby and Park, 2013). They have become such common items in our throw-away society that about 50 % of global plastic annual production is used to produce single-use items (Plastic Oceans, n.d.).

Single use items are nowadays mostly associated with consumerism and excessive waste generation (European Commission, 2018; Hall, 2017), even though one of the primary reasons for their invention was sanitation. The idea of disposable cups is said to be inspired by an American public health officer, Samuel J. Crumbine, at the beginning of the 20th century. Mr. Crumbine was on a train with his tuberculosis patient, who drank from a common dipper and water bucket. After him came a young girl and drank from the same dipper and bucket. Seeing the germs spreading this way inspired the health officer to ban publicly shared utensils in public spaces (Bandini, 2018; Giordano, n.d.). Not long after this ban had come into force two entrepreneurs invented a disposable paper cup to be used at public spaces and prevent illness from spreading (Giordano, n.d.).

Introduction of disposables to the market was not just a matter of sanitation but soon it became a matter of convenience too. Fast food restaurants, amusement parks, sport stadiums started to realise other advantages offered by disposable tableware. They did not have to worry about theft, breakage or washing-up of reusable dishware anymore (Giordano, n.d.). Disposables were also cheaper than their reusable counterparts (Giordano, n.d.; Gitschlag et al., 2009). Furthermore, as eating out was becoming more common (Giordano, n.d.), increasing demand pushed the food service industry to become more efficient. A great example of this change in the food service industry is McDonald’s. The fast food restaurant chain introduced the self-service and take-away concepts to their restaurants based also on the use of disposable tableware (McDonald’s, n.d.).

When it comes to the history of disposable plate itself it is ambivalent. It has been manufactured from an array of materials, however, the first disposable plate is said to be made of paper. There are different names considered to be the first inventor of paper plate. Some argue it was the German bookbinder Hermann Henschel and his invention happened in Luckenwalde in 1867 (Bandini, 2018).

Others state that it was Martin Keyes of Lempster who invented the paper plate in 1903 in New Hampshire (*Encyclopedia of Products & Industries - Manufacturing*, n.d.). The differing information might be due to the material the paper plate was made of since Martin Keyes is said to invent moulded pulp paper plate, which has a sturdier structure than sheet paper (*Encyclopedia of Products & Industries - Manufacturing*, n.d.). The invention came to be instrumental in the restoration phase after the earthquake in San Francisco in 1906 as the demand for paper plates said to have escalated (Macken, 2017; Wonderopolis, n.d.).

During the 1940's and 1950's new materials began to emerge on the market. Different forms of plastics, such as polypropylene or polystyrene were developed and were later commercially available (Andrady and Neal, 2009). The properties they brought to the market – light weight, versatile mouldability, insulation properties (Andrady and Neal, 2009) were also applicable and beneficial to the food service industry. Disposable plates could have now been manufactured from plastic, which unlike paper plates without lamination, made them soak proof, lighter, more cut resistant and still economical (Gitschlag et al., 2009).

It was around this time when the concept of *throw-away* living appeared for the first time in a popular magazine. The magazine LIFE dedicated a full page to disposable items such as "disposa-pan", disposable pet bowls or single use barbecue grills, which they considered to be part of throw-away living (*LIFE*, 1955). In the magazine they were advertised as items that "cut down the household chores", saving time and labour (*LIFE*, 1955, p. 43). However, "behind the scenes" of this throw-away culture lies a marketing strategy developed as early as the 1930's based on obsolescence of products (Whiteley, 1987). The main idea of this strategy is to convince consumers that they need a new product because the current one has become obsolete due to its old design, disregarding its full functionality. This led to consumers throwing away their old products and replacing them with new ones in relatively short periods of time.

Unfortunately, this consumer mentality is still prevalent in our society and with the aid of globalisation expands to economically developing countries too (Cole, 2010; Kuhn, 2009). What's more our lifestyles have been changing driven by convenience and fast-paced living (Business Wire, 2018; FMI, 2017). As a result, home delivery and online food service platforms have been experiencing growth as well as fast-food, ready-made food and drinks to-go have become common in our culture (Business Wire, 2018; FMI, 2017). The inevitable part of this culture is then the use of disposables, in which the food and drinks come in. This trend is also reflected in the projected high demand for single use items in the future. According to freely available online market research sources the global disposable plates market is estimated to grow to the value of US$ 6 Billion by the end of 2027 from around US$ 3.5 Billion in 2017 (FMI, 2017). The disposable cups and lids market is also projected to experience a growth of almost 7% annually between 2018-2022 (Business Wire, 2018).

With increased demand for single-use items comes an increased amount of waste generated. A problem never talked about in the 1950's has become a frequently discussed topic of the present day (*BBC*, 2018; European Commission, 2018; Hall, 2017). Single-use items made of plastic are rarely recycled and their leakage causes severe damage to the marine environment and littering (European Commission, 2018). Therefore, as mentioned above, the European Parliament has approved the Directive to ban plastic single-use items, including disposable plastic plates, from the EU market from 2021 (*European Parliament News*, 2018).

These concerns have brought businesses as well as the general public to think about and demand ecological alternatives to plastic disposable plates. Thus, biodegradable disposable plates have been emerging on the market recently. These are made of renewable materials such as wood, sugar cane, bamboo or leaves (Duni, n.d.(a); Leafymade, n.d.; Little Cherry, n.d.). Paper plate has been a long-standing alternative to the plastic plate since the 19th century, as mentioned above. However, these plates are often coated with a plastic layer, which could be made of fossil- or bio-based plastic, in order to become soak proof (MiniMaid Ab, n.d.). Another alternative is a leaf plate, made entirely from leaves, which are heat pressed. This plate is based on a long-lived Indian tradition, serving food on leaves instead of ceramic plates (Leafymade, n.d.; Little Cherry, n.d.). Bagasse plate, a recent, popular biodegradable alternative to plastic plates, is made of a by-product of sugar and ethanol production. Usually burnt in the production process in order to supply bioenergy to the production (Dias et al., 2015), it can also be used for production of paper and board (Tsiropoulos et al., 2015). Another alternative is tableware made of bamboo. The base for this plate material is sawdust generated from chopstick production (CINK, n.d.).

3. Methods

3.1 Life cycle assessment (LCA)

Life cycle assessment is a well-established, internationally recognised method of analysing and quantifying environmental impacts of products and services through their whole life cycle, starting from extraction of raw materials, through processing materials, to production, use and final disposal of a product (European Commission, 2011).

There are three different models of life cycle assessment – "cradle-to-gate", "cradle-to-grave" and "cradle-to-cradle". "Cradle-to-gate" LCA model takes into consideration all the processes from raw material extraction to the factory gate of the product life cycle (Baumann and Tillman, 2004). "Cradle-to-grave" model includes the whole product life cycle from raw material acquisition to the disposal of the product (Baumann and Tillman, 2004). Lastly, "cradle-to-cradle" model maps the circular product life cycle, where the product is not discarded after use but instead re-used or refurbished again.

Life cycle assessment can be used for different purposes. Most common reasons for LCA application are learning about a product or service; decision making support and communication of specific properties of the product (Baumann and Tillman, 2004). When carrying out a life cycle assessment, it is inevitable to explore the product system in detail, thus learning about it. This can reveal critical points for improvement. If the LCA is applied for a product system, learning about the deficiencies can serve as a base for new product design or for a change in the existing supply chain. In the public sector, LCA can be used to motivate a policy change (Baumann and Tillman, 2004). Finally, the results of an LCA can be used for justifications for environmental product declarations or identification of crucial indicators for requirements for eco-labelling (Baumann and Tillman, 2004).

In order to maximally utilise and compare the results of world-wide LCA studies, a standardisation of the LCA methodology had to be carried out. This would reassure the quality of datasets and harmonisation of the methodology across the globe. Therefore, the International Organisation for Standardisation (ISO) issued an LCA standard, which comprises of two related standards, 14040:2006 and 14044:2006 (Matthews et al., 2014) However, the international standard still leaves practitioners with their own choices to make that can affect the overall quality of the study (European Commission, 2011). For this reason, the Joint Research Centre of the European Commission published The International Reference Life Cycle Data System Handbook. The Handbook is to provide technical guidance for LCA practitioners and facilitate consistent and quality assured LCA data collection for easier comparability of results within the EU (European Commission, 2011)

According to the ISO LCA standard there are four essential phases in a life cycle assessment: goal and scope definition, inventory analysis, impact assessment, and interpretation (Matthews et al., 2014). Interpretation is a continuous process and happens throughout the assessment as, for example, goal and scope might be changed after interpreting the inventory analysis.

The first phase, the goal and scope definition, is the most essential as it influences all the subsequent phases (European Commission, 2011). The goal definition states the intention of the study. The goal should include the following four aspects: intended application(s) of the results; reasons for carrying out the study; target audience of the results and comparative assertions (Baumann and Tillman, 2004; European Commission, 2011; Matthews et al., 2014). A clear goal definition is vital for a correct interpretation of the results (European Commission, 2011).

The goal definition guides the scope definition. The scope is defined by a number of qualitative and quantitative information implying the extent of the study. The ISO LCA standard states 12 different parameters denoting the scope, including function, functional unit, product system description, system boundary, inventory inputs and outputs, impact categories and methods of impact assessment (Baumann and Tillman, 2004; European Commission, 2011; Matthews et al., 2014).

Function of the studied system is expressed quantitatively by a functional unit. It is a reference point and all the results should be normalised by it. It also serves as a unit of comparison in comparative studies (Baumann and Tillman, 2004). Further scope parameters are product system description and system boundary. Product system describes all the necessary unit processes and flows that together deliver a certain function of the product (Matthews et al., 2014). System boundary indicates what processes and flows were included in the study and what is considered as surrounding environment. The system description and its boundary are often accompanied by a diagram for the ease of understanding.

The second phase of a life cycle assessment is inventory analysis. In this phase data are collected to meet the stated goal and scope. The smallest element considered in the analysis is a unit process (Matthews et al., 2014). Each unit process has inputs flowing in and outputs flowing out, after the process has been undergone (Fig.1).

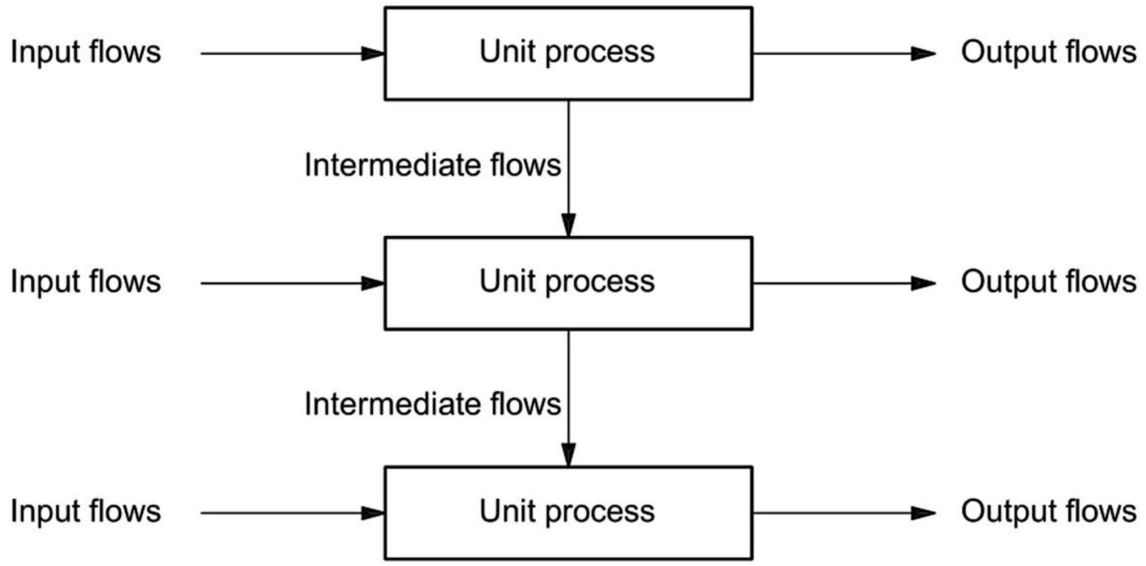

Fig. 1. Diagram depicting the inputs and outputs flow to unit processes in a product system (ISO 14040:2006).

Inputs are material, product or energy flows that enter a unit process, which could include raw materials, intermediate products or co-products (Matthews et al., 2014). Inputs can come from nature such as resources from the ground, water and air or from technosphere, i.e. human altered environment, such as products from other unit processes (Matthews et al., 2014).

Similar to inputs, outputs are material, product or energy flows that leave a unit process and can include raw materials; intermediate products; products; waste and releases to the ground, water and air (Matthews et al., 2014). ISO defines raw materials as “primary or secondary material that is used to produce a product”(Matthews et al., 2014, pp. 93–94). Intermediate products are products that are not final yet but will be assembled to become one whole product. Such products can also be called components. Co-products are “two or more products of the same unit process or system”(Matthews et al., 2014, p. 94).

The third process in life cycle assessment is impact assessment. This is a required part of LCA, otherwise the study can be considered a mere life cycle inventory (Matthews et al., 2014). Impact assessment translates inputs and outputs calculated in the inventory analysis into impacts on the environment or humans. It makes the results more understandable and possible to relate to. First, impact categories are selected together with their indicators, followed by the choice of characterisation model (Baumann and Tillman, 2004; Matthews et al., 2014). The choice of impact categories depends on the goal and scope definition and the data collected during the inventory analysis (Baumann and Tillman, 2004). For example, if releases of SO_2, HCl, NH_3 or NO_x to the air were documented during a product’s life cycle, the impact category “acidification” could be assessed. The indicators for this category are the amounts of SO_2, HCl, NH_3 and NO_x and the characterisation model could be the model developed by the Centre of Environmental Science at Leiden University (CML 2002 in Baumann and Tillman, 2004).

After the impact categories, indicators and characterisation models have been selected, the next step is classification. Classification organises inventory results under their relevant impact categories (Matthews et al., 2014). The subsequent step is characterization, when the extent of environmental impacts are calculated based on characterization factors (also called equivalency factors) (Baumann and Tillman, 2004). In the case of acidification described above, all the emissions causing acidification are added together based on the equivalency factors. Here the equivalency factors are based on the potential to release H^+ ions, which in turn causes acidification (Baumann and Tillman, 2004). Each SO_2 molecule reacts with water and oxygen to form sulfuric acid that in turn causes the release of two hydrogen ions, while each HCl molecule releases one hydrogen ion (Baumann and Tillman, 2004). Thus, the equivalency factors are 2 to 1, respectively.

The final stage of life cycle assessment is the interpretation phase. Although, as mentioned above, interpretation takes place throughout the life cycle modelling, at the end of the assessment the results for the specific impact categories are interpreted. If comparative LCA was undertaken, results from different systems are compared with each other. Consequently, recommendations for improvements to reduce impacts could be made.

Life cycle assessment was chosen as a method of analysis in this study. In order to fulfil the aim of this research two different product systems were selected to be compared with each other. First one is the system of a disposable plate made of Sal tree leaves (lat. *Shorea robusta*), grown in India. This plate was selected because it is a far-travelled product, which has an impact on its carbon footprint. As it is a relatively novel material for production of disposable plates in the Western world, an investigation into the mode of its production and the associated environmental impact could be informative for sustainable consumption within Europe. The second plate analysed is a disposable, paper plate produced within the Nordics. This product was chosen due to its shorter distance in its supply chain as opposed to the leaf plate. In addition, paper plate has been manufactured for over a century now, thus its production is relatively advanced and well-studied within Europe in comparison with the leaf plate. Therefore, comparing these two products might reveal some new knowledge about sustainable production and consumption of disposable plates and create some spill-over effects between the product systems.

3.1.1. Functional Unit

ISO 14040 defines the functional unit as “quantified performance of a product system for use as a reference unit” (Benoît et al., 2010, p. 4). It allows quantitative assessment and comparison of impacts (Benoît et al., 2010).

It is important that the functional unit is defined in a way that it is comparable within the different systems in question. For the purpose of this study, the functional unit has been defined as follows: one flat disposable plate. As a flat disposable plate can have different dimensions, the functional unit needed to be further defined as one flat disposable plate of 20 (+- 2) cm diameter. These seem to be the common dimensions of disposable plates on the market (Duni, n.d.(b); Leafymade, n.d.; Little Cherry, n.d.)

3.1.2. System boundary and description

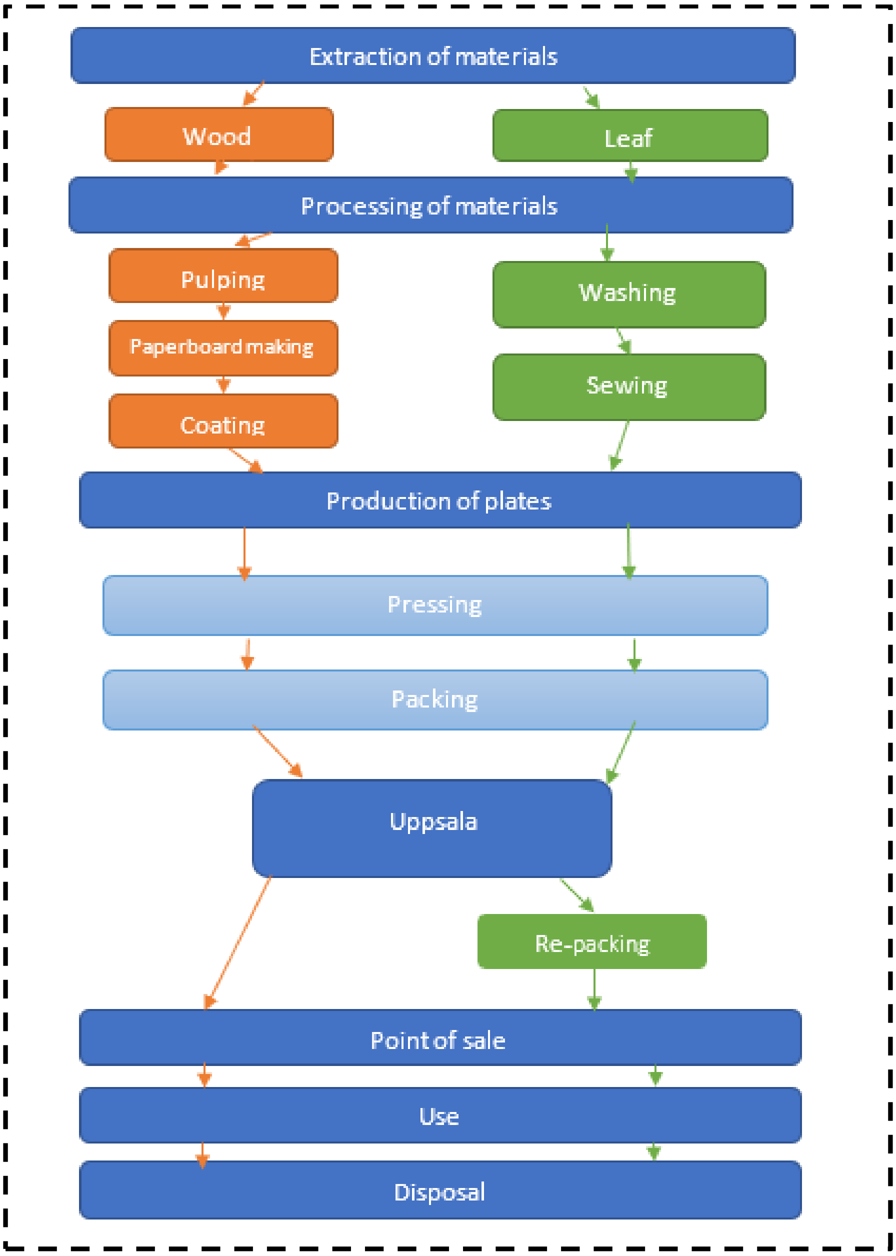

Fig. 2. A diagram of the product systems of both plates**.** The green boxes represent the processes specific to the leaf plate and the orange boxes represent the processes specific to the paper plate. The dashed line depicts the system boundary, showing that a "cradle-to-grave" LCA was carried out.

System boundary

This study took into consideration the whole life cycle of the two studied product systems, i.e. "cradle-to-grave" perspective (Matthews et al., 2014). The cradle represents the initiation of the product journey, starting from the extraction of materials, moving to processing, manufacturing, and subsequent use. Eventually, if the product is not reused or refurbished, it comes to the end of its life, which is represented by the grave.

Both disposable plates are used and disposed of in Uppsala, Sweden. The product systems of the leaf and paper plate are to a large extent similar and are depicted in Fig. 2. The life cycle stages preceding the "Use" stage of each product system will be described below. Packaging of the products is a part of the system studied. Furthermore, it was assumed that the customer comes to the shop by bicycle. When it comes to transportation means within the two systems studied, only the use stage of vehicles, i.e. transporting, was included in this study. The manufacturing of the vehicles was excluded. Similarly, the life cycle of the food served on the plates is not included in the studied systems. Therefore, the use stage of the plates was assumed to have no energy requirement.

At the end of their life, both plates could be either composted, anaerobically digested or incinerated with energy recovery. Recycling is not an option as plates are heavily contaminated by food leftovers, therefore, it would be impossible to recycle them. Landfilling of organic waste is forbidden by law in Sweden (SFS 2001:512).

System descriptions

Leaf plate

Fig. 3. A picture of the leaf plate made from Sal tree leaves (Leafymade, 2019)

There are few companies producing leaf plates (Eco-gecko, n.d.; Leafymade, n.d.; Little Cherry, n.d.), however, the leaf plate produced by Leafymade was selected as a representative of the leaf plate scenario in this study. The leaf plate is produced by a young start-up called Leafymade located in Uppsala, Sweden. The production takes place in eastern India, in the state of Odisha. Tribal women collect leaves of Sal trees (lat. *Shorea robusta*) in the local rainforest. The leaves have special properties such as water resistance, rigid structure and colour retention.

When leaves are picked they are washed first and then sewn together. The tribal women sew them on mechanical sewing machines therefore no electricity is required. One plate requires six leaves. This extraction and processing of the material for the plate is done in Daringbadi, India. After the leaves have been sewn together and bundled (Fig. 4), they are transported to another city Bhubaneswar, India (246 km).

Fig. 4. A picture of Leafymade's employees with bundles and sewn leaves, ready to be transported further (Leafymade, 2019).

In Bhubaneswar the sewn leaves are pressed at electrical heat-press machines. The plates are then packed in corrugated cardboard boxes and sent to Kolkata, India (442 km). In some cases (8% of all the shipments so far), the plates are transported from Bhubaneswar, India to Stockholm, Sweden by airplane (Mehta, 2019). This is in case of time pressure, when Leafymade needs product samples as soon as possible (Mehta, 2019). Most of the time (92% of all the shipments so far) the goods are transported by ship from Kolkata, India to Gothenburg, Sweden (Mehta, 2019). Compared to shipping goods by air, the sea transport is markedly longer and can take about a month (Searoutes, 2019).

After arrival in Sweden, the shipment continues to Uppsala by road. In Uppsala, plates are re-packed to packages of 12 plates each. Packaging is made of bio-based polyethylene (Bio-PE), which is 100% recyclable, however not biodegradable (Braskem, 2019). Each packaging has 2 paper stickers containing information about the product. Packages are then ready to be sent to points of sale.

Paper plate

Fig. 5. An illustrative picture of paper plate made from paperboard (MiniMaid, n.d.)

Since its invention, disposable paper plate has been manufactured by many different companies around the world, each of them with specific manufacturing processes. In this research, the paper plate produced by the Finnish company MiniMaid was selected as a case study due to the relatively close proximity of the production line to Uppsala, Sweden.

The journey of the paper plate starts with wood harvesting. This involves a number of processes, starting from the site preparation for tree planting, subsequent logging and final transport to a pulp mill (González-García et al., 2009). Upon arrival to the pulp mill wood logs need to be debarked and processed into wood chips. Wood chips can be turned into pulp by three different main methods of pulping – mechanical, chemical or biopulping (Das and Houtman, 2004). Mechanical pulping involves applying mechanical forces to grind wood against a rotating stone (Das and Houtman, 2004). The wood chips can be pre-treated by steam (thermo-mechanical pulp) or the combination of steam and sodium sulphite (chemi-thermomechanical pulp) (CEPI, n.d.; Das and Houtman, 2004). Mechanical pulping is energy-intensive, gives higher yields but lower strength fibres than pulp obtained by chemical pulping (Das and Houtman, 2004).

Chemical pulping uses chemicals in a cooking process to remove lignin from the wood and separate it to cellulose fibres (CEPI, n.d.). This gives lower yield but fibres of higher strength than mechanical pulping (CEPI, n.d.; Das and Houtman, 2004). Biopulping is the third method of pulping, where lignin-degrading fungi is applied before pulping (Das and Houtman, 2004). The integrated pulp and board mill that produces the paperboard used for MiniMaid's paper plates uses both chemi-thermomechanical pulping and chemical pulping methods (Metsä Board Husum, n.d.).

Even though each board grade is produced by machines tailored to its specific standard, the overall basic process of paper and board making is similar (Ottenio et al., 2004). After pulp has been obtained, it can be bleached depending on its final use (Australian Packaging Covenant, n.d.; Iggesund, n.d.; Ottenio et al., 2004). In this study, unbleached pulp was assumed to be used for the paper plate. Unbleached pulp is then screened, cleaned and diluted in water (Iggesund, n.d.; Ottenio et al., 2004). Following the cleansing process, chemicals are added into the mixture of raw fibres and water, which is then pumped to the headbox, a device controlling the flow of the mass (Ottenio et al., 2004). The headbox feeds the stock onto the wire section, a woven mesh conveyor belt (Ottenio et al., 2004). As the paper mass travels on the conveyor belt the water is drained away, leaving fibres on the mesh. By the time the mat of fibres arrives at the end of the wire section it has become a sheet of paper (Ottenio et al., 2004). A paperboard machine has a number of formation devices in headboxes and wires which manufacture multi-ply sheets, combined later in the process (Ottenio et al., 2004). The moist sheets of paperboard move to the press section, where more water is squeezed out, which binds the fibres together (Ottenio et al., 2004). The sheets are then dried by steam. Halfway through the drying process paperboard can be coated with pigments and binding agents (Ottenio et al., 2004).

According to the wishes of the customer paperboard can be coated by a number of soak-proof materials such as polyethylene (PE), water-based barrier (MiniMaid Ab, n.d.) or a compostable polylactic acid layer (Shah et al., 2008). MiniMaid provides their customers with the options of PE- or water-based dispersion coating (MiniMaid Ab, n.d.). The process of coating can be performed at the paperboard mill or at a separate factory (Knutar, 2019). At MiniMaid most of the coating is done at a separate factory (Grahn, 2019). After the paperboard has been transported to and coated in a separate factory, it is sent to MiniMaid.

The production process at MiniMaid starts with forming plates by pressing them out of the paperboard. The plates are then packed using polyolefin shrink film and placed into a corrugated cardboard box to be shipped to customers (Knutra, 2019). Most of the time (70% of deliveries) a full truck of 2 million paper plates is sent at once (Knutar, 2019).

3.1.3. Inventory data collection

In this section, inputs and outputs of unit processes of the life cycles of the two plates are described. Processing of the data will be discussed in the succeeding section.

Leaf plate

Data for this system were collected in close collaboration with the company Leafymade through regular visits to the company, emails and phone calls.

The first stage of the life cycle is extraction of material. In Leafymade's product system this stage only comprises of one unit process - picking leaves. Picking leaves does not require any other energy than manpower. The only raw material needed for this process is leaves collected from the rainforest, which are also the only output of this process.

The second stage of the life cycle is processing of the leaves collected. This includes washing and sewing of the leaves. Washing uses ca. 10 ml of water per six leaves (Mehta, 2019). No other natural or artificial materials are used for this unit process. The only output associated with this unit process is waterborne dust washed off the leaves.

Sewing is done on mechanical sewing machines. As one plate is made of six stitched leaves, sewing one plate requires 40 cm of cotton thread, of which 5 cm is wasted in the process (Mehta, 2019). At the end of this life cycle stage the sewn leaves are stacked, bundled and transported from Daringbadi to Bhubaneswar. The distance between the two cities is 246 km and a light diesel truck is used for this journey. As the truck uses a diesel combustion engine, it generates outputs in the form of greenhouse gas (GHG) emissions.

The production of plates begins with the arrival of the stitched leaves in Bhubaneswar. Depending on the quality of leaves, a small amount of water (ca. 2 ml/plate) may be sprinkled on leaves in order to increase elasticity before pressing (Mehta, 2019). Pressing and drying of plates happens at the same time as leaves are hot pressed by heat press machine. Based on the daily energy consumption and daily plate production of the facility acquired from Leafymade, it was calculated that the electricity used per plate was 9 Wh. As production of electricity emits GHG so does utilisation of electricity for processes. Thus, the output from hot pressing of the plates are atmospheric emissions. When it comes to solid waste, after pressing one plate, the cut-off pieces of leaves generate 390 cm^2 of solid waste per plate.

After the production stage, plates are packed in corrugated cardboard boxes. The standard number of plates per box is 1350. One shipment consists of 19 boxes of 260 kg of gross weight and 237 kg of net weight according to the shipment list used for calculations (Mehta, 2019). In this shipment, 25 485 plates were transported from India to Sweden. Therefore, the weight of one plate was calculated as 9.3 g.

Once the plates are ready to be shipped, they are sent from Bhubaneswar to the port city Kolkata, India. The distance between the two cities is 442 km and the goods are transported by a light truck. From Kolkata the plates travel to the port of Gothenburg, Sweden. This can take almost a month as the journey is about 15 663 km long (Searoutes, 2019). From Gothenburg the goods are transported to Uppsala by a rigid truck. The distance between the cities is 453 km. All this transportation emits greenhouse gases.

In case of shipment via air freight, the goods are sent from Bhubaneswar airport to Stockholm, Arlanda airport. Five boxes out of 65 boxes shipped so far have been transported by air from India to Sweden. After arrival in Stockholm, the shipment is later transported to Uppsala by a rigid truck. This is 71 km. The outputs of these processes are again GHG emissions.

In Uppsala, plates are re-packed to packages of 12 plates each. Packaging is made of bio-based polyethylene (Bio-PE), which is 100% recyclable, however not biodegradable, and is made of sugar cane (Braskem, 2019). Each package of 12 plates has two paper stickers on with information about the product.

Paper plate

Data for this plate were collected in collaboration with the company MiniMaid through communication via emails and phone calls. MiniMaid is a private label manufacturer, thus it is the customers who choose parameters of their desired plate, including thickness of paperboard or numbers of plates per packaging. Therefore, the figures provided here are for a hypothetical average paper plate (Knutar, 2019). All figures refer to the calendar year of 2018 (Knutar, 2019).

Since only the production of paper plates takes place at MiniMaid all the data for upstream processes had to be acquired from businesses MiniMaid contracts with. There is a number of businesses MiniMaid gets their supplies from thus for the purpose of this study one significant supplier of paperboard was chosen. This integrated pulp and paperboard mill is located in Husum, Sweden (Knutar, 2019).

As attempts to interview Husum mill were not successful information on wood supply had to be assumed based on literature sources. Hence, the data for the first stage of the paper plate life cycle – extraction of wood – were derived from the study performed by González-García et al. (2009). This study investigated the whole process of extraction of wood; from site preparation, logging to wood transport from forest landing to the pulp mill gate (González-García et al., 2009). It was chosen to be representative since both the pulp mill examined in the study and the pulp and paperboard mill used in the paper plate scenario are located in Northern Sweden, in close proximity to each other (González-García et al., 2009; Grahn, 2019). The pulp mill studied by González-García et al. (2009) delivers 25% of its wood supply from Baltic countries, 30% from South Sweden and 45% from Central Sweden. This delivery is done by a combination of trucks and ships. All the energy required by silviculture[2], logging and transport is considered as inputs to the first phase of the paper plate's life cycle. The total non-renewable energy consumed in these processes is 370 MJ/m^3 of wood (González-García et al., 2009). The outputs of the aforementioned processes are the total GHG emissions associated with the energy use, which is 36.1 kg CO_2 eq/m^3 of wood (González-García et al., 2009).

After the delivery of pulpwood to Husum's mill gate, chemical and chemi-thermomechanical pulping start. The pulp yield from wood is normally around 55% for chemical pulping (FEFCO and CEPI Containerboard, 2015), meaning that 1000 kg of wood yields 550 kg of pulp. In order to find out more information about GHG emissions from the processes at the integrated mill in Husum, the mill's website was searched for environmental profiles of their products. Only two kinds of paperboard were found suitable for paper plate application, one uncoated and one coated (Metsä Board, n.d.). The uncoated paperboard was selected as representative since MiniMaid have their paperboard coated in a separate factory (Grahn, 2019). Hence, the environmental profile of the "MetsäBoard Natural FBB 175–325 g/m^2" was selected. Based on the environmental profile of this paperboard the process of making pulp and subsequent paperboard emits 44 kg of fossil CO_2 /tonne of paperboard (Metsä Board, 2018). This is due to the fact that 82% of the total fuels used in all the mills within the Metsä Board group are derived from biomass (wood, bark, black liquor[3]) (Metsä Board, 2018). According to the environmental profile of the paperboard investigated, 84 % of its content is made up by pulp, 8% by moisture, 5 % by binders and 3 % by pigments and fillers (Metsä Board, 2018).

After the paperboard has been manufactured it is shipped to a separate factory for coating. The distance is between 10 to 50 km (Knutar, 2019). MiniMaid provides two kinds of coating; PE-based coating or bio-coating (water-based dispersion barrier) (MiniMaid Ab, n.d.). Bio-coating is based on dispersion of solid material dissolved in water. The solid material used can vary from titanium dioxide (TiO2) nanoparticles in combination with polyolefin copolymers (Mates et al., 2016) to fluoroacrylic copolymer in combination with hydrophilic bentonite nanoclay (Mates et al., 2014) as well as their proportion in relation to water; 5 % and 3% respectively (Mates et al., 2014, 2016). One plate uses 0.39 g of bio-coating or 0.55 g of PE coating (Knutar, 2019). As the exact composition of bio-coating

[2] The branch of forestry that is concerned with the cultivation of trees (The Free Dictionary, n.d.).
[3] black liquor is the waste product from the kraft process when digesting pulpwood into paper pulp removing lignin, hemicelluloses and other extractives from the wood to free the cellulose fibres (Climate Technology Centre & Network, 2016)

applied on Minimaid's paper plates was unknown and considering that some bio-coating is still based on elements found in plastic, the end of life of the paper plate coated with such material is ambivalent. Therefore, PE layer was chosen as coating for the paper plate scenario, since the process of production is relatively known and the end of life of such paper plate is unambiguous; incineration with energy recovery.

Coated paperboard is later transported to MiniMaid by a 20-tonne truck (Grahn, 2019) over a distance of 330 km. The entire truckload of 40 tonnes of paperboard is shipped to MiniMaid at once (Knutar, 2019). The sheets of paperboard are then pressed into plates. Electricity required for pressing one plate is 2,8 Wh (Knutar, 2019). The weight of one plate is 8.4 g, with a layer of PE coating it is 9 g (Knutar, 2019). A pressed plate is then packed using 0.05 g polyolefin shrink film per plate (Knutar,2019). Stacks of plates are then placed into corrugated cardboard boxes. The average number of plates per box is 600 and the weight of the corrugated cardboard box is 277 g (Knutar, 2019). The packed paper plates are ready to be shipped to customers. A standard delivery comprises of 2 million plates with a fully loaded truck (Knutar, 2019).

3.1.4. Inventory data processing

This section will explain what software and methods were used to process the collected data above in order to calculate greenhouse gas emissions of the two plates.

Leaf plate

Transportation

In order to calculate GHG emissions from transportation of leaf plates throughout their life cycle, The Network for Transport Measures' (NTM) Calculator Advanced 4.0 was used ("NTMCalc 4.0", n.d.). In this calculator, among the most important variables influencing the overall GHG emissions from transportation are "cargo load factor" and "cargo carrier capacity". Cargo load factor is the percentage of the maximum weight/volume load capacity that is actually utilized by the shipment ("NTMCalc 4.0", n.d.). Cargo carrier capacity is maximum weight/volume load capacity of the vehicle used for transportation ("NTMCalc 4.0", n.d.).

For the first leg of the journey from Daringbadi to Bhubaneswar (246 km) a vehicle type "van" was used as it corresponds most to the light truck used in India. It was assumed that the van runs on fuel corresponding to Diesel B5-EU and its fuel consumption was 8.5 l per 100 km. The cargo load factor was 100% and 50% of this load is taken by Leafymade's shipment, which represents 4 m^3.

For the second leg of the journey, from Bhubaneswar to Kolkata (442 km), the same vehicle type as above with the same vehicle specifications is used. The calculation model was based on the shipment weight. The cargo load factor for this shipment was 50% of the total cargo capacity 2.25 tonne and Leafymade's weight was 260 kg.

When it comes to transportation by sea from Kolkata to Gothenburg (15 663 km), the sea routes calculator was used to estimate the route of the ship (Searoutes, 2019). This route was then entered into the NTM Calculator. The vehicle type used for this calculation was "bulk carrier" as its weight corresponds most to the actual vessel's weight used for transportation of Leafymade's shipment. The shipment weight was 260 kg. The default cargo load factor (55 % of the full cargo capacity) was applied.

From Gothenburg to Uppsala (453km) "rigid truck of 7.5-12 t" was used as a transportation mode, using Diesel B5 with the engine of Euro 3 class. Its fuel consumption was 17.8 l per 100 km and full cargo carrier capacity 6 tonne. Cargo load factor was kept as in the default option (40 % of the total cargo carrier capacity) and Leafymade's shipment weighed 260 kg.

For air transport "belly freighter – cargo, range based averages" was chosen in the NTM Calculator. The shipment was transported from Bhubaneswar airport to Arlanda, Stockholm airport (6996 km).

Cargo carrier capacity was 14 000 kg and the default cargo load factor was 65 %. The weight of shipment was 14 kg.

The last leg of the journey from Stockholm to Uppsala (71 km) was done in the vehicle type "van" with the same specifications as described above. Cargo carrier capacity was 1.5 tonne, cargo load factor was 20 % of the full capacity and Leafymade's shipment weighed 14 kg.

Processing

As processing of leaves is done on mechanical sewing machines no electrical power is required. The only unit process in the production phase of the leaf plate that utilises electric power is heat pressing. Even though a proportion of electricity produced in India is made from renewable energy sources, most of the electricity still comes from coal (Central Electricity Authority, 2019). Therefore, in order to quantify GHG emissions of the electricity used in pressing of the plates, the data for GHG emissions from Indian electricity mix had to be acquired. For this calculation the "Standard values for emission factors v.1.0." dataset compiled by the European Commission (2014) was used. This dataset stated that per 1 MJ of electricity produced in India 292 g CO_2 eq is emitted to the atmosphere. The electricity used per plate was 31 kJ.

Packaging

Packaging can be divided into two subgroups. Packaging used for transport from business to business and the final packaging of plates designated for the end customer. Business to business packaging is described first, followed by the end consumer packaging.

The leaf plates are packed in corrugated cardboard boxes with these dimensions (LxWxH) 0.63 m x 0.42 m x 0.42 m (Mehta, 2019). Each box weighs 1 kg (Mehta, 2019). For the purpose of calculating GHG emissions from packaging the figures from a Finnish comparative study were used (Koskela et al., 2014). In this study the environmental impacts of reusable plastic crates were compared with those of corrugated cardboard boxes by the means of life cycle assessment. Koskela et al. (2014) took into account GHG emissions from manufacturing of the boxes, their use, the delivery routes to retailers and waste management/recycling of the boxes. They used a corrugated cardboard box with the dimensions 0.54 m x 0.33 m x 0.11 m (LxWxH) and of 0.2 kg weight (Koskela et al., 2014). GHG emissions of such cardboard box were 0.9 kg (Koskela et al., 2014). These figures were then scaled up to the weight of the corrugated cardboard box Leafymade uses (1 kg). The final number for GHG emissions of Leafymade's box seemed to be in agreement with another study examining environmental impact of corrugated cardboard boxes (Yi et al., 2017). When the figures from this study were scaled up to the weight of Leafymade's box, the number for GHG emissions was almost identical with the number based on the Finnish study.

The end consumer packaging for the leaf plates is made of bio-based polyethylene (Bio-PE), which is 100% recyclable, non-biodegradable and made of sugar cane (Braskem, 2019). The length of the package (31 cm) was calculated based on the overall length of the bio-PE roll supplied by the supplier and the number of packages made from it. The width of the package (25 cm) was obtained from the supplier (Högström, 2019). The supplier also stated that in order to manufacture bio-HDPE used for packaging 23-27g/m^2 of Bio-PE is needed (Högström, 2019). As the area of one packaging is 0.2 m^2 and 25 g of Bio-PE is needed for 1 m^2, one package uses 4 g. There are 12 plates in one package, therefore the amount needed per one functional unit is 0.3 g. According to a cradle-to-gate life cycle assessment study of bio-PE production, which included ethanol production; bio-ethylene production; polymerisation to bio-HDPE and final transport of the polymer from Brazil to Europe; production of bio-HDPE emits 2.45 kg CO_2 eq/kg bio-HDPE (Tsiropoulos et al., 2015).

The processing of bio-HDPE resin to bio-HDPE film used for packaging requires 0.5 kWh/kg bio-HDPE film produced (Högström, 2019). As one plate needs 0.3 g bio-HDPE, then the electricity required for the production of film per plate is 0.15 Wh. In order to calculate GHG emissions from this process, GHG emissions from the electricity mix for Sweden had to be acquired, since the production of bio-HDPE film takes place in Sweden. This number was found in Moro and Lonza (2018), where they accounted for upstream production as well as import and export of electricity for each Member state of the EU. For Sweden the carbon intensity of electricity was 47 g CO_2 eq/kWh when taking into consideration upstream electricity production and import and exports of electricity (Moro and Lonza, 2018).

Disposal

In order to calculate GHG emissions from the specific waste management methods available for the leaf plate the methodology from Eriksson et al. (2015) was applied. As their study area was Uppsala municipality, the waste management facilities they investigated are the same as the leaf plate would end up in.

As mentioned above, there are three different options for the disposal of the leaf plate – composting, incineration with energy recovery and anaerobic digestion. It has been previously calculated that composting in Uppsala emits 0.043 kg CO_2 eq/kg composted waste (Eriksson et al., 2015). This includes production of windrows, the composting process, production of soil amendment, machinery use and the transport to composting facilities. The compost produced was used for covering a landfill and thus was assumed not to replace any other product or service (Eriksson et al., 2015). Incineration with energy recovery is another option. Based on the heat content of the Shorea Robusta leaf (242.8 J/g) identified in Singh et al. (2016), the GHG emissions and the amount of substituted peat could be calculated. Finally, the GHG emissions from anaerobic digestion of a leaf plate were calculated on the basis of water content (0.45%) and heat content of the leaf (242.8 J/g) obtained from Singh et al. (2016). As anaerobic digestion produces biogas, in this calculation, substituted diesel used by city buses in Uppsala were accounted for. Since biogas production requires electricity use and the biomass needs to be transported to the biogas plant, emissions from these processes were also factored in. Anaerobic digestion was selected as the default option for the leaf plate as this is where organic waste normally ends up in Uppsala.

Paper plate

Transportation

In the first stage of the paper plate life cycle, the calculations of GHG emissions from transportation were based on González-García et al. (2009). As mentioned above, the pulp mill investigated in González-García et al. (2009) was assumed to be the same as the integrated pulp and paperboard mill used in the paper plate scenario. According to the study, the total global warming potential (GWP) of silviculture, logging and transport of wood was 36.1 kg CO_2 eq/m^3 of wood (González-García et al., 2009). About 58 % of the GHG emissions originated from the transport of wood and the remaining 42% came from logging and silviculture (González-García et al., 2009). In order to calculate the GHG emissions released from transport of wood per plate, the amount of wood needed for the production of one plate had to be calculated. This was calculated as follows; the weight of one uncoated plate is 8.4 g, of which 84 % is comprised of pulp. Therefore, the weight of pulp per plate is 7.1 g. If the pulp yield from wood is 55 % (FEFCO and CEPI Containerboard, 2015), the amount of wood needed for the production of 7.1 g pulp is then 12.9 g of dry wood. As González-García et al. (2009) base their calculations on wood with moisture content of 40 % and density of 399 kg/m^3 , the moisture content had to be accounted for on a per plate basis too. Thus, the total weight of wood required per plate is 21.5 g, where 40 % is made up by moisture and 60 % by dry wood. Therefore, if processing and transporting 665 kg of solid wood under bark (40 % moisture content) emitted 36.1 kg CO_2 eq, then the GHG emissions from these processes per plate are 1.2 g. Since 58 % was associated with transport of the pulpwood to the pulp mill gate, the GWP of wood transport required for one paper plate was 0.7 g.

The following calculations of GHG emissions from transportation in the subsequent stages of the paper plate life cycle were calculated using the NTM Calculator Advanced 4.0 (“NTMCalc 4.0”, n.d.). After the pulp and paperboard were produced, sheets of paperboard were shipped from Husum to MiniMaid. This journey was divided into four legs.

The first leg of the route was from Husum, Sweden to Holmsund, Sweden (93 km). The vehicle type “truck with trailer 50 – 60 t” was selected as its typical cargo capacity (40 tonnes) is the same as the cargo capacity of the truck used for transportation of paperboard to MiniMaid (Knutar, 2019). It was assumed that the truck runs on Diesel B5 – EU and its fuel consumption was 68 l per 100 km. The shipment weight was 40 tonnes and as the cargo capacity was 40 tonnes the cargo load factor was 100%.

The second leg of the journey was the ferry ride from Holmsund, Sweden to Vaasa, Finland (103 km). The vehicle type used in the NTM Calculator was "Ro-Ro ship", which stands for roll-on/roll-off ship designed to carry wheeled cargo that is driven on and off the ship on their own wheels ("NTMCalc 4.0", n.d.). The default ship size was 10 000 dwt and the default cargo load factor in the NTM Calculator was 70 %. The shipment weight was 60 tonnes (paperboard weight plus the weight of the truck).

From Vaasa, Finland, the paperboard was transported to a factory for coating (30 km) by the same truck with the same specifications as in the first leg of the journey "truck with trailer 50 – 60 t". The shipment weight was assumed to remain unchanged even after coating (40 tonnes) and the cargo load factor was 100 %. The fourth leg of the journey was from the coating factory to MiniMaid (135 km). The very same data as above were inserted into the NTM Calculator.

After the paperboard was converted to paper plates, they were packed and shipped to Uppsala. A shipment of 2 million plates was sent at once to Uppsala. As the average number of plates per box is 600 and one box weighs 277 g (Knutar, 2019), it was calculated that the shipment of 2 million plates were packed in 3334 boxes and the weight of the boxes only was 924 kg. The weight of 2 million plates (17.9 tonnes) was calculated based on the weight of one coated plate (9 g). Thus, the total weight of the shipment was calculated as 19 tonnes. This shipment travelled from the production line in Terjärv, Finland to Vaasa, Finland (135km). The vehicle type of "rigid truck 20-26 t" is used for this and the subsequent journeys. It was assumed that this truck ran on Diesel B5 – EU and its fuel consumption was 35 l per 100 km. The shipment of 19 tonne took up its full cargo capacity, therefore, a 100% cargo load was assumed.

In Vaasa, Finland the truck is loaded on the ferry, which is represented by the "Ro-Ro-ship" in the NTM Calculator. From Vaasa, Finland the ferry travelled to Holmsund, Sweden (103 km). The ship size and the cargo load factor were the same as specified above. The shipment weight was 26 tonne, comprising of the shipment itself and the weight of the truck.

The same rigid truck was then used to transport the goods further from Holmsund, Sweden to Uppsala, Sweden (579 km). The vehicle specifications stayed the same, the shipment weight stayed the same (19 tonne) as well as the cargo load factor (100 %).

Processing

Processing of material starts with the processing of wood, which included silviculture and logging. As mentioned above, about 42 % of the total GHG emissions arising from the phase of wood harvesting derived from silviculture and logging (González-García et al., 2009). This is due to the use of diesel, petrol and lubricant oils to power and maintain the machinery used in these processes (González-García et al., 2009). Since the total GHG emissions arising from the phase of wood harvesting were calculated above as 1.2 g per plate, the proportion allocated to silviculture and logging was thus 0.5 g.

The following processes of pulp and subsequent paperboard making generated 44 kg of CO_2/tonne of paperboard produced (Metsä Board, 2018). The weight of one plate is 8.4 g (Knutar, 2019). Hence, the GHG emissions from the pulp and paperboard needed for the production of one paper plate were calculated as 0.4 g.

Next, the paperboard was coated with a layer of polyethylene. It was assumed that low-density polyethylene is applied on the paperboard. According to Plastics Europe's research (2014), the production of 1 kg of LDPE emits 1.9 kg CO_2 eq. If one plate uses 0.55 g of LDPE coating (Knutar, 2019), the GHG emissions associated with this process were calculated to be 1 g.

Finally, upon arrival of the paperboard to MiniMaid, the paperboard was pressed into paper plates. Pressing of one plate requires 2.8 Wh (Knutar, 2019). To quantify the amount of GHG emitted from this process, the carbon intensity of the Finnish electricity mix had to be researched. This was found in Moro and Lonza (2018), where they accounted for upstream production as well as import and export of electricity for each Member state of the EU. The carbon intensity of Finnish electricity was thus found to be 211 g CO_2 eq/kWh (Moro and Lonza, 2018).

Packaging

Same as in the leaf plate system, two different types of packaging were considered, packaging used to protect the goods during their transport and the final packaging for the end consumer.

In case of the protective packaging used for transport, corrugated cardboard boxes (CCB) were used. The weight of one box is 277 g (Knutar, 2019). For the purpose of calculating GHG emissions from the production of a CCB used by MiniMaid the same Finnish study (Koskela et al., 2014) was used as a basis for calculations as for the leaf plate scenario. According to Koskela et al. (2014), a CCB of 190 g emits 0.9 kg greenhouse gases. Thus, a CCB weighing 277 g was calculated to emit 1.3 kg GHG. As there were 600 plates per box (Knutar, 2019), GHG emissions per plate were 2 g.

The other type of packaging, end consumer packaging, is made of polyolefin shrink film (Knutar, 2019). Polyolefin is a collective term for polyethylene and polypropylene thermoplastics (Plastics Europe(a), n.d.). These can be of different types; LDPE (low-density polyethylene), LLDPE (linear low-density polyethylene), HDPE (high-density polyethylene) or PP (polypropylene) (Plastics Europe(a), n.d.). For this study, LDPE was chosen as it is commonly applied in packaging as shrink film (Barlow and Morgan, 2013; Plastics Europe(b), n.d.). According to an extensive review of 52 plants producing polyolefins in Europe, the GHG emissions for the production of 1 kg of LDPE amount to 1.9 kg CO_2 eq (Plastics Europe AISBL, 2014). In order for the LDPE resin to be used in packaging, it needs to be converted into shrink film. The amount of electricity required for this conversion was assumed to be the same as the amount of electricity used for producing bio-HDPE film from bio-HDPE resin. This figure (0.5 kWh/kg bio-HDPE film produced) was obtained from the producer of the bio-HDPE film (Högström, 2019). To calculate GHG emissions released from this process, the carbon intensity of Finnish electricity mix (211 g CO_2 eq/kWh) was taken from (Moro and Lonza, 2018).

Disposal

When it comes to the last stage of the paper plate's life cycle; disposal, the methodology from Eriksson et al. (2015) was applied to quantify GHG emissions from the waste management options available. Their study area was Uppsala municipality, therefore, the waste management facilities would be the same as the paper plate would end up in.

Since the paper plate was coated with a plastic (LDPE) layer to make it soak-proof, the option of composting and anaerobic digestion had to be excluded, as it would not decompose fast enough. In addition, the LDPE plastic would only decompose into microplastic. Thus, the only possibility left for the disposal of the paper plate was incineration with energy recovery. In order to be able to calculate GHG emissions and the amount of peat substituted by incineration of a coated paper plate, the calorific value of the paper plate had to be researched. The low heat value (LHV) of paperboard (14.77 MJ/kg) was taken from Phyllis2 database (ECN.TNO, n.d.) and was assumed to correspond to the low heat value of the paper plate studied. As LHV for coated paperboard could not be found, emissions from burning the plastic LDPE layer were not accounted for in these calculations.

3.1.5. Impact assessment

In this section the choice of impact assessment category will be described and justified.

For the purpose of the study the impact assessment category – global warming potential was selected. This is due to the fact that both products chosen for the comparative LCA need to be transported. Transportation generates GHG emissions, which in turn have an impact on the climate.

Indicators for this category are greenhouse gases emitted from processes. Greenhouse gases are defined by Kyoto Protocol as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) (UNFCCC, 2012). However, this study accounted only for CO_2, CH_4 and N_2O. Biogenic CO_2 was not considered apart from the disposal stage where biogenic carbon from both plates were awarded credits for substituting fossil carbon. The characterisation model adopted was the IPCC model as it is the most up-to-date and scientifically robust model available (European Commission, 2011).

The impact of GHGs is expressed through their global warming potential (GWP). The GWP was introduced in the IPCC First Assessment Report (IPCC, 2014) and it expresses the amount of energy a gas absorbs over a particular period of time, compared to carbon dioxide (US EPA, 2015). The more energy it absorbs the stronger warming it will cause. Methane, for example, can absorb 84 times more energy than carbon dioxide over a period of 20 years (IPCC, 2014).

The length of the period a GHG stays in the atmosphere varies among gases too. Thus, the global warming potential of a GHG over a 20-year period will differ from the 100-year period. The IPCC model comes with three different timeframes; 20-year, 100-year, and 500-year; however, the 100-year GWP (GWP_{100}) was adopted by the United Nations Framework Convention on Climate Change (UNFCCC) and is used widely as the default metric (IPCC, 2014). Therefore, in this study GWP_{100} was used as a metric to assess the impact of the two products on the climate. The equivalency factors of different greenhouse gases change over time with new reports issued by the IPCC. In order to harmonise GHG emission calculations across the systems the GWP_{100} of CH_4 and N_2O were based on the IPCC's Fourth Assessment Report (2007). Here the GWP_{100} of methane was defined as 25 and of nitrous oxide as 298 (IPCC, 2007).

3.1.6. Scenario analysis

Life cycle assessment is a tool applied not only to analyse the current systems of given products and their impacts but also to asses impacts of possible future changes to the systems. As carrying out an LCA can reveal critical points for improvement in product systems, future scenarios can also serve as a projection of impacts of these improvements once they are realised.

Since the company producing the leaf plate is a start-up business, it is reasonable to expect it to become a well-established business in the future. This will bring some inevitable changes to its current mode of production, thus, it is important to estimate the impact of these changes on the environment. A scenario where the leaf plate company becomes an established business will also place it on an equal footing with the paper plate company and then the comparison can become fairer. With respect to the paper plate, using fossil-based plastic for its coating eliminates other options than incineration with energy recovery from its waste management options. Thus, if the paper plate was coated with a biodegradable layer, it could be digested anaerobically or composted too. In addition, the European parliament is going to ban oxo-degradable plastic packaging from the market starting 2021 (European Parliament News, 2018). It is, therefore, highly probable that the plastic packaging currently used for the paper plate will also need to be substituted with a biodegradable material.

All these changes will have an impact on the carbon footprint of both plates. Therefore, they served as a basis for modelling future possible scenarios for each plate. Each scenario is described in detail in the following paragraphs. Results from the scenario analysis are presented in the results section.

Leaf plate

In the leaf plate scenario analysis, the plates were shipped solely via the sea route and it was assumed that two million plates were shipped at once from India to Sweden. This number was chosen as it corresponds with the number of plates the paper plate company ships to their customers. If two million plates are to be shipped at once, the production needs to grow exponentially since with the current rate Leafymade would have to wait over seven years for this number of plates to be produced.

Transportation

All the legs of the journey of the leaf plate were adjusted to suit the scenario when two million plates would be shipped at once. Since in the current scenario the cargo load of all the vehicles used on the route between India and Sweden is shared with some other goods besides leaf plates, so are the overall GHG emissions from the particular journey. Therefore, if the vehicle's cargo capacity stays the same, but the number of leaf plates transported increases, the share of their GHG emissions increases and the result per plate stays the same. Thus, if the carbon footprint per plate is to be reduced, a vehicle of a larger cargo capacity needs to be utilised for the same journey. Then, the vehicle can be fully loaded only with leaf plates and the amount of GHG emissions per plate decreases.

Thus, the type of vehicle used for transport of bundles of leaves between Daringbadi and Bhubaneswar (246 km) was changed from "van" to a "rigid truck (20-26 tonne)" with its full, default, volumetric cargo capacity of 56 m^3 ("NTMCalc 4.0", n.d.). Leafymade's shipment would take up its full cargo capacity (56 m^3) and its fuel consumption would be 27 l of Diesel B5 per 100 km as set in the NTM Calculator (n.d.). It was calculated that 56 m^3 of bundles of leaves would make about 356 790 plates, based on the information that 4 m^3 yield 25 485 plates (Mehta, 2019).

The subsequent journey from Bhubaneswar to Kolkata (442 km) would be carried out by a "rigid truck (20-26 tonne)" as opposed to a van in the current scenario. The rigid truck would have a fuel consumption of 35 l of Diesel B5 per 100 km. As 25 485 packed plates weigh 260 kg (Mehta, 2019), the weight of two million packed plates was calculated as 20.4 tonnes. Thus, the weight of shipment on this journey would be 20.4 tonnes, which is also the full cargo capacity of the truck.

When it comes to the sea transport from Kolkata, India to Gothenburg, Sweden (15 663 km), if the boat with the same specifications as in the current scenario was used (full only to 55 % of its cargo capacity) the carbon footprint per plate would stay the same. This is because the higher share of GHG emissions generated by a 20.4 tonne heavy shipment, as opposed to 260 kg, would also be divided by a larger number of plates transported (two million) in comparison with 25 485. Therefore, if reduced GHG emissions from this journey were to be achieved, the boat would need to be fuller, for example, to 75% of its full cargo capacity. As this is outside of Leafymade's influence, the same, default, cargo load (55 %) was assumed as in the current scenario.

For the last leg of the route from Gothenburg to Uppsala (453 km) the "rigid truck 7.5-12 t" was changed to "rigid truck 20-26 t" with the same specifications as defined in the second leg of the journey.

Processing

In regards to processing, the following adjustments were done. As leaf plate uses three times more electricity per plate (31 KJ) for pressing than the paper plate (10 KJ), the production of the leaf plate was increased three times to 2250 plates per day. It was assumed that no extra heat press machines were acquired, since the production would get more efficient, using the same amount of energy to produce more plates. In this way the electricity use per plate could be reduced to the level of the paper plate. The same electricity emission factor for India was used as in the current scenario (292 g CO_2 eq/MJ). However, in case two million plates were to be manufactured during the same period (34 days) as 25 485 plates were manufactured, the productivity would have to increase over 78 times. Due to insufficient data on productivity of the heat pressing process, such as the number of machines currently used or their maximum production capacity, no further calculations in this scenario could be made. Therefore, only the three-fold increase in productivity was assumed for the scenario analysis, as this was deemed achievable with the current manufacturing equipment.

If the production of plates was to increase three-fold, so would sewing of leaves. So far sewing is done on mechanical sewing machines. No data was collected on the productivity of the workforce in regards to sewing leaves. Therefore, it could not be said with certainty if the three-fold increase in the production could still be maintained by the use of mechanical sewing machines only. In this case, more workers would definitely need to be employed. It is, however, very probable that the growth in manufacturing of plates would lead to acquiring electrical sewing machines, especially if production would need to increase 78 times. Hence, a very rough estimate was made in regards to the production capacity of electrical sewing machines and the workforce. It was estimated that an electrical sewing machine requires power of 100 W (Storgaard, 2018) and it would be used six hours per day constantly. This would require then 0.6 kWh per day for one machine. Furthermore, it was estimated that one machine would produce one plate per minute, which would yield 360 plates per working day. In order to produce 2250 plates per day, six electrical sewing machines would be required. Thus, six machines working for six hours would need energy of 3.6 kWh to produce 2250 plates.

Paper plate

When it comes to the paper plate potential future scenario, the current LDPE coating was replaced with coating made from polylactic acid (PLA). PLA can be produced from a number of starch-rich crops such as corn, rice, potato, cassava or sugarcane (Papong et al., 2014) and was applied here as a biodegradable, water-resistant material. For this scenario analysis PLA from cassava produced in Thailand was applied. PLA was selected as it seems to be the most popular and feasible material for the application on paper-based disposables (Häkkinen and Vares, 2010; Van der Harst et al., 2014; Van der Harst and Potting, 2013). As it is biodegradable, the whole paper plate could now be composted or anaerobically digested. In addition, plastic packaging currently used for paper plates was also substituted with biodegradable PLA-based plastic.

Processing

When calculating the carbon footprint of polylactic acid (PLA) production, the GHG emissions were taken from Papong et al. (2014). These emissions did not account for the biogenic carbon stored in the plant. Three different scenarios for GHG emissions from the production of PLA were provided. The base case scenario, where 2.48 kg CO_2 eq per kg PLA resin produced is emitted (Papong et al., 2014). The improved production scenario, when the biogas from the wastewater treatment of cassava starch production was utilised. Consequently, the net GHG emissions would reduce to 1.96 kg CO_2 eq per kg resin (Papong et al., 2014). The third scenario includes a further improvement of production where a combined heat and power (CHP) system was installed instead of the use of grid electricity and steam energy from natural gas. Consequently, GHG emissions would drop to 1.54 kg CO_2 eq per kg PLA resin (Papong et al., 2014). Based on these options, the best-case and the worst-case scenario was calculated for the paper plate coating. In the best-case scenario it was assumed that the production of 1 kg PLA resin was responsible for 1.54 kg GHGs. In the worst-case scenario the PLA production generated 2.48 kg GHGs per kg PLA resin. The amount of the coating material needed per plate remained unchanged (0.55 g).

Disposal

Since PLA coating layer is biodegradable the whole paper plate could also be composted and anaerobically digested in the future scenario. As it has been described earlier, in the current situation in Uppsala, where the plates would be disposed of, the compost obtained is used only to cover the landfill in the area, thus not providing nutrients to any plants. Therefore, it is not substituting any fertiliser and only generates GHG emissions from the production of windrows, the composting process, machinery use and transport (Eriksson et al., 2015). Based on the calculation that composting in Uppsala emits 0.043 kg CO_2 eq/kg composted waste (Eriksson et al., 2015), the emissions associated with one coated paper plate (9 g) were calculated as 0.4 g GHGs.

The potential of production of biogas from a coated paper plate was investigated on the basis of the same methodology applied in Eriksson et al. (2015). The biogas acquired would save the use of diesel used by city buses in Uppsala. In order to quantify the GHG emissions from anaerobic digestion, properties of both paperboard and PLA had to be researched. The moisture content (8%) of the paperboard was found in the environmental profile of the paperboard used (Metsä Board, 2018). The volatile matter of the paperboard (78 %) and PLA (100%), moisture content of PLA (0.1%) were all acquired from Phyllis 2 database (ECN.TNO, n.d.). Polylactic acid was assumed to have the same material properties as low-density polyethylene in the database. Furthermore, methane yields from both materials needed to be acquired too. The methane yield from paperboard vary depending on its pulping method and composition (Bayr and Rintala, 2012; Carlsson and Uldal, 2009). It was assumed that the methane yield was 0,12 m^3 CH_4 per kg volatile solids (Karlsson et al., 2011 in Bayr and

Rintala, 2012) of the paperboard used in the paper plate. Methane yield of polylactic acid used for the calculations was 0.53 m^3 CH_4 per kg volatile solids based on research of Benn and Zitomer (2018). Since anaerobic digestion saved some use of fossil fuels in comparison with composting, it was chosen to be used in the scenario analysis of the paper plate.

Packaging

The last amendment in the paper plate life cycle for the scenario analysis was the material used for packaging (B2C). Currently, fossil-based low-density polyethylene (LDPE) is applied, which was replaced by packaging made of polylactic acid (PLA) in the future scenario. However, the amount used per plate is so small (0.05 g) that even if substituted by a more environmentally friendly option, its impact would still be negligible. For comparison, the current GHG emissions per plate wrapped in LDPE are 0.09 g, as opposed to 0.08 g[4] when the plate is wrapped in PLA.

[4] The best-case scenario applied, when 1.54 kg GHGs/ kg PLA resin are emitted.

4. Results

What follows are the results for global warming potential of the current life cycle of disposable leaf and paper plate, succeeded by the results for GWP of future scenario of each plate. It is important to notice that the weight of the two plates was very similar; 9.3 g for the leaf plate and 9 g for the coated paper plate, thus direct comparisons could be made.

The paper plate had a lower impact on climate change than the leaf plate (Fig. 6). The total carbon footprint of the paper plate was negative (-8 g CO_2 eq) as it decreased the use of fossil fuels more than it required. On the other hand, the leaf plate generated more GHG emissions than it substituted, hence its carbon footprint was 18 g CO_2 eq. The disposal option for the leaf plate depicted in Fig. 6 was anaerobic digestion; it is its best-case scenario and saved 8 g of fossil GHG emission. The disposal scenario for the paper plate was incineration with energy recovery, which was the only possible scenario and saved 14 g fossil GHG emissions. If the waste management of both plates was not taken into consideration the leaf plate would still generate 20 g greenhouse gases more than its paper counterpart (Fig. 6).

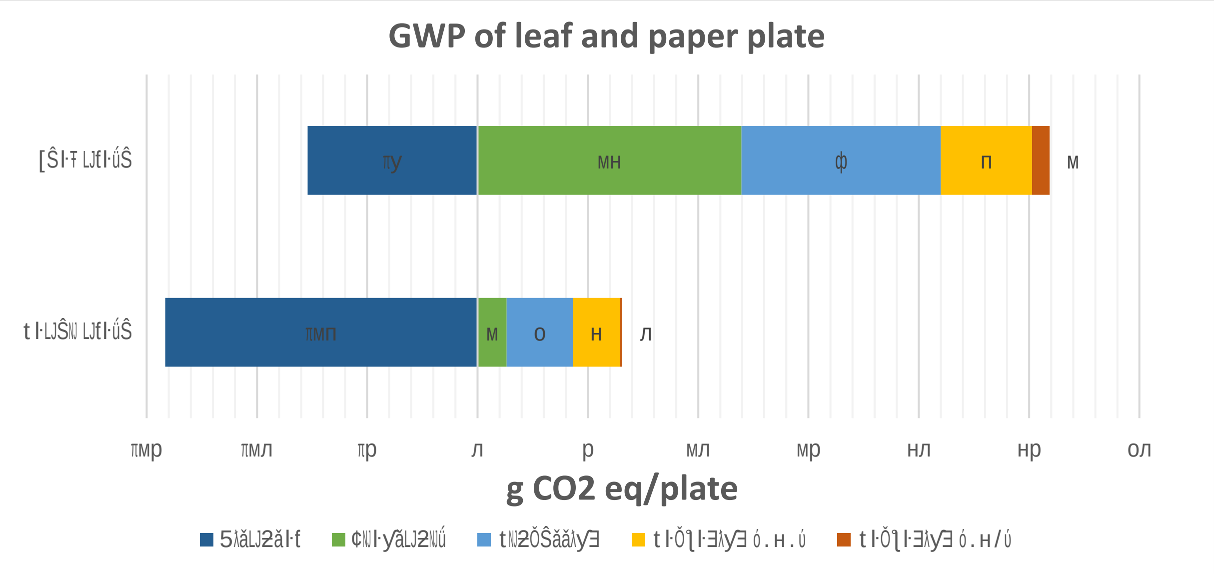

Fig. 6. A graphical representation of global warming potential of the life cycle of the disposable leaf and paper plate showing contributions of each stage to the total global warming potential.

A closer analysis of the results indicated that the hotspots of the leaf plate life cycle, contributing the most to the overall impact and with the largest potential for improvement, were transport (12 g CO_2 eq) and processing of materials (9 g CO_2 eq). Transportation accounted for the fact that 92% of all the shipments until now was realised by sea and 8 % by air. If the leaf plate was sent entirely via the sea route it would emit 5 g GHG. On the other hand, if the plate was to be sent via air cargo, its GHG emissions would be 92 g. Hence, the GHG emissions arising from transport of one leaf plate were 12 g, where 5 g represented 92% of all the shipments and 7 g represented 8% of all the shipments so far (Fig. 7). Even if the leaf plate was sent solely by sea its carbon footprint arising from transport only would be 4 g higher than from the transport of the paper plate (1 g CO_2 eq).

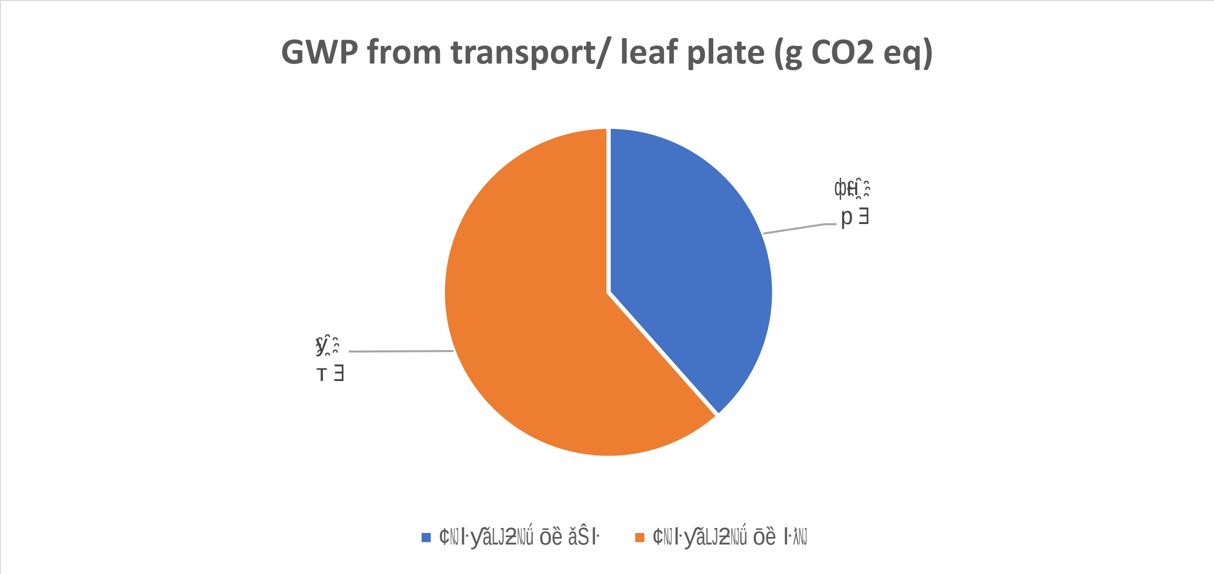

Fig.7. A graphical representation of global warming potential arising from transport of the leaf plate, when 92 % of all shipments so far were done by sea and 8% of all shipments so far were carried out by air.

The other hotspot of the leaf plate; *processing*, was made up merely of heat pressing of plates and was responsible for 9 g GHG emissions per plate. Other manufacturing processes included in the processing stage were collecting, washing and subsequent sewing leaves, however, they did not utilise any other power apart from manpower. Thus, no GHG emissions were generated from these processes.

Another process with a quite substantial positive contribution to the leaf plate carbon footprint was its disposal (-8 g GHGs). As mentioned above the disposal scenario represented anaerobic digestion and its savings represented the diesel substituted by the use of leaf plate turned into biogas. There were other waste management options available for the leaf plate, however, the results for these showed lower GHG savings or they generated GHG emissions as opposed to substituting them (Fig. 8). Incineration of a leaf plate with energy recovery could save 0.2 g CO_2 eq of the peat replaced, which is normally used for district heating or cooling (Eriksson et al., 2015). On the other hand, composting of the leaf plate gave rise to 0.4 g CO_2 eq as it did not replace any other product. The compost produced was only used to cover the landfill in Uppsala, hence not providing nutrients to any plants (Eriksson et al., 2015).

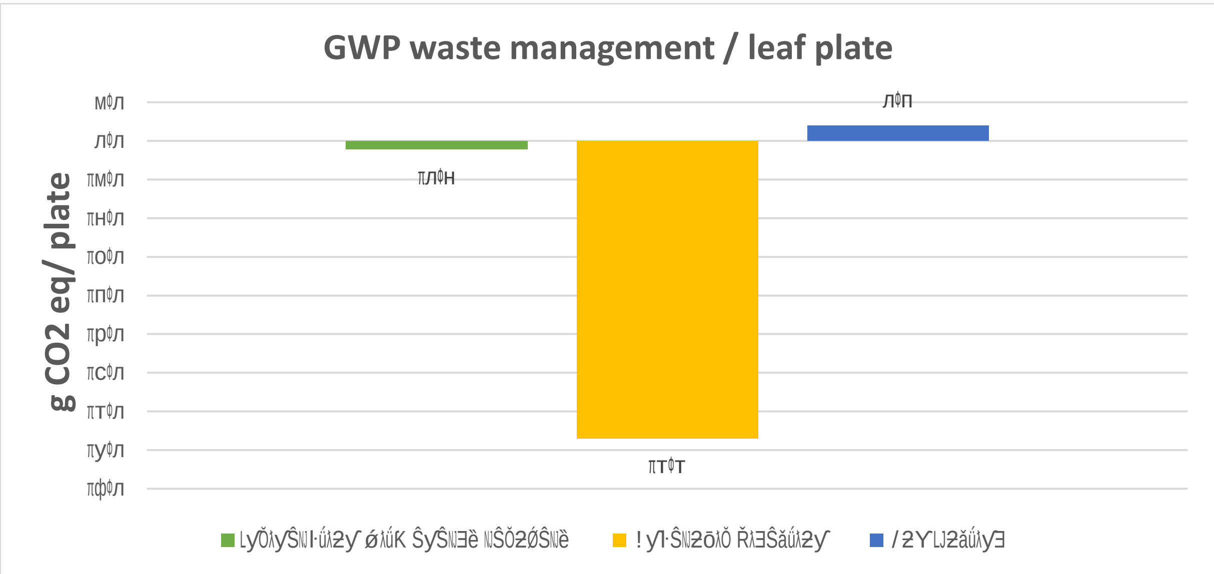

Fig. 8. A graphical representation of global warming potential of the three waste management options for the leaf plate – incineration with energy recovery, anaerobic digestion and composting.

In the paper plate life cycle, the processing stage released the most GHG emissions (3 g CO_2 eq). The processing stage of the paper plate included extraction of wood, pulp and paperboard making, production of the coating material and pressing of paper plates. Yet, all these processes combined generated about 6 g less GHG emissions than heat pressing of the leaf plate. The second process contributing the most to the overall GWP of the paper plate was its disposal. Here it represented incineration with energy recovery but since it was negative (-14 g CO_2 eq) it substituted the same amount of fossil GHG emissions from peat and thus was considered as a positive impact on the paper plate life cycle. The emissions from burning the LDPE layer were not accounted for.

Results for scenario analyses

In this section, results of the potential future scenarios for each plate will be demonstrated. First scenario is the leaf plate scenario, where it was assumed that Leafymade, the company producing the leaf plate used as a case study, became a well-established business and could ship two million plates at a time, solely via the sea route. In addition, the productivity of the company would increase three-fold. The data for both types of packaging as well as disposal of the leaf plate stayed the same as in the current system. The disposal option did not change as the other options for the leaf plate performed worse in terms of GHG emissions.

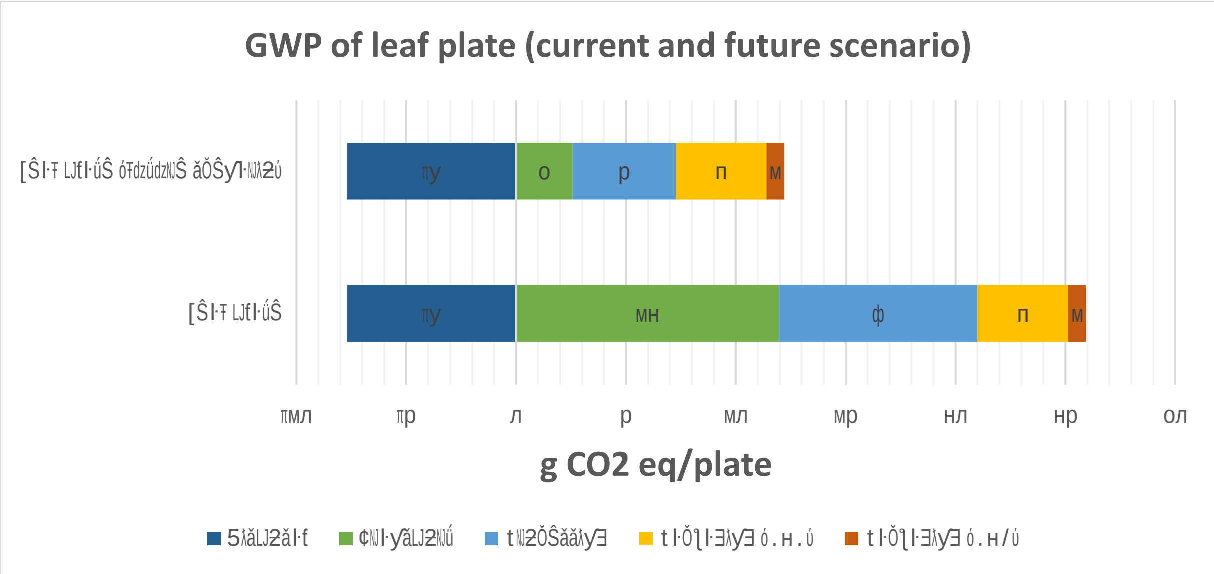

Fig. 9. A graphical representation of global warming potential of the leaf plate in the current scenario and the future scenario assuming a three-fold increase in production and two million plates shipped to Sweden only by the sea.

The results of the future scenario described above are shown in Fig. 9. The global warming potential of the leaf plate life cycle would decrease by 13 g to 5 g GHG emissions per plate. The largest decrease would be done in transport (-9 g). The transport via the sea route would decrease from 5 g per plate in the current scenario to 3 g per plate in the future scenario. Processing in the future scenario included emissions from pressing plates (3 g) as well as sewing leaves (2g). If sewing could still be done mechanically, the overall carbon footprint could be further decreased. However, more realistic option for decreasing the footprint would be increasing the number of plates sewn on the electric sewing machines per day.

Even after increasing production and the number of leaf plates shipped, the paper plate would still have a lower global warming potential. The leaf plate of an established company would generate 5 g GHGs, whereas the paper plate saved GHGs (- 8 g CO_2 eq). However, when the credits for waste management options of both systems were not taken into consideration, the difference between the plates would only be 7 g, as opposed to 20 g in the status quo.

The second scenario is the potential future scenario where the paper plate was coated with a biodegradable layer made from polylactic acid (PLA), which would make it possible for the paper plate to be digested anaerobically or composted. In addition, fossil-based plastic used for packaging (B2C) was replaced with PLA-based plastic. Any other processes in the paper plate's life cycle stayed the same.

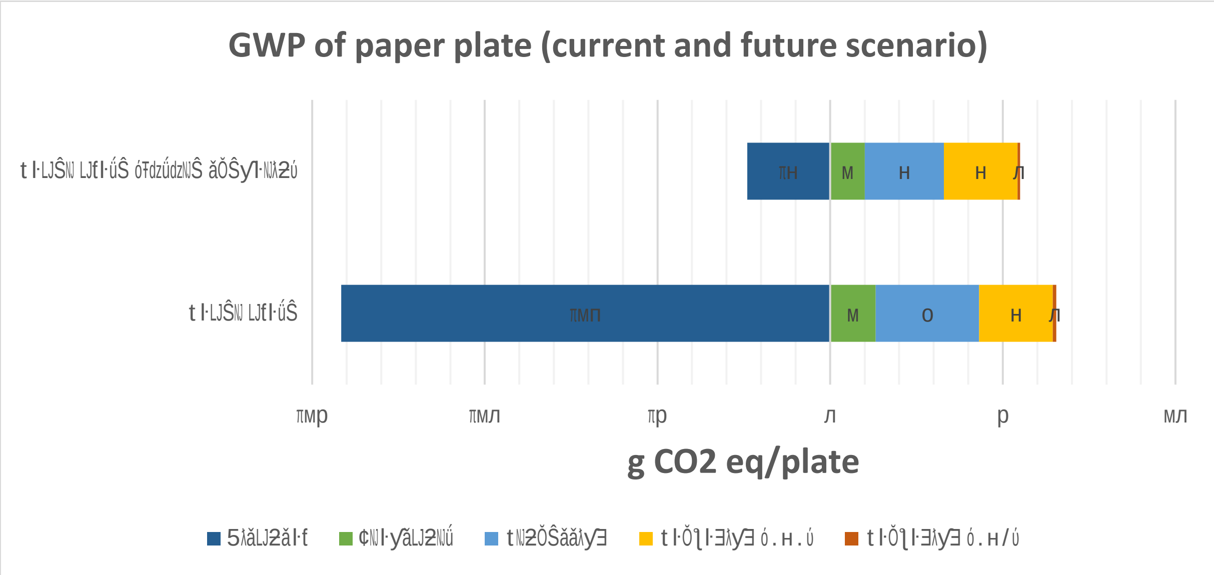

Fig. 10. A graphical representation of global warming potential of the paper plate in the current scenario and in the potential future scenario, when the coating material is biodegradable PLA, the plate is anaerobically digested and the packaging (B2C) is made of PLA.

Fig. 10 depicts results for the potential future scenario described above together with the results for the current paper plate scenario. When the paper plate was anaerobically digested, coated with and packed in PLA-based plastic its total GWP was 3 g, as opposed to -8 g GHGs in the current scenario. A great change can be noticed in emissions from the paper plate's disposal. When the plate was anaerobically digested to produce biogas it could save about 12 g less GHGs than when it was incinerated. This is due to the low degradation rate of cellulose, hemicellulose and no degradation of lignin in anaerobic conditions (Carlsson and Uldal, 2009; Häkkinen and Vares, 2010). When it comes to coating, the carbon footprint decreased to 0.8 g GHGs per plate from previous 1 g GHGs, when the best-case scenario for polylactic acid production (1.54 kg CO_2 eq/kg PLA) was taken into account. However, when the worst-case scenario for PLA production (2.48 kg CO_2 eq/kg PLA) was applied, the carbon footprint of coating increased to 1.4 g per plate. Therefore, the best-case scenario was used in the end for the future scenario for the paper plate. The substitution of fossil-based plastic with cassava-based plastic in packaging used for the end consumer did not cause any real change in the GHG emissions from this process. For comparison, the current GHG emissions per plate wrapped in plastic based on low-density polyethylene were 0.09 g, as opposed to 0.08 g[5] when the plate is wrapped in plastic made from polylactic acid.

[5] The best-case scenario applied, when 1.54 kg GHGs/ kg PLA resin are emitted.

5. Discussion

The results have shown that the regionally produced paper plate coated with a layer of low-density polyethylene has lower global warming potential than the uncoated leaf plate shipped from afar. As specific studies on disposable plates could not be found, analyses of environmental impacts of disposable cups were looked into for validation of the results.

Häkkinen and Vares (2010) compared two paperboard-based disposable cups, one coated with two layers of polyethylene (PE) and the other coated with two layers of polylactic acid (PLA). PLA is based on fermented sugars of corn and is applied here as a biodegradable, water-resistant material (Häkkinen and Vares, 2010). Their results indicate that the cup manufactured from all bio-based materials has a slightly higher global warming potential than the cup coated with PE. Furthermore, Vercalsteren et al. (in Van der Harst and Potting, 2013) showed that a disposable cup made solely from PLA-based plastic has a higher impact on climate change than paperboard cup coated with polyethylene. These results seem to confirm the results of this study where all bio-based plate has a higher impact on the climate than a bio-based plate coated with fossil-based plastic. However, none of the studies were comparing a far-travelled product with a regionally/locally produced one. Only in Van der Harst et al. (2014) did they take into consideration averages of PLA production done far from the place of use of the disposable cups. Nonetheless, they could not identify a single best material for disposable cups when comparing environmental performance of polystyrene, polylactic acid and paper lined with bioplastic across multiple impact categories.

Therefore, the results of this study should be interpreted with caution as it solely focused on the performance of the two disposable plates in one impact category; global warming potential. This category was chosen because the impact of transporting of products influences their global warming potential the most. However, if acidification and eutrophication were taken into consideration, the paper plate could have performed worse than the leaf plate. This is due to the application of various chemicals in the processes of pulp and paperboard making, which gives rise to acidification, whereas the leaf plate does not use any chemicals in the process of manufacturing. Moreover, fertilisers are used in the planting of trees in the life cycle of the paper plate (González-García et al., 2009), which in turn can cause eutrophication. In the life cycle of the leaf plate, on the other hand, no fertilisers are applied for the trees the leaves are obtained from. Thus, general conclusions about the overall environmental impact of the plates based on the results should be avoided.

Furthermore, the aforementioned studies, take into consideration various waste management options (including landfill). Many materials do not decay in anaerobic conditions of a landfill and thus do not release any GHGs (Häkkinen and Vares, 2010). In a similar vein, recycling a certain material may release less GHG emissions than composting it (Van der Harst and Potting, 2013). Therefore, waste management choices and credit allocations due to these choices influence markedly the overall global warming potential of products (Häkkinen and Vares, 2010; Van der Harst et al., 2014; Van der Harst and Potting, 2013).

This is illustrated in an extensive review of life cycle assessments of ten disposable cups made from various materials (Van der Harst and Potting, 2013). The review showed that none of the cup materials were consistently better than the others. The varying results for GWP can be assigned to multiple factors such as production processes, waste processes, allocation options, data used (Van der Harst and Potting, 2013). However, elsewhere, three processes were identified to have the highest environmental impact: production of the cup's basic material, cup manufacturing, and waste processing (Van der Harst et al., 2014). These results are aligned with the findings of this study as the hotspots identified here were almost identical (processing, transport, waste management). Disposal of the plates has a substantial but positive influence on their total carbon footprint as both plates substitute use of fossil fuels. In the case of waste management of the leaf plate, the option that saves the most GHG emissions was chosen for the comparison with the paper plate. In this way, the waste management processes of both product systems substitute a considerable amount of fossil fuels. Other options for the leaf plate, composting (0.4 g CO_2 eq/plate) and incineration with energy recovery (-0.2 g CO_2 eq/plate) had no or lower credits for substitution of fossil fuels respectively. In the paper plate system, there was only one possibility identified, incineration with energy recovery and was shown to have the highest positive impact on the paper plate life cycle.

Hence, it could be said that each product should be looked at as a case study with specific manufacturing processes for a specific disposable product in a specific location for its use. Any conclusions derived should be applicable merely for the case studies in question. The location for this study was Uppsala, where the products are used and disposed of. Therefore, the results for GWP of the two disposable plates may be applied in a location with similar waste management facilities to Uppsala. Since each product system should be examined as a unique case study, what follows is an analysis of hotspots of each product system separately and suggestions for their possible improvements.

Hotspot analysis

As mentioned above, the processes contributing the most to the GWP of the leaf plate life cycle are transport, followed by processing. In order to be able to decrease the GHG emissions from these processes, it is necessary to examine where they originate from. Transport generates the most GHG emissions in the leaf plate life cycle, since the plate travels over a long distance. The leaf plate travels first within India to be produced and later travels to Sweden to be used. The mode of transportation heavily influences the amount of GHG emissions generated. If the leaf plate is sent by air its carbon footprint only from transport increases 18 times than if it was sent via the sea route. The reason why some plates are shipped by air is the need for samples to be delivered as fast as possible (Mehta, 2019). Furthermore, the leaf plate travels from afar due to social aspects. The production of the leaf plate provides employment for tribal women living in the area where the leaves come from in India. They collect abundant, fallen leaves in the rainforest they live in (Mehta, 2019). They receive training on how to sew the leaves from the local non-governmental organisation so that they can earn an extra income in addition to their crop yields (Mehta, 2019).

When it comes to the second hotspot; processing of leaves and turning them into a leaf plate, there is only one unit process which generates the GHG emissions; heat pressing. This is because it uses electrical power, whereas sewing leaves is done on mechanical sewing machines and leaves are collected by the tribal women, thus only manpower is required. Nevertheless, the one process gives rise to 9 g of greenhouse gases as opposed to 3 g generated from the processing of materials for the paper plate. In comparison, processing of the materials for paper plate includes extraction of wood, pulp and paperboard making, coating and pressing of paper plates, where each process requires different types of energy (including electrical). The key factor causing the difference in the amount of GHGs emitted is the source of energy. India derives the majority of its electrical energy from coal (Central Electricity Authority, 2019), hence its high carbon footprint. Finland, where the paper plate is produced, however, produces the majority of electricity from carbon-free sources (Finnish Energy, n.d.), regarding biomass fuel as carbon neutral as it is composed of biogenic carbon. Wood processing industries, such as pulp and paper industries, are a great example of efficient use of biomass waste from their production for powering their own manufacturing processes. They use black liquor[6] and forest residues to produce steam and electricity needed for the pulp and paper manufacturing (Mantau, 2012), which in turn makes it carbon neutral. This is the case of the pulp and paperboard mill represented in the paper plate life cycle (Metsä Board, 2018). Therefore, even if more electricity and other types of energy are used in the whole processing stage of the paper plate system, it still has a lower carbon footprint than the processing of the leaf plate.

Even though the paper plate performs better than the leaf plate in terms of GHG emissions, it still has room for improvement in the processing of raw materials and turning them into a product. Harvesting wood involves use of heavy machinery, which runs on fossil fuels. Based on González-García et al. (2009a) used for calculations in this study, silviculture and logging are responsible for 0.5 g GHG emissions per plate. Pulp and paperboard making emit about 0.4 g GHG emissions per plate considering that a substantial amount of the energy consumed in the production comes from biomass.

[6] black liquor is the waste product from the kraft process when digesting pulpwood into paper pulp removing lignin, hemicelluloses and other extractives from the wood to free the cellulose fibres (Climate Technology Centre & Network, 2016).

Another contribution of GHGs comes from pressing paper plates and is responsible for 0.6 g GHG emissions per plate. The highest proportion of GHG emissions generated from processing originate from the production of the coating material (1 g). In this case the material is fossil-based low-density polyethylene (LDPE). The life cycle of the production of LDPE comprises of a multitude of complicated and energy intensive processes which give rise to 1.9 kg GHGs/kg of LDPE resin produced (Plastics Europe AISBL, 2014). Consequently, if a different material was used for coating it could potentially be less energy intensive and thus decrease the impact of coating on the overall GWP. The material used for coating also influences the end-of-life options for the paper plate. If the paper plate was coated with a biodegradable layer, it could be digested anaerobically or composted too.

Room for improvement in the leaf plate life cycle is vast. When, for example, the amount of electricity utilised for pressing plates is compared between the systems, the leaf plate seems to be using three times more electricity per plate (31 KJ) than its paper counterpart (10 KJ). This could be improved by increasing efficiency of the heat pressing machines currently employed, whereby more plates could be produced with the same amount of electricity consumed. Thus, no extra machinery would have to be obtained. If the production increased, more plates could be shipped at once and consequently emissions per plate from transport could decrease too. In addition, growth in production could also save flying of plates to Sweden, as there would be enough samples of leaf plates to store. Therefore, the scenario analysis for the leaf plate was based on a future scenario when Leafymade, the company used as a case study, became a well-established business and shipped two million plates at once, solely via the sea route.

The improvements outlined above were translated into the future scenarios of each plate. The results of the future scenario analysis are discussed in the following section.

Scenario Analysis

The results of the future scenario for the leaf plate have shown that the GWP of the leaf plate can be decreased substantially if the transport is done only via the sea route and if the production increases without rising electricity consumption. However, if production is to grow further more electricity will be required for sewing leaves. If this is to be the case then attention should be paid at the production capacity per electrical sewing machine and how to increase it. Nevertheless, even after increasing production and the number of leaf plates shipped, the paper plate still has a lower global warming potential. As both leaf plate scenarios already use its best option for waste management, no further improvements are possible there. On the other hand, further improvements are still possible in terms of packaging. In case of packaging used for transport between businesses (Packaging B2B) a lighter corrugated cardboard box could be used and/or more plates could be packed in one box. Nonetheless, Leafymade already packs more plates in one box (1350) then its paper counterpart (600). When it comes to the packaging for the consumer more plates than 12 could be placed in one pack so that the consumption of the material per plate decreases further.

A radical change that would reduce the carbon footprint of the leaf plate markedly is to locate the production in Sweden and start producing the leaf plate from Swedish leaves. In this way the carbon footprint of production would not be as high due to Sweden's less carbon intensive electricity production. For comparison, the 5 g GHG emissions from processing in the future scenario would change to 0.21 g GHG emissions per plate in case the production would take place in Sweden. However, then, the social aspect of the production in India; providing employment and rising standards of living of the local inhabitants in India would be lost. Thus, if the production is still to be kept in India, but its carbon footprint is to lower, it could start using alternative renewable sources of energy. Similar to the pulp and paperboard mill in the paper plate scenario, the production facilities of the leaf plate could be powered by its own biomass waste. As the leaf gives the most energy when it is digested anaerobically, a small-scale biogas plant or a community biogas plant ("Small Scale Biogas Design", 2015) could be installed on the property. Electricity generation could be backed up by installation of solar panels, in case of lack of electricity from biomass.

When the future scenario of the paper plate is analysed it can be said that for the paper plate to have the lowest carbon footprint possible in the context of the city of Uppsala, it should be incinerated, as in this way it is substituting the most fossil fuels. Coating with a biodegradable layer is preferable to a fossil-based layer, even if the production of the biodegradable material emits more GHG emissions than the fossil material. This is because the final emissions from decaying biodegradable coating are in fact carbon neutral due to the carbon uptake of the biological material during plant growth. In addition, it gives the paper plate more waste management options, in case incineration with energy recovery was not available in other local conditions. Finally, if the amount of packaging (B2C) used per plate is to stay the same the choice of material will have almost no impact on the GWP of the whole life cycle of the paper plate. Nonetheless, as fossil-based plastic has severe impacts on the environment no matter how much of it is produced, a material which is recyclable and biodegradable in the end of its life is advisable to be used in the packaging for the end consumer.

6. Conclusion

This study carried out a comparative, cradle-to-grave, life cycle assessment to quantify global warming potential of two disposable plates made from different renewable materials; leaves and paper. The study compared the leaf plate manufactured by a start-up in India with the paper plate manufactured by a well-established business in the Nordics. Both plates were used and disposed of in Uppsala, Sweden, therefore, the results of this study can be applied only to a location similar to Uppsala, in regards to its waste management or transport distances.

The comparison has shown that the leaf plate has a substantially higher global warming potential than the paper plate due to its long-distance transport and energy source used in processing of raw material. When the leaf plate transport was carried out merely by sea and larger vehicles were fully loaded with more plates, the impact of transportation dropped significantly. In the similar vein, the impact of processing could be decreased by increasing the production of leaf plates per day and changing the source of energy utilised. Thus, it can be concluded that long-distance transport and mode of transportation can influence the overall impact of a product on climate change markedly and should be paid attention to, when choosing shipment options for goods. Furthermore, efficiency of production and the source of energy utilised in manufacturing processes are crucial factors for global warming potential of products as they have a potential to be the largest contributors to the total carbon footprint.

This has been demonstrated in the paper plate life cycle, where a significant amount of energy used for processing wood fibres comes from biomass and the overall carbon intensity of electricity used in the region of production is significantly lower than in the case of the leaf plate. Thus, even though manufacturing of the paper plate includes many more operations requiring energy than the processing of the leaf plate, it still emits one third of the GHGs emitted from the manufacturing of the leaf plate. Nonetheless, processing of the paper plate is still the hotspot for the paper plate life cycle, where the highest emissions of GHGs originate from manufacturing of the coating material. Therefore, coating is a critical aspect of the paper plate not only for the carbon footprint associated with processing but also for the waste management options of the paper plate. This study has shown that applying biodegradable coating has the potential to decrease GHG emissions from processing and increases the options for disposal of the paper plate. However, the best option for disposal of the paper plate depends on the local waste management conditions and the biodegradable material chosen for the coating. In Uppsala, the best disposal option for the paper plate coated with polylactic acid is incineration with energy recovery.

As this study performed a comparative life cycle assessment based only on the impact category global warming potential, further comparisons of these disposable plates need to be done in more impact categories. Since the paper plate life cycle is subject to substantial chemical use, the impact categories acidification and eutrophication could be of interest for further research.

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