Tampere University of Applied Sciences

Biocomposite as An Alternative Packaging Material in Beverage Industry

Comparison of environmental aspects against aluminium and PET plastic

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ABSTRACT

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Biocomposite as An Alternative Packaging Material in Beverage Industry
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This thesis was commissioned by a start-up company aiming to place a new, innovative beverage container in the market. The main research question was whether a biocomposite could be seen as more environmentally friendly solution as a packaging material when compared with the two most common materials in the beverage industry, aluminium cans and bottles made of PET (polyethylene terephthalate). The purpose of this study was to compare the most significant environmental effects of the three materials during their life cycles.

Hypothesis was that biocomposite is more environmentally friendly due to its renewable raw materials and lower risks related to the different stages of production. Problems related to this study consisted mostly of the comparability of the three materials. Whereas PET and aluminium are subjects of number of studies and research, not a single biocomposite container has yet been placed on the markets and the wide interest in the material has only recently risen, and so the comparison is merely theoretical. Additionally, the comparison itself is forced to be limited to merely the most significant environmental aspects. Since the life cycle related processes of the three materials vary greatly depending on the country and used technologies, rather than on exact numbers and values, attention is paid on the magnitude of the real or potential effects. Also, the focus of this study has been only on fully renewable wood-based biocomposite which is the intended material for the invention. The methodology used is a comparison based on literature review covering scientific research, life cycle assessments and environmental reports are studied.

The results of the study showed that renewable biocomposites may not automatically offer an environmentally friendly solution. During the life cycle biocomposite was credited with the highest carbon dioxide emissions. Energy and water consumption levels varied between the compared materials. Still, the benefits of biocomposites lie on renewability, when renewable raw materials are chosen, in carbon dioxide sequestration, and minimized risks related to production cycles.

Possibilities for further studies are related to different types of biocomposites and opportunities for recycling of them since newest biocomposites vary regarding renewability due to raw material choices.

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biocomposite, renewability, circular economy, environmental affects, life cycle

CONTENTS

TERMS

ALLOYING	the process where additional elements are added to the main metal
ALUMINA	a material achieved from bauxite; (Al_2O_3)
ANODE	an electrode used in electrolysis where the positive polarity is applied
BAUXITE	the primary raw material for aluminium
BENEFICIATION	a bauxite preparation method
BIO COMPOSITE	a heterogenous material made of partly or fully of biological raw materials
BIODEGRADABILITY	material resulting with carbon dioxide in aerobic and methane in anaerobic biologic breakdown
BISPHENOL A	a chemical used in plastics
CATHODE	an electrode used in electrolysis where negative polarity is applied
CAUSTIC SODA	sodium hydroxide (NaOH)
CAVITY	a mould can poses numerous cavities which each are used to produce a desired piece of product
CELLULOSE	the main raw material for fibre derived from wood
CESSPOOL	the method of storing sludge
CLOSED LOOP	the method where material is used in the original purpose
COIL	a package of thin rolled metal in spiral layers
COKE	Result after heating coal or oil in the absence of air
COLD ROLLING	the method of rolling metal ingots to desired thinness without additional heat
CRUDE OIL	petroleum; an unrefined, drilled oil
DEXTROSE	a sugar derived by hydrolysing starch and used as raw material for PLA

DIGESTER	a pressure vessel used for dissolving bauxite
DRILLING RIG	an oil extraction platform used in the offshore drilling
DROSS	a mass of solid impurities floating on a molten metal
ELECTROLYSIS	the process for purifying alumina from oxides
ETHYLENE GLYCOL	a product from petroleum or bio refining
ETHYLENE	a product of petroleum industry refined from crude oil
EU27	the member countries of European Union
FRACTURING	the method in oil drilling for breaking unground rocks
FRACTION	the result of crude oil distillation (e.g., naptha)
FLARING	the method for burning excessive gases during oil extraction
FLUXING	the method to remove impurities from molten metal with gases
FUGITIVE EMISSIONS	uncontrolled emissions caused by leaking
GASOLINE	petrochemical product from refining of petroleum
GREEN LIQUOR	a caustic solution used in bauxite refining
HOT ROLLING	the method of rolling metal ingots to desired heat with additional heat
INGOT	a slap of metal which is a result of melting process
INGOT CASTING	the casting of metal from pristine (primary) or pristine and recycled materials (secondary)
KEROSINE	a petrochemical product from refining of petroleum
LCA	life cycle assessment, a method for analyzation of environmental impacts related to a product
LPG	liquefied petroleum gas
MIL	a unit used for measuring plastic sheets, 1/1000 of an inch

MICROPLASTICS	small particles of plastics which separate during wearing of the material
MONOMER	a single molecule used forming polymers
NAPTHA	a petrochemical product from refining of petroleum
NIR SEPARATOR	a spectroscopic (near infrared) technique used for plastic separation
OFFSHORE DRILLING	the oil drilling method where oil is extracted from below the seabed
OPEN LOOP	the recycling method where material is recycled on purposes variating on original purpose
OVERBURDEN	the soil and rock overlying a mineral deposit
PE	Polyethylene, a plastic resin
PET	Polyethylene terephthalate, a plastic resin
PETROCHEMICAL	a refined product derived from refining of petroleum
PETROLEUM	crude oil; an unrefined drilled oil from earth’s crust
PLA	Polylactic Acid
INJECTION STRETCH BLOW MOULDING	the technique of moulding which uses pressurised air air for stretching the objective to desired form
POLYCONDENSATION	a process technique used in polymer manufacturing
POLYMER	a combination of several monomers
POP	permanent organic pollutants
PP	Polypropylene, a plastic resin
PULP	a material delivered during pulping process
PRUNING	a silvicultural phase where only desired trees are left
PVC	Polyvinyl chloride, a plastic resin
P-XYLENE	a product of petroleum industry
QUALITY GRADE	an extent where product value is increased for example during refining

RED MUD or SLUDGE	a caustic sludge from washing of bauxite
RESIN (synthetic)	an artificial synthesized high molecular polymer
ROTATING KILN	a device for raising materials to a high temperature in continuous process
SECONDARY RECOVERY	the second stage of oil extraction during which the wells pressure is maintained by injected water or gas
SILVICULTURE	the art and science related to forestry activities
STRIP or OPEN MINING	the mining method where topsoil is removed over the deposit
STAND-BY VESSEL	a ship used by offshore drilling for supplying, supporting, etc.
TEREPHTHALIC ACID	a product of petroleum industry
WOOD PULP	mechanically or chemically processed fibrous material

1 INTRODUCTION

1.1. Background for the research topic

The research topic was commissioned by a start-up company intending to place a new, biocomposite based beverage container on the markets. As respecting the confidentiality, the company is further referred as *The Start-Up Company* or *The Client*. The demand for the innovation is based on the requirements given by the *Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment,* later referred as SUP-directive. Generally, the SUP-directive sets restriction for certain disposable plastic products as well as introduces various product specific requirements applicable to a wide range of actors in the field. As the most important requirement for the beverage industry and specially for the packaging manufacturers could be seen the article 6, which gives clear product requirements such as “caps and lids made of plastic may be placed on the market only if the caps and lids remain attached to the containers during the products intended use stage”. Since this is applied to “beverage containers with a capacity of up to three litres” requirements need to be covered by majority of the current *PET* bottles in the market. (Directive (EU) 2019/904). The innovation made by The Start-Up Company does not only cover those requirements but also aims to offer a sustainable alternative for conventional packaging materials not only by its innovative, space efficient hexagonal design but also by renewable biocomposite material solution. Patent of this invention was accepted by Patent and Registration Office in June 2021. As a new and renewable beverage package is the intended objective of The Start-Up Company, the negative and positive environmental effects of biocomposite during the various phases of life cycle compared to existing and widely used materials should be known. Based on this demand, the question offered by the Client was whether biocomposite could be more environmentally friendly solution compared aluminium cans or bottles made of PET. It was presumed that aluminium production is highly energy intensive due to the high energy demand when *bauxite* is refined to *alumina*, melting aluminium, and processing the *ingots* eventually to the desired end products which in this case are aluminium cans. Also, *petroleum* industry has its own environmental aspects related to nature of the petroleum products, fossil origination and accidents caused by the activities related to drilling, production, and transport. Before the study, environmental effects caused by biocomposite production was not known.

Biocomposite as material is currently interested and researched by the manufacturers of various fields. For instance, major forestry companies in Finland like StoraEnso, UPM Kymmene and Metsä Group have all focused on new, wood-based biocomposites and their utilization trough own or cooperated projects. Currently biocomposites are utilized for example in vehicle parts, furniture's and kitchen utensils or cutlery and are suitable for replacing wood or plastic in number of applications. With quick internet search companies providing biocomposites as an alternative material included as known brands as LG and Mysoda. Wide number of smaller companies and start-ups are inventing and developing solutions own their own.

1.2. Methodology

The chosen research method for this study was a systematic literal review which is especially suitable when theory or evidence needs to be confirmed (Snyder 2019, 334). Systematic literal review has numerous advantages which are as mentioned by Shaffril et al. (2020, 1320) "extensive searching methods, predefined search strings, and standard inclusion and exclusion criteria". Systematic literal review may be seen as method for maintaining quality during the research by offering transparency and justification for the used material.
Since the hypothesis of the study was that biocomposites are more environmentally friendly than PET and aluminium, systematic literal review was self-evident choice as the research method. Generally conducting literal review follows through four phases which are designing, conducting, analysis and writing up the review (Snyder 2019, 336). The most essential theoretical background

related to those phases and observing of them during this study are explained in following.

1.2.1 Designing the literal review

According to Snyder et al. (2019, 336) the literal review process should start with the reasoning of the work by questioning whether the literal review is needed. (Snyder 2019, 336). Since the topic was commissioned by The Client and biocomposite related research was required, justification for the literal review was clear. Since not a single biocomposite based beverage containers are yet placed on the markets, also studies related to the subject were not available. Besides offering the answer to The Start-Up Company, purpose of the thesis was also to offer data to existing knowledge gap.

Oversight of the relevant data should also be included to the designing phase so the borders of the usable data could be understood and hence relevant research question along with the purpose and scope of the study could be formulated. Strategy for choosing the relevant sources including criteria for inclusion and exclusion of the sources, used databases and search term selection are required also to be defined. All decisions for the selection criteria should be recorded to provide transparency and understanding for the reader how the data was analysed, identified and the literal review planned. (Snyder 2019, 336-337). For this study, Tuni Andor library system provided by Tampere University of Applied Sciences was first of the databases used but which rapidly turned ineffective. Even using the Boolean search methods searches resulted with unusable sources. After this search were primarily conducted using Google engine search or Google Scholars. Especially the former search method resulted with suitable scientifical but also non-scientifical results like life cycle assessments which were used as the core sources for the life cycle review part of the study. After resulting with promising article, access was gained using Tuni Andor library system if source was not publicly available. The first oversight over the discovered potential research data showed that the search words should be chosen carefully. First key search words used were *aluminium LCA, PET LCA, biocomposite LCA, aluminium production, PET production* and *biocomposite production*. It turned out that recently published (0-5 years) material for PET and aluminium was widely available, but significantly less related to biocomposite. Strategy for achieving also relevant data for the biocomposite part of this work was required.

Based on the knowledge over potential data and its limitations, research questions, purpose and approach method are to be defined (Snyder 2019, 337). Focus needs be paid especially on the research question which must be the guideline during the whole writing process. Depending on the topic, research question may be set on general level or if required, narrowed only to limited scope. Too narrowed research scope may have hold risk for limited data input. (Shaffril et al. 2020, 1328-1329). Since the purpose of this thesis was to provide the answer to The Start-Up Company whether biocomposite is more environmentally friendly than the compared materials, research question was constructed based on the Client demand. The scope of this study was already in the beginning narrowed only to beverage utilization of comparable materials, which was suitable and acceptable limitation but should still allow enough research material to be available. Although the question provided by the client was clear, the question required slight modification since the research question was recommended not to hold possibility to answer with simply yes and no (Shaffril et al. 2020, 1329). Due to this, the research question for the thesis was crystallized and supported with two sub-research question as follows:

1. **How biocomposite, when used as a beverage container, stands out compared to aluminium cans and plastic (PET) when environmental aspects are reviewed?**
2. **Which are the main production phases related to each comparable material?**
3. **Which are the main environmental aspects including the relevant inputs and outputs related to each phase?**

The first question was the most important question offering the guideline through the study and the baseline for the results. Since life cycles of the three materials were presumed to be complex with number of production and refining phases, production processes were required to be opened and reviewed to gain understanding of the relevant aspects. The second question offered the method for approaching the first question. Third question narrowed the work to acceptable extent since due to assumed volume of background material related to context, all of the environmental aspects could not be included. During the work environmental aspects were selected based on their impact and severity. Presuming these aspects included but were not limited to carbon dioxide emissions, other airborne emissions, water consumption and wastewater, electricity and other energy consumption, potential risks and accidents and produced waste including hazardous waste. If relevant, any other factor could be included if magnitude of the impact was showing its severity.

Based on the search results, also the scope of the study was required to be modified. Since it turned out that rather than being homogenic material, biocomposites existed in various forms depending on the raw material choices made by the manufactures. Even material made by a single manufacturer, like wood-fibre based DuraSense by Stora Enso, included several options for the polymer matrix which were for fossil, recycled fossil and bio-based. After negotiations with The Client, interest was paid not only on a bio-based but also biodegradable biocomposite. Based on this decision, the scope was limited to compare only single product, a biodegradable and fully biobased DuraSense (wood fibre and PLA based biocomposite option) to aluminium and PET. This was justified since comparison including several biocomposite options would have expanded the work over the limitations for regular master's thesis. Additionally, also transportation of the materials in different quality grades was decided to be excluded from the scope. This was reasoned since transportation scenarios hold wide number of variations and even rough average estimation would have expanded the work.

Since the author of this study was employed by The Client as a project/product manager, extra focus on avoiding bias was required. During the work also the sources contradictory with the wanted results are included to the work to provide as truthful results as possible.

1.2.2 Conducting the literal review

In the second phase in the literal review process and before the actual conducting of the work, testing of the planned method is suggested. If necessary, according to the results and especially suitability of for example search terms from the planning phase, adjustments may be needed. Many methods for reviewing the sources exist (Snyder 2019, 337) but during the process of this thesis, first focus was paid on the titles of the articles following with reading of the abstracts. Especially as recent articles as possible were favoured. If the titles and abstracts both turned to be unusable, source was excluded. Final decision for inclusion was made during the short review of the source itself. Many of the articles were excluded from the list of potential sources due to too specific approach or lack of relevant data required for the work. Examples of these exclusions were several laboratory case studies which did not offer any comparable input.

Aluminium and plastics turned out to be subjects of many studies and publications, but the sources desired were expected to especially include life cycle assessments with usable scope. The scope of the sources was one of the most important selection criteria and reasoning for further improvement of the key search words. When focus of this study was beverage utilization, used sources were also required to deal with beverage related utilization. Especially different life cycle phases with relevant inputs and outputs, like energy and water demand, carbon dioxide emissions, etc. were the expected sources. Numerous LCA: s was able to be found, but majority of the sources hold entirely different and unusable scope. It was again discovered that biocomposites lacked information especially suitable for the intended purpose. Due to the enormous number of publications with only limited results of usable ones, basic keywords were rapidly improved by defining the desired scope like *PET bottle LCA* and *aluminium can LCA*. By improving the keywords more relevant hits were resulted. Non-scientifical life cycle assessments offered the key input and structure for the work whereas scientifical papers required additional data to understand the concept and characters of the materials.

1.2.3 Analyzation of the data

In the analyzation phase achieved and approved source material needs to be considered. Data from the articles should be abstracted using standardized methods. Chosen method needs to be applied in the process and especially the research question should be considered. (Snyder 2019, 337). Based on the search results, data was available especially for aluminium and PET, but biocomposite lacked as robust sources. This may be due that biocomposites are still relatively new materials and they are since less studied compared to aluminium and PET which are materials being on the market and used as beverage packaging already for decades. Data used was combined from different sources to produce comparable tables with life cycle phase specific inputs and outputs of each comparable materials. Major uncertainties were tied especially with biocomposite life cycle, since directly adaptable life cycle assessments were not available. Also, uncertainties are related to the scopes of the life cycle assessments since data used may variate according to the scope and boundary of the studies as well as monitored system and socio-economical characters, resulting that rather than offering exact numerical results this study is expected to reveal only the magnitudes and potential risks of environmental affects related to the materials. For example, main data used for reviewing aluminium, was a LCA performed in US. This may include differences in energy sources and energy streams compared to European production but since as collective data is not available related to Europe, the source is used acknowledging the possible differences between the systems. The data used for bio composite life cycle review part is rather than based on volume driven calculations, mostly based on laboratory results or similar biocomposite life cycle assessments and since may hold acknowledged uncertainties. Despite the uncertainties, data used is still the best available and adaptable.

1.2.4 Writing the literal review

In the final phase, writing the review, the need and motivation must be provided to the work. Structuration of the final review should be planned while keeping in mind required levels of details and types of information (Snyder 2019, 337) and if available, existing publication or reporting standards needs to be followed (Shaffril et al. 2020, 1328). Additionally, the work should be useful to its designated audience. (Snyder 2019, 337-338). For this study, the thesis reporting template by Tampere University of Applied sciences is followed which sets standards for the reporting including for example general structure and outfit for the final report. The final structure is modified following the production phases of each of the materials to provide robust approach to them.

Especially required is to describe how the data was for example identified, collected, analysed, and processed. (Snyder 2019, 337-338). If relevant, possible changes for example due to lack of data needs to be justified and recorded. Also, important is that the literal review is besides replicable also provides something new compared to the previous studies. (Shaffril et al. 2020, 1328). Since lack of existing studies, purpose of the study was to cover the topic and provide a new knowledge on environmental friendliness of biocomposites. Despite the mentioned uncertainties, the objective given by the client and the was fulfilled and the research questions answered. According to the results which contradictory results potential

Based on the results, it may be justifiable to declare that any bias caused by the position in The Start-Up Company was avoided. Results indicated contradictory results with the pre-study presumptions and hence study was conducted following scientifical objectivity.

1.3. Structure of the thesis

The thesis is structured in the following way. **Chapter 1.** includes introduction and background for the thesis as well as the scientifical approach and methodology. Also, the research question and scope are presented in this chapter. **Chapter 2.** reveals theoretical background related to each of the compared materials including data not relevant during the life cycle presentation but essential for understanding the materials, their life cycles, and characteristics. Also, if known, the current utilization as beverage container and challenges for recycling are introduced. **Chapter 3.** presents the life cycles and production phase specific results related to each of the compared materials. Life cycles are opened to most important phases where key environmental inputs and outputs are presented. These phases include extraction of the material, refining to different quality grades and recycling. Utilization phase is excluded from the scope since its presumed that its energy demand and emissions are relatively limited to production and recycling. Also, generally transportation is excluded since considering all possible transportation scenarios would have required entirely own piece of work. **Chapter 5.** summarises results by comparing the key figures related to each of the materials. **Chapter 6**. as the final chapter of this work presents the suggestions and possible field for the further biocomposite related studies.

2 THEORY

2.1. Aluminium

2.1.1 Aluminium can

Aluminium is widely used material hence its properties of conductivity, durability, relatively low weight, and recyclability which allows aluminium to be recycled unlimited times (European Aluminium Association 1,5 n.d.). Aluminium can (PICTURE 1) is a container designated as packaging for various types of beverages. It is especially suitable for long-term food preservation purposes since it offers protection not only against oxygen but also moisture, light and other contaminants. Aluminium does not rust and has suitable strength against pressure caused by carbonated drinks. (The Aluminium Association 1 n.d.).

PICTURE 1. Regular 0,33 litre aluminium cans (Bloxsome 2018)

Commonly cans are made of two or three pieces (Can Manufacturers Institute n.d.) excluding the intact opening mechanism, so called “stay-on tab” (The Aluminium Association 1 n.d.) or “ear” (Aluminium guide n.d.). Package volumes variates but is commonly between 0,25 to 0,5 litres.

2.1.2 Origination

Currently aluminium is not seen as scarce material and not listed as critical raw material (Eur-Lex 2020). Already known aluminium reserves are expected to last more than 100 years and with expected potential reserves, supply may last as long as 250-340 years (Hydro 2021). Aluminium is a result of various steps of mining and refining activities of bauxite, a compound consisting of alumina and other elements. Although bauxite is a relatively common compound in the earth’s crust, bauxite deposits are the primary source for aluminium (The Aluminium Association 2 n.d.) located on relatively limited areas on “wide belt around the equator”. Major producers are Australia, Central and South American countries, Guinea, India, China, Russia, Kazakhstan and Greece in Europe (European Aluminium Association 2010, 19).

Aluminium supply chain is complex (European Aluminium Association 2013, 14). Products on different quality grades are transported across the oceans to be further processed and finally delivered to Europe (FIGURE 1). For example, bauxite may be first mined in Brazil, then transported to Jamaica to be refined, and again transported, this time to Europe, for primary aluminium production after which aluminium may finally end to can production. And this is just a single scenario out of numerous options.

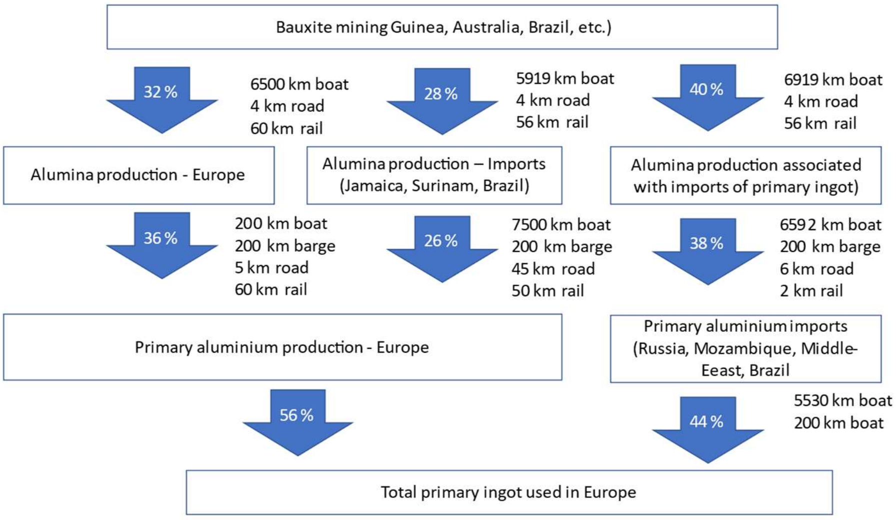


FIGURE 1. Average transport distances of bauxite, aluminium and imported aluminium (European Aluminium Association 2010, 14)

Besides bauxite, alumina and primary ingots, the figure lacks so called semi-fabricated aluminium products, products refined and produced to some extent, but which are not finalised products. Major countries of origin for semi-fabricated products are China and Turkey holding together majority of imported material (European Aluminium Association 2019). Since complexity of the supply chain and known efficiency (for example 5246 kg bauxite is needed to yield 1915 kg alumina) transportation holds significant environmental impact (European Aluminium Association 2010, 14) but is generally left calculated from the results of this study.

2.1.3 Aluminium recycling

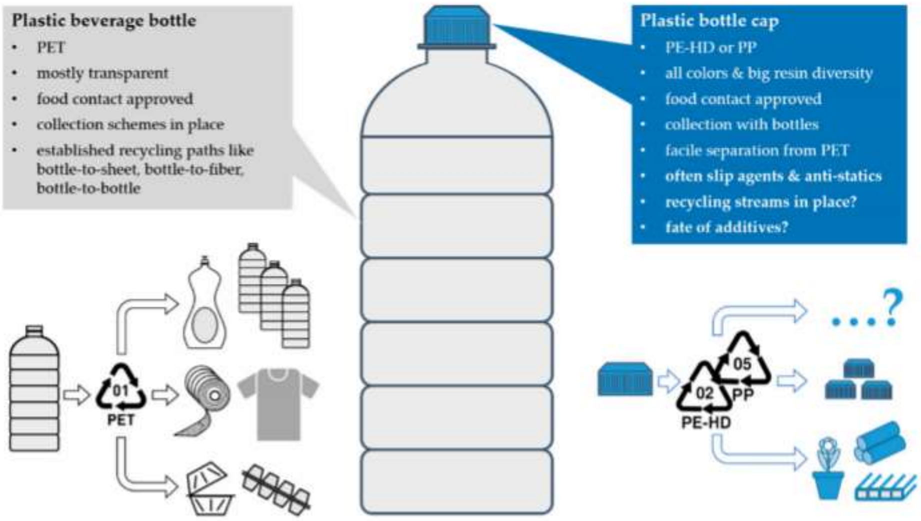
Recycling of aluminium is environmentally beneficial since energy demand for its recycling is reduced to only 5 % when compared to production of virgin material (Palpa 2). Actual numerical savings are credited with 6 ton of bauxite, 4 ton of chemical products and 14 000 kWh (50 400 MJ) electricity per tonne of material (Recycle now n.d.) clear offering justification for the recycling. Besides ecological benefits, recycling is also economically beneficial when compared to recycling of plastics. For example, ton of recycled cans are in U.S. worth of 1,210 dollars same volume of PET bottles being only worth of 237 dollars (The Aluminum Association & Can Manufacturers Institute 2020, 3). In EU recycling rates variates between the countries but average was for year 2020 76 % (Srebny 2021). In Finland 95 % of cans were recycled (Palpa 3 n.d.). It is not certain that in EU recycled cans return automatically as cans, although recycling in U.S seems to be following principles of *closed loop* (The Aluminum Association & Can Manufacturers Institute 2020, 3). For example, 12,99 gram can in U.S. consist of 27 % primary aluminium, 43 % of used cans, 7 % of recycled other material and 23 % post-industrial scrap (The Aluminum Association & Can Manufacturers Institute 2020, 13).

2.2. PET

Generally, plastics could be seen as a combination of a polymer (like PET), additives and/or modifiers. Since polymer itself may not be sufficient for designated purposes, additives are used to enhance the desired properties (Kutz 2016, 489). Polymer itself is something which is formed when a molecule (monomer) is put through a polymerization process in which it is combined with other monomers thus forming a polymer, a chain of monomers. In commercial plastic chain length when each monomer is counted variates between 10,000 and 100, 000 monomers. (Crawford et al. 2016, 3) Since for instance DNA and hair could be seen as polymers, Crawford et al. (2016, 4) has specified that “although all plastics are polymers not all polymers are plastics”.

2.2.1 PET bottle

One of the many commercially utilized plastics, PET, has its benefits “due to its durability, strength and transparency” (Gomes et al. 2019, 532) as well as its unbreakability and low weight especially when compared to glass bottles which is has commonly substituted (Welle 2011, 865-866). Also, PET is resistant against impacts and shatter as well as wear, heat, and ageing. Especially good barrier properties against gases and moisture (Crawford et al. 2016, 67) are desired in container designated for beverage purposes. Hence these properties it has reached its position as “the most favourable packaging material word-wide for beverages” (Welle 2011, 865). Plastic beverage bottle or rather the body itself (PICTURE 2) is made of PET and the cap made commonly of *PE-HD* (polyethylene) or *PP* (polypropylene) plastics (Gall et al. 2020, 1).



Plastic beverage bottle
- PET
- mostly transparent
- food contact approved
- collection schemes in place
- established recycling paths like bottle-to-sheet, bottle-to-fiber, bottle-to-bottle

Plastic bottle cap
- PE-HD or PP
- all colors & big resin diversity
- food contact approved
- collection with bottles
- facile separation from PET
- often slip agents & anti-statics
- recycling streams in place?
- fate of additives?

PICTURE 2. A PET bottle and cap with potential recycling scenarios (Gall et al 2020, 2)

While many sources focus on recycling and environmental effects of the body, less attention is paid to the caps. Reason may be that compared to recycling of PET, caps currently lack similarly valued path for reutilization (Gall et al. 2020, 2). Since this cap are also excluded from this study although they are recognized as essential part of the bottle.

2.2.2 Origination of oil

Current oil reserves are expected to last no longer than approximately 50 years (Learn 2021). Since this, alternatives for fuels but also for packaging relied in plastics may be needed. Conventional plastics are based on *petrochemicals*, a fossil raw material defined by Kirsen-Dogan (2008, 18) as organic compound yielded from *petroleum* raw materials or natural gas. Petroleum is a hydrocarbon resulted from very small organics transformed trough chemical and biological processes influenced by absolute heat and pressure caused by tectonic and geological movements during millions of years. Petroleum could refer both to gaseous (natural gas) and liquid hydrocarbons (*crude oil*). (Kirsen-Dogan 2008, 13). It should be noted that compared to the total volume of petrochemicals used, production of plastics represents only a fraction. In Europe approximately 87 % of oil is used as energy by vehicles, heating, and electricity production and only 4-6 % is credited to be used as raw material for plastic production (British Plastics Federation 2019).

Petroleum products are transported across the oceans forming a complex supply chain although 75 % of oil production and approximately 93 of global oil reserves are divided between only 15 countries (Atwater et al. n.d.) most notable producer being United States. This position is gained by 69 % of domestic resources (Fawthrop 2020). Other globally acknowledged producers are Saudi-Arabia, Russia, Canada, Iraq, United Arab Emirates, China, Iran, Kuwait, Brazil. Complexity is caused also by the countries like South-Korea, Germany, and Japan and China, which have refineries but not mentionable own reserves (Jing et al. 2020, 527-528).

Refined petrochemical products are used as raw material for PET by plastic companies. Leading PET manufacturers are located to Thailand, Luxembourg, China, Taiwan, Mexico, United Kingdom, and India (Plastic Insight 2016). Again, logistics of petrochemical products are recognised as relevant source for environmental effects, but due to lack of relevant data and limitations needed, logistics are forced to be excluded from this study holding an interesting theme for further studies.

2.2.3 Plastics recycling

Benefits of plastic recycling variate according to used purpose for recycled material. Recycled PET bottles could be used again in the new bottles (bottle-to-bottle, referred also as B2B or BtB) forming a closed loop where material streams continue to remain in the same designated purpose. When material ends up being used on purpose variating from the original use, material stream is seen as *open loop*. Material in open loop ends up commonly to be used in clothes (bottle-to-fibre, BtF or B2F) but could be used also for example on plastic sheet products (bottle-to-sheet). (Gall et al. 2020, 2). Recycled PET bottles are often used as raw materials for fleece garments (Crawford et al. 2016, 67).

When compared the alternatives for recycling, open and closed loop, it was discovered that closed loop where material is used on the same purpose results with reduced net CO_2, CO, acid gases, particulate matter, heavy metal, and dioxins emissions (Gomes et al. 2019, 535). Alas, results seem to be variating according to the target country and recycling system since Shen et. al. (2011, 534) presented on the study that B2F (bottle-to-fibre) recycling may be more environmentally beneficial than B2B recycling (bottle-to-bottle). This could be even more beneficial when material is reused as fibres, sheets, containers, or straps (Welle 2011. 866). Reason may be that these applications do require less purity and processing than those intended to high performance utilization, in this case bottle applicable to be used as container with direct intact with consumables intended for human consumption. Also differences on LCA scopes and exclusions may cause differences.

Effective retrieval and recycling are required especially for plastics which possess potential negative impacts to environment due to their chemistry and features related to degradability. Degradation can be divided to biotic and abiotic degradation of which first requires influence of living organisms (for example presence of bacteria) and the later various environmental factors like temperatures (thermal degradation), light (photo-oxidative degradation), oxygen (atmospheric oxidation and hydrolytic degradation) and mechanical strain (mechanical degradation) (Crawford et al. 2016, 87, 89). What comes to plastics, generally they are degraded only by abiotic degradation process since the material slowly wears to smaller particles by natural phenomena and currently only few living organisms are known for consuming plastics (Crawford et al. 2016, 85). *Microplastics* are seen as one of the negative results of discarded plastics (Crawford et al. 2016, 43-44). Generally, microplastics are defined to being "small spherical microbeads". Variating from intentionally produced microplastics like ones used in cosmetics, secondary microplastics have reached the shape and size due to degradation from larger plastic particles (Crawford et al. 2016, 102, 105). Size along with chemistry forms together a serious combination. Since having relatively large surface area compared to their size or as described by Crawford et al. (2016, 145) "much larger surface-area-to-volume ratio" microplastics have ability to hold concentration on substances compared to their surroundings. For example, permanent organic pollutants (*POP*s) are chemical pollutants which has been observed concentrating in microplastics up to 1 million times higher levels than the concentration in the seawater surrounding (Crawford et al. 2016, 145). Other potential substances are chlordane, DDT, hexachlorocyclohexane (HCH) just to name few not forgetting heavy metals such as lead, cadmium, nickel, and cobalt (Crawford et al. 2016, 148, 154). Microplastics may not only be associated with discarded and old plastics, but even recently purchased bottles may provide a source for microplastics. According to a single study by Mason et al. (2018, 14) out of 259 pieces of newly purchased plastic bottles 93 % "showed signs of microplastics".

Besides microplastic, plastics are also associated as source for bisphenol A (BPA), an endocrine disruptor which is seen as potentially having negative effective for example to reproductivity. Scientists argue the actual affects to human health, but studies have evidenced the threat to animals' trough tests and in general level authorities have declared BPA:s as safe. (Hand 2010).

2.3. Biocomposite

Since this part is concentrating on *biocomposite*, terms biocomposite and composite should be first defined. First, composite can be defined as a material structure formed by two or more macroscopically identifiable, distinct constituent materials. Some of the materials like fibres are acting as reinforcers proving strength and other desired properties and when combined with matrix (*polymer*) yields as a material “with improved performance over individual constituent materials” (Rudin 2013, 523). Composite is thus a heterogenic sum of polymer and fibres compared for example to a conventional and homogenous single *resin* polymer plastic. Biocomposite then is a composite made of fully or partially from biobased materials of which especially natural fibres are used for enhancing properties of weaker natural polymer (Rudin 2013, 523).

When compared to natural fibres over synthetic a few advantages arouse. Biocomposites may have besides the improved properties also potential for reduced cost as well as positive environmental affects like cardon dioxide emission reduction and *biodegradability* (Mohanty et al, 2016, 20-21). Like conventional plastics, also biocomposites exist in various qualities based on the raw materials. Flax, kenaf, jute, sisal and hemp are examples of commonly used fibre materials, but also different leaves, straws and grasses could as well used (Mohanty et al. 2016, 21). Also, possibility is to use wood-based fibre. Since the composite intended to be used as raw material for the biocomposite container, this study focuses on so called wood-plastic composites (WPCs). Matrix, the polymer part, for biocomposite can be either bio- or fossil based. Again, since renewable and sustainable material is valued, this study focuses only on bio-based options.

Composite reinforced with natural fibres are material suitable to be used in many purposes like in vehicles, packaging, flexible electronics, construction, just few to mention. Material itself is suitable for processing machines, easily processed and biodegradable (Misra et al 2015, 4, 6). Biodegradability, decomposition of mass either by bacterial enzymes or hydrolytic degradation in a reasonable time depends on the materials chosen but could theoretically be applied to all organic materials which are not based on non-degradable petrochemical materials (Majamaa 2012, 13). It is also possible that bio-based products from renewable resources may be carbon dioxide neural. Again, among other things, origination of the raw materials as well as the life cycle needs to be taken consideration (Mohanty et al, 2016, 20).

It should be noted that wide utilization of biocomposites is still waiting itself. This is due that the material has been widely placed in the markets no longer than a decade (Fitzgerald, A., et al. 2021, 15) and manufactures are still seeking and studying the possible applications. Still concept of biocomposites cannot be seen as relatively new innovation since for instance soybean-based bio plastic with natural fibres was invented as yearly as 1941 by non-other than Henry Ford (Allen 2018). One reason for only recently aroused interest may be that previously biocomposites have lacked structural integrity and compatible costs (Mahalle et al. 2013, 1306).

2.3.1 Beverage bottle

Currently not a single beverage container made of biocomposite is not known to be placed on the domestic markets yet several projects for biocomposite applications for other fields of industry exist. One example of this is the cooperation with Valio and Stora Enso. Valio replaces plastic curd caps with caps made of biocomposite (Valio 2020). Since objective of this study is to justify utilization of biocomposite beverage container against conventional packaging, focus is paid on the most likely production process as well as properties of possible container. Presumed and planned production method is injection moulding. Material of which the product could be manufactured may potentially be any wood-based biocomposite but since data scarcity related to the subject, review on production process is mostly based on DuraPulp, a product manufactured by Stora Enso.

2.3.2 Origination

Since biocomposite is based on two materials, the matrix and the wood-based fibre, review is needed to be paid on both. First, wood-based fibre for DuraPulp originates from Swedish forests (Hermansson 2013, 12). When viewing global forest reserves, currently 31 % of global land areas are covered by forest but division is not equal between the countries since Russia, Brazil, Canada, USA, and China are credited with more than half of existing forests. Deforestation and forest degradation are raising concern mostly due to agricultural expansion (FAO and UNEP 2020, 10), yet forests are conventionally seen as renewable raw material source. According to Hermansson (2013, 16) wood material for DuraPulp is transported “average for 80 km by trailer, 20 km by train and 47 km by boat from the extraction site to the pulping plant” causing relatively low environmental effects caused by the logistics. Secondly, polymer part could be either fossil or renewable based but since fully renewable product is favoured, in this study focus is paid only on *PLA* (Polylactic Acid) matrix. Main raw material for PLA is corn of which origination is unknown. Global raw material reserves for corn relate to the availability of suitable land for agriculture which currently is 11 % (1,5 billion ha) of world’s land surface of which all may not of course be suitable for corn cultivation. Potential for increasing the agricultural areas still exist (Bruinsma 2003, 127) but as mentioned above it may be achieved with expense of the forest coverage. To the question whether global food supplies may have notable effect if volumes directed to raw material utilization rather than human consumption increased significantly, answer cannot be given, but it is forecasted that extreme weather conditions caused by climate change may result with greater crop losses (Bruinsma 2003, 358).

2.3.3 Biocomposite recycling

Benefits of the recycling of biocomposites may variate according to the material but according to Stora Enso, biocomposites could be “reprocessed up to 5-6 times” which is claimed actually improving the material properties during the first cycles (Stora Enso n.d.). Generally composite recycling is seen challenging due to the nature of composites. Separation of matrix and fibres would be needed for efficient material reuse which is expected to result with increased recycling costs. Also, challenges may be caused by “sensitivity of the bio-based polymeric matrix and/or reinforcements to thermal processing”. This may reduce options available (Vilaplana et al 2010, 2151) but currently efficient recycling of composites is under study. One known example of this is the KiMuRa project where composites from industrial origination are planned to be collected, crushed, and used as a raw material by the cement industry. Other proposed methods for composite waste management are pyrolysis, electromechanical processing, solvolysis, mechanical grinding and fluidized bed technology (Pietikäinen n.d.). Studies or projects related to customer originated composites were not able to be found.

Composting is seen as one of the potential waste management methods, but may be needed to be maintained in industrial level due to environmental factors like temperature, pH, and moisture, needed to be controlled (Vilaplana et al 2010, 2151). And when composting is desired, fully biodegradable biocomposite is required which is achieved only when both biodegradable resin and biodegradable fibre are combined alas biocomposites currently placed in the market’s variates from fully bio-based to different variations. Benefits of composting would include increased biodiversity, enhanced soil quality, reduction in landfilled waste and global warming potential (Fitzgerald et al. 2021, 17).

One proposition would be maintaining the material flow within a closed loop (Matilainen et al. 2018) along with extended service product life (Vilaplana et al 2010, 2152). This would require that material should be used either on long-life purposes or recycled rather than composted or incinerated. This is especially desired when sustainable beverage container are desired and new containers could be made of recycled material.

3 RESULTS – LIFE CYCLE REVIEW WITH RELEVANT ENVIRONMENTAL EFFECTS

3.1. Aluminium

The aluminium life cycle includes mining of bauxite, alumina production, *electrolysis*, primary *ingot casting*, rolling and sheeting, can production and recycling (TABLE 1). Utilization phase during which beverages are consumed by the customer is excluded since focus of the study is the material itself.

TABLE 1. Process phases of aluminium life cycle

Process phase	**Definition**
Bauxite mining	Extraction from the ground and crushing, washing and *beneficiation* of bauxite
Alumina production	Refining of bauxite to alumina including grinding, digestion, separation and washing, crystallization and calcination
Electrolysis	Melting and deoxidisation of alumina to pure, molten aluminium
Primary ingot casting	Casting of the pure, molten aluminium into ingots
Rolling and sheeting	Rolling of the ingots to *coils* or sheets
Can production	Production of cans from coils or sheets
Utilization	User phase where can is used
Recycling	Recycling of retrieved cans and preparation to electrolysis

3.1.1 Bauxite mining

Since bauxite deposits are found relatively near ground, *open mining* (also known as *strip mining*) is favoured which results with removal of vegetation and soil in large areas. Alumina is commonly found from surface to 600 feet (180 meters) average mining depth being 80 feet (24 meters). Especially open mining results with high volumes of *overburden*, the soil needed to be removed over the deposit (PE America 2010, 32) and which is commonly returned during rehabilitation after the deposit has been depleted (Aluminium Association 2). Exposed areas cover vast areas since mines can be as wide as 1,26 million hectares as is the mine in Jarrah Forest Australia owned by Alcoa Word Alumina Australia (Gardner et al. n.d.).

After the deposit is exposed by removing the earth, mining of bauxite follows including drilling, explosives, and heavy machinery like bulldozers. Yielded ore is transported with truck to crushing site where it is beneficiated. Beneficiation includes for example grinding, washing, and drying (PE America 2010, 33) to remove impurities like silica, various minerals and oxides of titanium and iron from the crushed bauxite (Donoghue et al. 2014, 12). During mining, crushing, and washing electrical power, energy (electric, heavy fuel and diesel) as well as of water are used (TABLE 2). Since LCA by PE America (2010) used as main source did not credit any emissions to air during bauxite mining, results from CO_2 emissions are added from different source. Values of carbon dioxide emissions variate between average literature values (4,6 $kgCO_2$) and company sustainability reports (10 $kgCO_2$) providing magnitude of the emissions (Tost et al. 2018, 8.) Approximately half of mined bauxite ends up being refined (Morris 2013, 19). Prepared bauxite is then transported by conveyor, ship, or rail to be refined to local site or exported (Donoghue et al. 2014, 12).

TABLE 2. Selected inputs and outputs during bauxite mining related to 1000 kg primary aluminium production (PE America 2010, 32; * Tost et al. 2018, 8)

Input	**Unit**	**Amount**
Bauxite	kg	5775,8
Electric power	MJ	36,2
Thermal energy (heavy fuel oil, natural gas, diesel)	MJ	379,0
Surface and sea water	m^3	2,6
Output	**Unit**	**Amount**
CO_2*	kg	4,9-10,0
Overburden	kg	529,6
Surface and sea water	m^3	2,5
Bauxite	kg	2731,5

Exposed vast areas do not only lead to local loss of land, deforestation, and soil erosion but depending on the location, mines may also cause severe damage to water systems affecting potential droughts and floods in low stream areas as is feared related to mining plans in Central Highlands, Vietnam (Morris 2013, 17-18). Besides potential displacement of local and ingenious communities' mining may also stir the local economics. Local people may lack the necessary skills needed in mining site and hence non-local workers may be favoured. Also, low quality grade especially when unrefined bauxite is exported may result with relatively low income since net profit would be low per invested dollar compared for instance to coffee and rubber. (Morris 2013, 17-18, 22).

3.1.2 Alumina production

In the refinery, bauxite is first grinded to a fine slurry (Donoghue, et al. 2014, 13). High temperatures and pressure are needed to dissolve slurred bauxite with the help of *caustic soda* (NaOH) in so called *digesters* (PE Alumina 2010, 35). After separating and washing insoluble materials like sand and mud off, the solution, *green liquor*, is then crystallized to remove caustic soda, and calcinated (Donoghue et al. 2014, 13) with heat in *rotating kilns*. When remaining water is removed by heating, alumina powder (Al_2O_3) is resulted (The Aluminum Association 2007, 18). Besides mined new material refining also takes advantage of materials from previous production cycles maximining the yield and minimising waste. The spend liquor which is resulted from the crystallization phase consisting mostly of caustic soda is reused again in digestion (Donoghue et al. 2014, 13). What is not currently used is the sludge resulting from washing of bauxite, commonly referred as the *red sludge* or red mud, is a caustic by-product with high sodium aluminate concentration (PE Alumina 2010, 35). Since nearly half of mined material entering the refining process ends up as red mud (TABLE 3) and taking concentration the volumes mined, the solution forms a formidable risk when not managed with care. One of the methods for treating the red mud is storing it on so called cesspools until the surface of the sludge dry. After that, *cesspools* are covered with concrete and topsoil and if necessary, replanted. (Morris 2013, 20). During definition high volumes of water, caustics and energy are required. CO_2 emissions variate according to the sources but may be between 400-830 kgCO_2 per produced ton of alumina. This is the result from year 2007 related to refining in *EU27* countries (Ecofys 2009, 2). Separate diesel volumes in kilograms presented in the original source was converted to megajoules combined with other fuel consumption.

TABLE 3. Selected inputs and outputs during alumina production related to 1000 kg primary aluminium production (PE America 2010, 36-37 & *Tost et al. 2018, 8).

Input	**Unit**	**Amount**
Bauxite	kg	5246,2
Sodium hydroxide (50 % caustic soda)	kg	172,0
Lime quicklime	kg	75,5
Electric power	MJ	856,6
Thermal energy (hard coal, diesel, heavy fuel oil, natural gas)	MJ	18881,0
Surface and sea water	m^3	15,4
Output	**Unit**	**Amount**
Red mud	kg	2187,0
CO_2 *	kg	400,0-830,0
Waste (industrial and solid)	kg	76,4
Surface and sea water	m^3	10,4
Aluminium oxide (alumina)	kg	1915,4

The red sludge may potentially contain radioactive materials and heavy metals, but the content may variate by characters of the soil and processing methods (U.S. Environmental Protection Agency n.d.). Since its high pH red mud has potent to “destroy the ground and plants it touches, and fish would perish if it made its way into rivers” (The Sydney Morning Herald 2010) causing a significant risk for direct negative environmental effects. The risk was realized in Brazil in year 2007 when heavy rains caused flooding and mud slides in bauxite mine resulting with dozens of deaths and over 8,000 homeless (Reuters 2007). In Europe same kind of event occurred in Hungary in year 2010 (Bilefsky et al. 2010). Besides as in liquid form, the red mud possesses risks also when let dried. For example, in Malaysia dust from aluminium mine has accused causing “mental distress, anger and community outrage” and even chronic physical illness are suspected (Abdullah et al. 2016, 1). Symptoms may be caused by the high aluminium content of the dust since living near aluminium mines may expose the residents to high levels of aluminium (Winchester Hospital n.d.).

3.1.3 Electrolysis

According to World Aluminium (2017, 38) process phase with the most significant impact is the electrolysis process. During electrolysis alumina (TABLE 4.) but also consumable carbon *anodes* and in some cases, fluoride are required (The Aluminium Association 2007, 19). Anode production is involved on the review since according to PE America (2010, 42) and World Aluminium (2017, 5) anodes are essential part of electrolysis process thus forming notable inputs and outputs during the production. Anodes are used for directing electrical current trough alumina (Al_2O_3) to remove oxygen resulting with almost pure (more than 99 %) aluminium (The Aluminum Association 2007, 19-20).

TABLE 4. Selected inputs and outputs during electrolysis and anode production related to 1000 kg primary aluminium production (PE America 2010, 36-37)

Anode production	**Input**	**Unit**	**Amount**
	Coke	kg	345,2
	Cooling water	m^3	0,2
	Electric power	MJ	213,1
	Thermal energy (hard coal, heavy fuel oil, natural gas)	MJ	1192,7
	Output	**Unit**	**Amount**
	Anode	kg	437,5
	CO_2	kg	177,6
	Input	**Unit**	**Amount**
Electrolysis process	Anode	kg	352,2
	Cathode	kg	7,6
	Aluminium oxide (alumina)	kg	1420,3
	Aluminium fluoride	kg	11,9
	Electric power	MJ	41762
	Fluorides	kg	0,6
	Water including sea water	m^3	9,1
	Output	**Unit**	**Amount**
	Tetrafluoromethane (CF_4)	kg	0,1
	Hexafluoroethane (C_2F_6)	kg	0,01
	Hazardous waste (incl. carbon, sludge and refractory)	kg	28,9
	Aluminium (liquid)	kg	757,1
	CO_2	kg	1181,6
	Water including sea water	m^3	11,9

Again, CO_2 emissions variates between the sources. LCA by PE America (2010) related to electrolysis in America credited with 1181,6 kgCO_2 per produced ton of aluminium and 177,6 kgCO_2 for anode production. However, emissions credited for EU27 emissions where 1500-2550 kgCO_2 for electrolysis and 320-575 kgCO_2 for anode production (Ecofys 2009, 2). Notable is that electrolysis process is a source for gases of CF_4 and C_2F_6 which are seen as strong greenhouse gases and compared to carbon dioxide previous being 6 630 and the later 11 100 times (Green Gas Protocol n.d.).

3.1.4 Primary ingot casting

Commonly casting is used for processing pure and molten aluminium to ingots weighting 15-30 tonnes (PE America 2010, 44, 69). *Alloying* and *fluxing* are performed before the actual casting. Alloying is “a chemical composition” where elements like iron, silicon, and copper are added to aluminium to “enhance its properties” (The Aluminium Association 3 n.d.) whereas fluxing is a method where nitrogen chlorine and other gases are blown trough liquid metal to remove any impurities (PE America 2010, 53). In ingot casting, molten metal is casted to moulds resulting with ingots which are then reprocessed (The Aluminum Association 2008, 31, 34). Ingot casting is credited with relatively low demand for energy and water. Since LCA related to aluminium production in America did not credit any CO_2 emissions they are added from European reports.

TABLE 5. Selected inputs and outputs during primary ingot casting for 1000 kg of primary aluminium production (PE America 2010, 42-43 & *Ecofys 2009, 3).

Input	**Unit**	**Amount**
Aluminium (liquid)	kg	1018,5
Alloying components	kg	15,0
Water	m^3	0,1
Chlorine	kg	0,055
Electric power	MJ	252,8
Thermal energy (hard coal, natural)	MJ	1295,0
Output	**Unit**	**Amount**
Waste (incl. *dross*, waste, refractory)	kg	3,9
Hydrogen chloride	kg	0,016
Aluminium ingot	kg	1003,4
CO_2*	kg	70,0-200,0

Primary ingot casting is casting of metal using pristine materials compared to the secondary casting where pristine metal is remelted together for instance with recycled material. All primary ingot smelters have reported to also having casting facilities (Ecofys 2009, 9) and hence ingot casting could be seen as part of electrolysis process. Although, since in various sources electrolysis and ingot casting are presented separately, this division is followed also in this work.

3.1.5 Rolling and sheeting

Compared to previous processes can manufacturing requires packaging materials and coatings, yet energy and water demand is relatively low (TABLE 6). Again, since LCA for American production did not include CO_2 emissions, values are added from European reports.

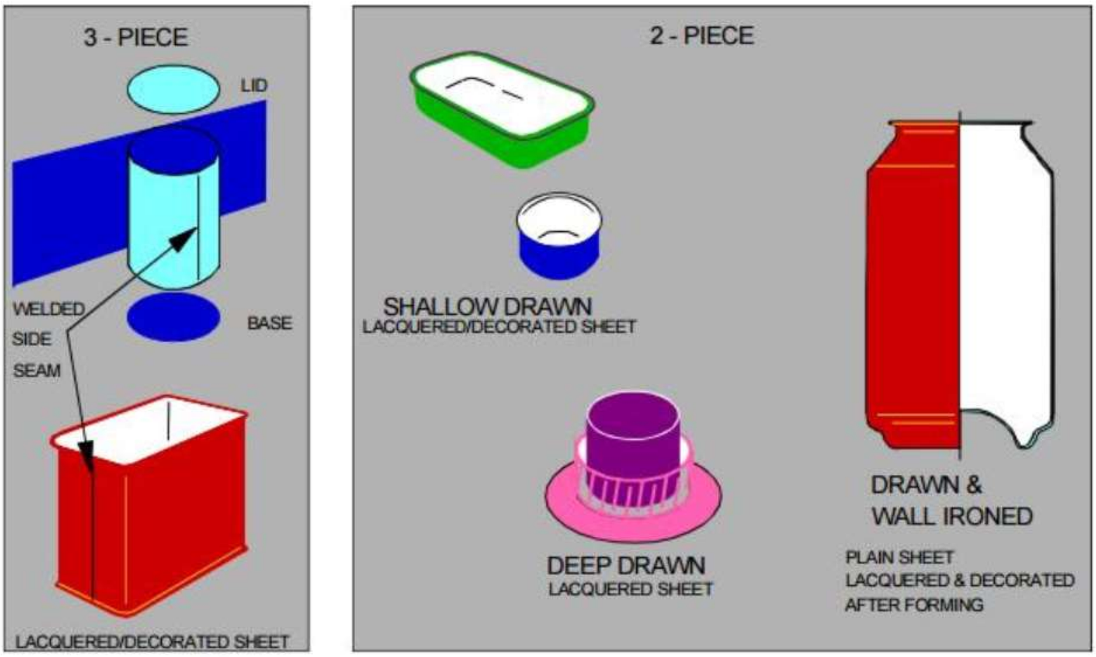
TABLE 6. Selected inputs and outputs for can sheet making for 1000 kg can sheet production (PE America 2010, 70-75 & * Ecofys 2009, 3)

Sheet production (780 kg of body components)			Sheet production (220 kg lid component)		
Input	**Unit**	**Amount**	**Input**	**Unit**	**Amount**
Power (undefined)	MJ	1025,0	Power (undefined)	MJ	636,5
Thermal energy (natural gas, heavy oil, light fuel oil, *LPG*)	MJ	3117,8	Thermal energy (natural gas, heavy fuel oil, light fuel oil)	MJ	976,0
Water (process and cooling)	m^3	1,3	Water (process and cooling)	m^3	0,4
Oils and lubricants	kg	5,9	Oils and lubricants	kg	7,4
Wooden pallets	kg	2,5	Wooden pallets	kg	3,8
Coatings	kg	2,3	Coatings	kg	0,6
Packaging (incl. cardboard, paper plastic composite, PE-film)	kg	0,5	Packaging (incl. cardboard)	kg	0,4
Acids	kg	0,7	Acids	kg	0,4
Aluminium ingots	kg	1072,0	Aluminium ingots	kg	316,9
			Epoxy resins	kg	9,3
Output	**Unit**	**Amount**	**Output**	**Unit**	**Amount**
Waste	kg	5,1	Waste	kg	4,7
Hazardous waste	kg	0,09	Hazardous waste	kg	2,4
Wastewater	m^3	2,0	Wastewater	m^3	1,0
Can stock body	kg	780,0	Can stock lid	kg	220,0
Calculated for one tonne of production:					
CO_2	kg	20,0-235,0*			

Generally, two types of rolling methods, *cold and hot rolling*, are used to achieve the desired thickness of the aluminium (The Aluminum Association 2007, 36,53). Before so called hot rolling, or pre-rolling, aluminium ingots are preheated offering homogenization, relieve of stresses and softening of the material so less force is needed (PE Americas 2010, 69). Rolling is performed between rollers both in hot and *cold rolling*.

3.1.6 Can production

Cans are generally made either from two or three pieces (PICTURE4) (Can Manufacturers Institute). Two-pieced can is produced by stamping discs or blanks from the aluminium coil which are "then pressed into cups" (PE Americas 2010, 76). Achieved cups are then ironed and domed forcing it "through a series of rings" to ensure desired form.



PICTURE 4. Illustration of 2- and 3-pieced aluminium cans (Aluminium Guide n.d.)

For example, the bottom dome is forced from the piece in comparison to three-pieced (PICTURE 4) can in which separate bottom part is seamed with the body. After shape of the can is achieved, trimming, washing, cleaning, printing, and varnishing are performed. Baking as well as inside spraying which adds protective properties are applied (Can Manufacturers Institute). Aluminium can production requires energy, aluminium, coatings, and water (TABLE 7.).

TABLE 7. Selected Inputs and outputs for the can making of 1000 cans and cans from 1000 kg of aluminium sheet (PE America 2010, 78-81)

Inputs and outputs for 1000 cans			**Inputs and outputs for cans from 1000 kg of aluminium sheets**		
Input	**Unit**	**Amount**	**Input**	**Unit**	**Amount**
Aluminium sheet	kg	16,8	Aluminium sheet	kg	1000,0
Power	MJ	77,6	Power	MJ	4625,4
Thermal energy (natural gas, LPG)	MJ	70,4	Thermal energy (natural gas, LPG)	MJ	4193,3
Sulphuric acid (96 %)	kg	0,2	Sulphuric acid (96 %)	kg	11,8
Lime quicklime	g	77,2	Lime quicklime	kg	4,6
Lubricating oils and inks	g	70,7	Lubricating oils and inks	kg	4,2
PE	g	13,6	PE	kg	0,8
PP	g	17,9	PP	kg	1,1
Water	kg	85,0	Water	m^3	5,1
Coatings	kg	0,9	Coatings	kg	54,6
Solvent	g	8,8	Solvent	kg	0,5
Output	**Unit**	**Amount**	**Output**	**Unit**	**Amount**
2 pc can	pcs.	1000	2 pc can	pcs.	59 590
Wastewater	kg	56,6	Wastewater	m^3	3,4
Formaldehyde	g	2,0	Formaldehyde	g	120,4
Sludge	kg	26,5	Sludge	kg	1578,2
Waste (incineration and landfill)	g	93,7	Waste (incineration and landfill)	kg	5,6
Hazardous waste	g	0,7	Hazardous waste	g	44,8

Generally, three-pieced can is also produced from coil of aluminium but instead of pressing preform cups, coil is cut into smaller sheets which are then applied with protective coating as well as printing. Different parts are seamed together (Can Manufacturers Institute). Since different properties are wanted from the lid, it is made from different alloy (PE Americas 2010, 76).

Internal foiling is essential to prevent aluminium corroding by acidy drinks. Generally, bisphenol A (BPA) is used which is associated with negative effects to hormonal system and reproductivity (Tekniikan maailma 2019) and is restricted to be used in plastic bottles and consumable packages designated for babies and children under three years old (THL 2021). Aluminium itself is associated by some studies with increased risk for neurological deceases like Alzheimer’s (Tuomisto 2020) or dementia.

3.1.7 Recycling

Before the actual recycling, collected cans are transported to processing plant and pressed to bales. Before remelting, material is shredded to remove other contaminants and water potentially pocketed inside the material (Palpa 2). Magnetic separators are used for removing ferrous metals and coatings are removed by heating (PE Americas 2010, 81). Preparation for recycling requires relatively low volumes of energy (TABLE 8.) compared to actual remelting and casting process.

TABLE 8. Preparation for recycling and remelting and casting for 1000 kg of rolling ingots. (PE America 2010, 83-86)

Preparation for recycling		
Input	**Unit**	**Amount**
Aluminium scrap	kg	1013
Power	MJ	30,9
Thermal energy	MJ	281,2
Output	**Unit**	**Amount**
Aluminium scrap (processed)	kg	1000,0
Waste	kg	56,7
Hazardous waste	kg	2,8
Casting		
Input	**Unit**	**Amount**
Aluminium	kg	1046,0
Alloy components	kg	5,7
Thermal energy (natural gas, LPG, light fuel oil, etc.)	MJ	1939,6
Power	MJ	1022,0
Water (cooling, process)	m^3	1,5
Oils and lubricants	kg	1,7
Acids	kg	0,9
Output	**Unit**	**Amount**
Wastewater	m^3	1,6
Waste (including dross)	kg	6,9
Dross	kg	46,3
Aluminium rolling ingot	kg	1000,0

Compared to the primary aluminium casting, recycled aluminium is melted using “mix of rotary and reverberatory furnace technologies” (European Aluminium Association 2010, 54). Melted aluminium is then turned into ingots with additional elements (European Aluminium Associate 5, 25).

3.2. PET

The PET bottle life cycle includes oil extraction, desalting, distillation, and further refining to different petrochemical products following with plastic production, utilization, and recycling (TABLE 9.). Utilization phase during which beverages are consumed by the customer is excluded since focus of the study is the material itself.

TABLE 9. Process phases of plastic life cycle

Process phase	**Definition**
Oil extraction	Drilling the soil from the deposit
Oil desalting	Desalination of drilled oil
Oil distillation	Distillation of desalted oil to naphtha, *kerosine*, light and heavy gasoline
Production on petrochemical products	Production of refined products from naphtha, kerosine, light and heavy gasoline
Polymer production	Production of plastics from refined petrochemical products
Injection stretch blow moulding	Manufacturing of the bottles
Utilization	User utilization phase
Recycling	Recycling of retrieved plastics and preparation to plastic production

3.2.1 Oil extraction

Oil can be extracted by drilling either on land or offshore reservoirs generally found on depth of 200-6000 meters (Kirsen-Dogan 2008. 13). Major environmental effects are caused by emissions to air and consumption of water and energy (TABLE 10). Water is used in drilling for cooling and lubricative, in hydraulic *fracturing* which is a method for forcing oil trough underground rocks

(Allison et al. 2018) and maintaining pressure of the reservoir during *the secondary recovery* (Office of Fossil Energy and Carbon Management n.d.). Wastewater forms approximately 95 % of all wastes associated with drilling. Since this water is contaminated with hydrocarbons consisting of chemicals treatment is needed before draining to nature expect if waters are disposed by returning it underground (Kirsen-Dogan 2008, 35). Besides hydrocarbons waste consists of mixture of water and clay which is commonly collected, solidified, and stabilized with cement and silica (Kirsen-Dokan 2008, 37).

TABLE 10. Inputs and outputs for 1000 kg of extracted crude oil (Meili et al. 2018. 17-18, 23, 27, 32, 38, 46)

Inputs	**Unit**	**Amount**
Water	m^3	790,0
Fossil energy	MJ	3980,0
Organic chemicals	g	90,0
Inorganic chemicals	g	118,0
Outputs	**Unit**	**Amount**
CO_2	kg	79,5
Methane	m^3	10,6
Wastewater	m^3	1000,0
Municipal solid waste	kg	1,0

Climate effects by drilling activities are caused by *flaring* both land and offshore activities but also by standby vessels (Kirsen-Dogan 2008, 37) which are ships used for various tasks like supplying the *drilling rig*. Flaring is a method for disposing residual gases by burning (Kirsen-Dogan 2008, 42). Flaring may be needed for safety purposes when over-pressure is needed to be avoided or as a disposing method for example due to remote location of the oil extraction site or simply by economical values due to difference prices of gas and oil (Meili et al. 2018, 25). Public concern has turned to flaring since only oil rigs under United Kingdom on North Sea have estimated to release yearly as many emissions than coal fuelled power plant (The Guardian, 2021). Besides flaring, emissions are also caused by *fugitive emissions*, emissions which are not controlled but released through seals, valves, and flanges (ICCT, 15) and hard to measure.

Besides natural gas, also methane is commonly credited as primary fugitive gas (Meili et al. 2018, 30, 44).

Energy demand variates for example according to the depth and pressure of the reservoir and properties (mainly viscosity) of the drilled oil (ICCT, 13). Energy is consumed for example by powering compressors for re-injecting gas, turbines for electricity generation, heating, steam production, pumps, and transport trough pipelines (Meili et al. 2018, 21).

Major environmental risks related to oil extraction are caused by the nature of the work especially when substances with flammable vapours and gases are processed (United States Department of Labor n.d.). Well known example of realized accident was the explosion of Deepwater Horizon oil rig. Considered as the biggest oil spill in the history of US, the accident resulted with leakage of over 750 million litres of oil into Gulf of Mexico in year 2010 (Dell A’more 2014). Besides visible accidents, contamination of ground waters (Sohns et al. 2016, 4) is also a relevant risk when water is pumped underground.

Social negative effects to residents may especially occur when risks are managed or supervised poorly. This happened in Chad where collapsed crude oil by-product caused contamination of the local river and the surrounding fields causing over 50 people with burns, skin lesions and other health issues as well as loss of livestock (Hodal 2021). Also in Chad, oil exploring may result with lake Chad, a natural and cultural site acknowledged by UNESCO, being withdrawn from the heritage list. It is estimated that possible oil extraction would affect 45 million people living off lake Chad (Gouby 2020).

Extracted oil is transported to be refined. Transports are performed for example using pipes and rails onshore and tankers in offshore (Laurenzi et al. 2016 a, 673). Well known accidents with wide environmental impact are for example Exxon Valdes oil spill in 1989 and ABT Summer in 1991 former causing oil spillage of 37,000 metric tons and latter 260,000 metrics tons (Leahy 2019).

3.2.2 Petroleum desalting

Desalting is method of which during extracted oil or petroleum is purified from water, suspended solids, inorganic salts and water-soluble trace metals with high temperature and pressure (Kirsen-Dogan 2008, 14). During this desalting water is used for cooling, heating and in washing directly (Laurenzi et al. 2019, 44). Except quantities of water, also small volume of energy is required (TABLE 11.)

TABLE 11. Inputs and outputs of desalting of 1000 kg of crude oil (Kirsen-Dogan 2008, 16, 33 and 39)

Input	**Unit**	**Amount**
Crude oil	kg	n/a
Electric power	MJ	0,405
Water	m^3	65
Output	**Unit**	**Amount**
Desalted crude oil	kg	1000

Highly contaminated wastewater from distillation contains for example hydrocarbons, solids and free oils and may be used in either treated or untreated in other refining processes. Solid waste contains sludge from frequently maintained clean-outs containing besides water also, rust, clay, and emulsified oil. (Kirsen-Dogan 2008, 16, 38-39).

3.2.3 Petroleum distillation

After the desalting phase, crude oil is distilled to various *fractions* (like *naptha*, kerosine, light and heavy gasoil) using different phases starting with heating and following with vaporization, fractionation, condensation, and cooling of the feedstock (Kirsen-Dogan 2008, 17-18). It should be noted that values presented in the TABLE 12 represents emissions and waste from only limited number of plants, say two crude oil and distillation units, and hence provide rather guiding than representative values for the whole industry.

TABLE 12. Inputs and outputs of oil distillation units for 1000 kg of produced crude oil (Kirsen-Dogan 2008, 32-33, 38 and 40)

Input	Unit	Amount
Desalted crude oil	kg	1000,0
Electric power	MJ	14,4
Energy	MJ	543,6
Water	m^3	4,0
Output	**Unit**	**Amount**
CO_2	kg	31,0
Wastewater	m^3	0,415
Distillate crude oil (naphtha, light products, light and heavy gas oil)	kg	1000,0

During distillation energy consumption is caused for example by heating of the feedstock which is then fed to atmospheric distillation column where vaporized oil separates into fractions like naphtha, kerosine and different gas oils. After hydro treatment these fractions collected by product strippers can be considered as finalized products. (Kirsen-Dogan 2008, 16-17)

3.2.4 Production of petrochemical products

Production of PET requires various petrochemical products which are further quality grades from the distillate products of which the most important are heavy and light naphtha. Naphtha is first processed to intermediate products (*P-xylene* and *ethylene*) which are processed further to the raw materials (*ethylene glycol* and pure terephthalic acid) (TABLE 13.) required by the PET production (Kirsen-Dogan 2008, 18).

TABLE 13. Inputs and outputs of production of 1000 kg of ethylene glycol and 1000 kg pure terephthalic acid. (Kirsen-Dogan 2008, 33, 41)

Inputs and outputs for ethylene glycol			**Inputs and outputs for pure terephthalic acid**		
Input	**Unit**	**Amount**	**Input**	**Unit**	**Amount**
Light naphtha	kg	3300	Heavy naphtha	kg	4300
Electric power	MJ	176,4	Electric power	MJ	111,6
Water	m^3	420	Water	m^3	258
Output	**Unit**	**Amount**	**Output**	**Unit**	**Amount**
Ethylene	kg	1000	P-xylene	kg	1000
Input	**Unit**	**Amount**	**Input**	**Unit**	**Amount**
Ethylene	kg	600	P-xylene	kg	665
Oxygen	kg	600	Electric power	MJ	1620
Electric power	MJ	1684,8	Water	m^3	213
Water	m^3	314			
Output	**Unit**	**Amount**	**Output**	**Unit**	**Amount**
Ethylene glycol	kg	1000	Pure terephthalic acid	kg	1000

Again, production of light naphtha to ethylene and ethylene to ethylene glycol as well as production of heavy naphtha to P-xylene and P-xylene to pure terephthalic acid contains various stages which are undoubtedly interesting but since focus of this study is to review the significant environmental effects throughout explanation is forced to be left out but are available as described more detailed for example by Kirsen-Dogan (2008). Generally, these processes are credited with relatively high energy intensity and water consumption since steam and heat is required (Kirsen-Dogan 2008, 18-24).

3.2.5 Polymer production

Depth and chemical details variates strongly when reviewing the descriptions of plastic production processes. To keep things simple, based on Kirsen-Dogan (2008, 11) PET is produced using three main phases which are melted state *polycondensation*, solid state polycondensation and *injection stretch blow moulding* manufacturing. First two phases are complex chemical processes whereas the latest one is the phase where the raw material is processed to desired, bottle-shaped form. In this study injection stretch moulding is focused on separate chapter since rather than being a complicated chemical process relying on special process equipment, theoretically injection moulding would be performed by larger number of actors. First phases are credited with high energy consumption but relatively low demand for water (TABLE 13). Firas et al. (2005) or Kutz (2016) have described production processes more detailed but since this study is focusing on environmental effects, these are not reviewed further.

TABLE 13. Selected inputs and outputs from 1000 kg PET production (Kirsen-Dogan 2008, 49-51)

Input	**Unit**	**Amount**
Ethylene glycol	kg	337,5
Pure terephthalic acid	kg	847,5
Electricity	MJ	18496,8
Water	m^3	5,2
Output	**Unit**	**Amount**
Polymer waste	kg	9,0
Other waste	kg	3,5
CO_2	kg	2330,0
PET resin	kg	1000
Input	**Unit**	**Amount**
PET resin	kg	n/a
Electricity	MJ	927,0
Water	m^3	7,6
Output	**Unit**	**Amount**
PET chips	kg	1000,0

Generally, when PET is produced, during melted state polycondensation terephthalic acid and ethylene glycol are combined resulting with PET chips. But since molecular weight of chips is yet too low to be sufficient for blow moulding, further process with solid state polycondensation is required. Solid state polycondensation is also required to reduce residual acetaldehyde to acceptable level. Common methods used are either vacuum or inert gases of which helium is generally used. (Kirsen-Doukan 2008, 27- 29)

3.2.6 Injection strecth blow moudling

Injection stretch blow moulding is the phase where PET resin is turned to the desired form, which in this case is a beverage container. In this process molten PET is injected to a mould where the designed shape is achieved by blowed air which stretches (Firas et al. 2005, 5) the material into so called preform. During the process, key environmental figures are credited to energy consumption (TABLE 14.). Since average energy consumptions were credited only for 1 kg of injection stretch blow moulded PET, values on the table are converted to represent energy consumption of 1000 kg of blow moulded PET.

TABLE 14. Selected inputs and outputs from 1000 kg and 1000 bottles injection moulded (Kuczenski et al. 2011, 34-25)

Per 1000 kg injection moulding			**Per 1000 bottles injection moulding**		
Input	**Unit**	**Amount**	**Input**	**Unit**	**Amount**
Electric power	MJ	6500,0	Electric power	MJ	120,9
Lubricating oil	kg	1,9	Lubricating oil	kg	0,4
Output	**Unit**	**Amount**	**Output**	**Unit**	**Amount**
Bottle	kg	53763,0	Bottle	pcs	1000

Preform being about a test tube sized miniature version of the real bottle (The Finnish Packaging Association 2018), to achieve bottle with desired volume for a beverage container, preforms are required to be again heated and stretched with blowed air by the beverage company (The Finnish Packaging Association 2018). Advantages of the preform, when bottles are not produced by the beverage company itself, are space saving (1/5 to 1/10) during transports. For instance, a single 10-ton truck can deliver 300,000 – 400, 000 pieces of preforms on single journey (RotaPack n.d.).

3.2.7 Recycling

PET bottles have numerous benefits what comes to recycling including high volumes, easy separation from other collected materials and non-PET materials.

Also, at least in EU only PET approved compatible with food requirements is allowed to be placed on the markets (Welle 2011, 686). Still generally
recycled material content is only 35 % on new bottles yet ratio of 65 % is still considered safe (Shen et al. 2011, 525, 534). On the other hand efficient separation and washing phases, say primary recycling, is critical for ensuring the raw material quality (Kutz 2016, 181-182). Goal of the primary recycling is, as defined by Achilias et. al. (2012, 3), to obtain “clean, uncontaminated single-type (plastic)waste” where material is sorted not only by resins but also by different colours (Firas et al. 2005, 7).
Impurities like other resins (e.g., PVC), dirt, metal, glass, paper, foodstuff, fuel, water, and additives used in the resin may have negative effect on both physical and chemical properties by decreasing the quality of the recycled product (Firas et al. 2005, 7; Kutz 2016, 176, 181-182).

Besides manual manpower, wide range of technology, like optical sensors, are used in separation and sorting. Optical sensors are based on colour or transparency of the plastics and especially suitable for bottles since clear PET is valued more than coloured. Some facilities use spectroscopic techniques, like *NIR* (near infrared) separator to separate different resins (Rigamonti et al. 2012, 45). After the unwanted materials are separated, single resin material, like PET, is “crushed into flakes and washed with chemical agents”. Water is essential input to exclude dirt, labels, and glue from grinded PET flakes. Generally caustic soda (or natrium hydroxide) and detergents are used as washing additives. (Welle 2011, 869). Washed PET flakes are dried depending on the technology applied (Firas et al. 2005, 8). Environmental impacts during the primary recycling as well as the chosen recycling method itself are mainly credited with energy demand of the machinery (TABLE 15.). It should be noted that the source represents retrieved material which was not pure PET bottles.

TABLE 15. Input material for the secondary production of PET expressed per 1000 kg of recycled PET (Rigamonti et al. 2012, 45 and 48)

Primary recycling phase including NIR separator, film removing, sieves, magnets, etc.		
Input	**Unit**	**Amount**
Electricity	MJ	104,4
Unsorted plastic waste	kg	1000,0
Output	**Unit**	**Amount**
Recycled PET	kg	N/A
Mechanical recycling phase		
Input	**Unit**	**Amount**
Recycled PET	kg	1000,0
Electricity	MJ	1152,0
Water	m^3	2,9
Sodium hydroxide	kg	0,3
Output	**Unit**	**Amount**
Methane	kg	19,5

Since 99 % of retrieved plastics are recycled mechanically in Europe (Plastics Europe) in this study concentration is focused only on this recycling method, yet it should be noted that chemical recycling may also be used. Mechanical recycling is seen as method in which “the polymer is separated from its associated contaminants, and it can be readily reprocessed into granules by conventional melt extrusion”. During mechanical recycling monomers or basic polymers are not altered (Achilias et al. 2012, 3; Ragaert et al. 2017, 2). Mechanical recycling is seen as, compared to chemical recycling, more environmentally friendly, requires lower investments and is simpler (Gomes et al. 2019, 535) at least what comes to used technology.

3.3. BIOCOMPOSITE

The potential biocomposite container life cycle includes agriculture and production of PLA (polylactic acid), silviculture and logging, pulping of wood, biocomposite manufacturing including injection moulding, utilization, and recycling (TABLE 16.). Again, utilization phase during which beverages are consumed by the customer is excluded since focus of the study is the material itself.

TABLE 16. Process phases of plastic life cycle.

Process phase	**Definition**
Agriculture and production of PLA	Agricultural activities for cultivating, harvesting, and collecting of corn following hydrolysis, fermenting and production polylactic acid
Silviculture and logging	Forest activities for planting, logging, thinning, *pruning*, and harvesting the wood
Pulping of wood	Refining of logged wood to *pulp* with high containing of fibres
Biocomposite manufacturing including injection moulding	Manufacturing of biocomposite from polylactic acids and wood fibres and injection moulding
Utilization	User utilization phase
Recycling	Recycling of retrieved plastics and preparation to plastic production

3.3.1 Polymer matrix: Agriculture and production of PLA

Production of PLA for the polymer matrix part of the biocomposite includes stages of cultivation, harvest and drying of the corn. Corn is put through *dextrose* process during which starch is separated and hydrolysed into dextrose enzymes. Dextrose is fermented to lactic acid, a raw material for polylactic acid polymers

(Hermansson 2013, 17). During PLA production relative high volumes of energy is consumed (TABLE 17.). During polymer manufacturing additives like coupling agents, light stabilizers, pigments, lubricants, fungicides, and foaming agents may be used (Hietala 2013, 4). One of the benefits of the biological raw material is carbon sequestration which is caused during growth when carbon dioxide is absorbed from the air and stored in the biomass. Relying on biological raw materials may cause unreliable sourcing, since yield may be unreliable due to different uncontrollable phenomena like seasonal fluctuations which may affect to crops (Fitzgerald et al. 2021, 13-14). Carbon sequestration related to the cultivation has been theme for many studies, but since mostly results have been presented in hectares, no relevant numbers was able to be found for this study.

TABLE 17. Selected inputs and outputs for PLA production for production of 1000 kg PLA (Ghomi et al. 2021, 3)

Input	**Unit**	**Amount**
Corn	kg	1280,0
$CaCO_3$	kg	790,0
H_2SO_4	kg	250,0
NaCl	kg	110,0
Other energy	MJ	23420,0
Electricity	MJ	6680,0
Output	**Unit**	**Amount**
PLA	kg	1000,0

Since origination of the corn is unknown, environmental effects caused by agricultural activities cannot be evaluated. Assumption is that fertilizers, pesticides, and water as well as fuel for vehicles used in cultivation and harvest is consumed. According to Sandhu et al. (2020, 2) growing of corn is responsible for pollution trough highly intensive use of fertilizers causing negative effects on not only surface waters but also to drinking water. Cultivation is also associated with air emissions of nitrous oxide and biodiversity loss (Sandhu et. al. 2020, 2).

3.3.2 Wood-based fibre: Silviculture and logging

First phase of production of wood-based fibres for biocomposite includes several stages related to the silviculture which is “the art and science of controlling the establishment, growth, composition, health, and quality of forests and woodlands to meet the diverse needs and values of landowners and society such as wildlife habitat, timber, water resources, restoration, and recreation on a sustainable basis”. This includes different actions and phases like thinning, harvesting, and pruning of forest to achieve maximum material output from forest. (U.S. Forest Service n.d.). It should be noted that since the logs are primarily material valued by the sawmill industry, mostly the material intended for fibre production is inferior, generally the material with smaller diameter (commonly under 15 cm) like treetop parts or smaller trees or larger trees not accepted by sawmills due to lower quality or rot. (Stora Enso n.d.; Puusta Puuhun n.d.). Also, generally trees cut during thinning, the stage of silviculture during which only desired trees are left grow to actual log size, are commonly considered as a raw material for fibre production (Cord n.d.). Relatively small volumes of energy are required for silviculture and transportation of the logs to pulp manufacturing site (TABLE 18.)

TABLE 18. Tonne of air-dried *cellulose* from pine (20 %) and spruce (80 %) during forestry operations (Gonsález-Garáa et al, 2011, 572)

Input	Unit	Amount
Diesel	MJ	2732,8
Output	**Unit**	**Amount**
CO_2	kg	145,6

Even the wood for fibres is obtained from FSC certified forest in Sweden, due to high density forest industry, nearly half of woodland is already too young for harvesting. Partly due to this, Red List of threatened and endangered species includes over 2100 threatened species native in Sweden (Hoffner 2011).

Also, wood is associated with carbon sequestration and again many studies have focused on carbon sequestration related to wood but most of the sources were not directly applicable for this study. Basically, half of the dry mass wood is carbon and based on this, carbon dioxide sequestration may be roughly 500 $kgCO_2$ per ton of wood (Bowyer 2012, 8).

3.3.3 Pulping of wood

The purpose of the pulping process is to separate desired fibres (terms like cellulose or wood pulp are also used) from wood (Cord n.d.). Preparation of wood starts with debarking, cutting, and chipping after which wood chips are washed with water and treated with steam. Obtained cellulose pulp is washed, screened (Hermansson 2013, 16). Sodium sulphite for softwood (leafy trees) and sodium hydroxide to hardwood (conifers) is added (Palonki 2021, 29) following with peroxide bleaching (Gonsález-Garáa et al, 2011. 572). At the end water is removed from the pulp (Hermansson 2013, 16). Environmental effects caused by pulp manufacturing is caused mostly by emissions to air and water (TABLE 19.).

TABLE 19. Selected inputs and outputs 1 tonne of air-dried cellulose from pine (20 %) and spruce (80 %) during pulping (Gonsález-Garáa et al. 2011, 574; *Marttila 2019, 28)

Input	**Unit**	**Amount**
Green logs	m^3	6,1
Water	m^3	185,6
NaOH	kg	107,8
H_2SO_3	kg	3,3
Fuel oil	MJ	1564,2
Electricity	MJ	4770
Output	**Unit**	**Amount**
Bleached pulp	kg	1000,0
Waste	kg	35,2
Ethanol	kg	59,5
Sludge	kg	60,0
Wastewater*	m^3	35,0
CO_2	kg	2790,0

Significant effects to water are caused by organic compounds which may cause eutrophication due to phosphorus and nitrogen. Also, wastewaters, if released untreated, are toxic to water organisms and contains traces of heavy metals (Cirbabc n.d.). Commonly produced wastewater volumes variates between 20-50 m^3 per produced ton of cellulose and average of this is used acknowledging that sources may not be directly comparable (Marttila, 2019, 28). As side product also ethanol is produced. Some facilities may be net producers of energy and provide especially steam even outside (Gonsález-Garáa et al. 2011, 152, 574).

3.3.4 Biocomposite manufacturing including injection moulding

Bio composite manufacturing process phases includes compounding, grinding, and drying (Mahalle et al. 2013, 1308). Phase is associated with relatively high energy consumption (TABLE 20), but it should be noted that values presented on the table are based on research made in laboratory and are expected to variate from actual volume driven production (Mahalle et al. 2013, 1313). In actual production, injection moulding may be seen as a separate phase since commonly material producers, like is the case with the start-up company, lacks the product specific manufacturing machinery and knowledge for the volume driven production. But since the study by Mahelle et al. (2013) included injection moulding to the biocomposite manufacturing phase and were impossible to allocate to own section, environmental values are also included to this section. The values associate with bio composite specific injection moulding and hence offers best compatible values among the sources.

TABLE 20. Inputs and outputs for 1000 kg of biocomposite (30 % of wood fibre and 70 of PLA) (Mahalle et al. 2013, 1312)

Input	Unit	Amount
PLA	m^3	700
Wood fibres	m^3	300
Energy	MJ	37 440
Output	**Unit**	**Amount**
Waste	kg	20
CO_2	kg	1130

One benefit of biocomposite with biological origination is reduction of net CO_2 emissions. As mentioned earlier, reduction caused by corn was not known but was associated with 500 kg per ton of wood. As wood fibres forms only 30 % of the total mass of biocomposite, reduction may be theoretically 150 kg per 1000 kg of wood-based biocomposite. This variates strongly from the study by Mahalle et al. (2013) which resulted with as much as 144 410 kgCO_2 for fibre and 5130 kgCO_2 for PLA per 1000 kg of produced biocomposite total reduction being 149 540 kg kgCO_2. Manufacturing was made based mostly on renewable energy, fossil sources forming one third (31,3 %). (Mahalle et al. 2013, 1311-1312, 1314). Production with fully renewable energy may result with more reduced carbon dioxide emissions or visa versa.

As mentioned, during the actual production, biocomposite provided by the manufacturer would be transported to the injection moulding company with the product machinery suitable for high volume production. Injection moulding is already widely used method among conventional plastic manufactures, and is also preferred by the start-up company, since reduced manufacturing costs are achieved through high production volumes, say due to number of *cavities*, a method of moulding. During injection moulding phases like closing the mould, clamping, injection, packing, dosing, feeding, screw reaction, opening the mould and ejection are included. Generally, bio-based composites have lower energy consumption (Franziska et al. 2017, 340) than conventional material which results with lowered energy demand during melting.

Considerable is that the wall-thickness for a product made of DuraSense, a relatively new biocomposite material by Stora Enso, is suggested being at least 0,8 mm resulting with relatively high mass of package compared to other materials (Stora Enso n.d.). Wall thickness of regular PET bottle is 12-25 *mils* (0,30-0,635 mm), a unit used for measuring plastic sheets one mill being one thousand of an inch (Snyder et al. 1982), and aluminium cans 0,097 mm (The international Aluminium Institute 2018). It is not known whether the thickness is required also when DuraPulp is used but this is an aspect needed to take consideration if subject is studied further. Thickness may result with more material required and in high production volumes cause significant environmental affects due to space and weight.

3.3.5 Recycling

Although in EU functional and existing recycling processes for aluminium cans and plastic packages as well as interest in improvement for example through objectives for the recycling rates exist, currently no comparable recycling system for biocomposite products is in effect. As mentioned earlier, this may be due that wide utilization of the material is still waiting itself since especially wood-based biocomposites are relatively new materials (Fitzgerald et al. 2021, 15). For example, Stora Enso currently “continuously collaborates with recycling facilities to consider the options and opportunities in collection, sorting and recycling” (Stora Enso n.d.). Since this no relevant data for the biocomposite recycling was able to be found.

4 CONCLUSION

Comparison of three entirely different materials with entirely different origination and life cycles was not an easy task. Studies and life cycle assessments for aluminium and plastic production were widely available but many of those were product specific, offered relevant data only on limited phases during the life cycle or the study contexts were based on different economical or technical systems (for example Europe vs. US). Only few studies (like Hermansson 2013, Kirsen-Doukan 2008 and PE Americas 2010) offered direct information for whole life cycle forming the nucleus of the input data whereas the other sources have acted as supportive information. Downside of those supportive sources was that they may not be directly compatible due to scope or studied system and context, and the results needs to be reviewed with slight criticism. Even more challenging was to find reliable sources with relevant data for biocomposites, especially for wood-based ones. The subject still lacks information, especially on form of life cycle assessments and exactly related to beverage packages. Also, since biocomposite beverage container currently exists only on theoretical level, comparison has indeed been challenging. As purpose of this study was, rather than offering exact numerical data, create an impression for magnitude of the chosen key environmental effects related to the comparable raw materials and to answer whether biocomposite may be more environmentally friendly than aluminium and PET. Despite the uncertainties mentioned above, purpose of the study was fulfilled and the answer to the research question was able to be offered, yet the answer was against the hypothesis. Based on the results, it may be justifiable to declare that possible bias caused by the authors position in The Client was avoided.

As turned out, both aluminium and PET plastic had complex supply chains. With the Nordic wood-based fibre and PLA based on corn, chain may potentially be shorter and require less volumes to be transported. But this was not confirmed since origin of the corn was not known. Although transportation of the raw materials or semi-refined products was excluded from the study scope, it should be noted that the transportation may have significant additional environmental effects to the life cycle potentially increasing the total emissions and energy consumption as presented by this study.

This study has concentrated on selected environmental effects and for example values commonly distributed in life cycle assessments like eutrophication and acidification were left out of the results. Mostly focus has been paid on energy consumption, CO_2-emissions and relevant or potential other affects like risks. As mentioned before but as an important factor related to this work, results of this study are not absolute but are rather offering the review to the life cycles and material specific production phases with approximate magnitude of the environmental effects. If reviewing only the numerical results, the hypothesis that biocomposite was more environmentally friendly material than PET and aluminium, was partly got broken. Especially when mitigated carbon dioxide emissions or energy efficient production is desired, the material does not stand out positively against its competitors when values in the comparison table (TABLE 22) are reviewed. The results are based on the literal review focusing on the essential product phases of PET, aluminium and biocomposite, and collected and combined from the overall summary tables available in appendixes (APPENDIX 1, 2 and 3). According to the results, biocomposite holds highest caustics/acids consumption, is second on carbon dioxide emissions, energy consumption, waste production and water consumption.

TABLE 22. Comparison of the selected inputs and outputs for 1000 kg of produced aluminium cans, PET bottles and biocomposite containers

Input or output	**Aluminium**	**PET**	**Biocomposite**
WATER			
Water consumption (m^3) *including surface and sea water*	**36,0**	**2079,8**	**186**
Waste water (m^3)	**33,0**	**1000,4**	**N/A**
ENERGY			
Energy (MJ) *including electric power and fuel energy*	**82 716,0**	**34 636,4**	**76 607, 0**
WASTE			
Waste (kg) *including dross and sludge*	**1777,0**	**14,0**	**110,0**
Hazardous waste (kg)	**79,0**	**N/A**	**N/A**
EMISSIONS TO AIR			
Methane (kg)	**N/A**	**30,0**	**N/A**
CO_2 (kg)	**3144,0**	**2441,0**	**2790,0**
CO_2 reduction (kg)	**-**	**-**	**-149 540**
CF_4 (kg)	**0,11**	**N/A**	**N/A**
C_2F_4 (kg)	**0,01**	**N/A**	**N/A**
MATERIAL SPECIFIC			
Acids and caustics (kg)	**186,0**	**N/A**	**361,0**
Overburden (kg)	**530,0**	**N/A**	**N/A**
Red mud (kg)	**2187,0**	**N/A**	**N/A**

One character presented in the table rises the environmental profile of biocomposites compared to fossil oil-based PET or non-renewable aluminium. Besides energy and raw material consumption or air emissions related to the material production, carbon dioxide sequestration by the biological raw materials used for biocomposites needs to be considered as a positive feature. Especially oil-based products result with additional carbon dioxide emissions when plastics and other materials are incinerated during waste management since oil with high carbon content would otherwise be secured in underground reserves. During the growth of trees and corn, carbon dioxide from the atmosphere is absorbed to plants, like trees and corn, during natural process called photosynthesis. This makes significant difference compared to the other materials, since rather than only producing carbon dioxide emissions, biocomposite has potential to reduced carbon footprint. Theoretically, the resulted carbon dioxide emissions may even be negative. It should be noted that the results based on the carbon reduction are based only on a single study and may require critical review.

According to the results, biocomposite may not automatically be more environmentally friendly raw material compared to aluminium and PET when focusing only on effects caused during production but may result with notable reduction in total CO_2 emissions greatly minimized risks during the product phases (TABLE 23). Aluminium is associated with high environmental risks especially during alumina production where caustic red mud is used. Several incidents have shown that those risks have actualized causing damage to environment and loss of lives. Also, oil associates with risk of contamination of soil and water bodies. Severe risks have shown that those risks cannot always be mitigated. As far risks related to biocomposites is limited strongly to incidents of eutrophication and loss of biodiversity during cultivation, silviculture, and pulping.

TABLE 23. Comparison of environmental affects the life cycles of the three materials

	Aluminium	**Plastics**	**Biocomposite**
Renewability	• Material cannot be considered as renewable; known reserves available over 100 years	• Material is considered as fossil, known reserves available only 50 years	• Only if all raw materials are renewable; fibres from certified forests and resin from renewable, sustainable sources;
Water consumption	• Relatively low during the life cycle (36 m^3)	• Highest compared to other materials (2079,8 m^3)	• Moderate compared to other materials (185 m^3), but data lack cultivation of corn
Energy consumption	• Significantly highest compared to the other materials (82 716 MJ) • When recycled material used, energy consumption is 95 % less (4136 MJ)	• Significantly high energy consumption (36 636 MJ)	• Significantly high energy consumption (76 607 MJ) • Pulp manufacturing may be energy net producer and provide for example steam outside • As side product ethanol may be produced

Environmental or health risks	**Bauxite mining** • Known accidents associated with red mud • Potential effects to water systems • Loss of biodiversity due to open mining • Dissolved aluminium associated by some studies with increased risk for dementia or Alzheimer's decease **Utilization** • Foil used in cans contain Bisphenol A which has negative effect to reproductivity and hormonal system	**Oil extraction** • Known accidents associated with oil extraction, for example Deep Water Horizon • Waste management processes for waste waters and waste required • Potential contamination of water bodies and soil **Oil transports** • Known accidents related with oil transports, for example Exxon Valdes **Utilization** • Even bottles recently purchased may contain microplastics • Bottles may be source for Bisphenol A	**Cultivation of corn and silviculture** • Possible biodiversity loss if forests are not maintained sustainable • Possible biodiversity loss related to cultivation of corn if farming is happening in expense of forests • Pollution caused by pesticides and fertilizers **Pulp manufacturing** • Risk for eutrophication and contamination of water bodies if waters are drained untreated
Transports	• Complex supply chain with relatively high energy demand; high volumes of lowly refined raw material (like bauxite) is transported	• Complex supply chain: high volumes of lowly refined raw material (like crude oil) is transported	• Complex supply chain: corn and wood need to be transported and refined

Disposal	- Do not degrade biologically, but do not possess direct threat to environment due to chemicals	- Do not degrade biologically; produce microplastics when material wear	- Biodegradable only if both matrix and fibre are chosen from biological origin - Effective composting may need industrially maintained factors like pH, temperature, and moisture
Recycling	- Easy and efficient to recycle; recycling is environmentally and economically preferable - Existing and functioning recycling processes	- Relatively demanding to recycle but environmentally and economically preferable; strict separation between resins needed, requirements for material purity - Existing and functioning recycling processes	- Recycling challenging due to character of the material; separation of matrix and fibres may be needed - Recycling processes do not exist or are still studied
Air emissions	- Relatively high carbon footprint (3144 $kgCO_2$/1000 kg)	- Moderate high carbon footprint compared to other materials (2441 $kgCO_2$/1000 kg produced material)	- Highest high carbon footprint compared to other materials (4066 $kgCO_2$/1000 kg produced material) - Theoretical carbon dioxide reduction high (148 540 $kgCO_2$/1000 kg produced material)

5 DISCUSSION

Besides focusing on the material after it has been already placed on markets, consideration is needed to be paid already during the design and development phase. Besides the characteristic and features of the material, also end-of-life phase should be planned beforehand to ensure recyclability. Securing the circulating material flow would need besides planning of a single manufacturer, cooperation between several actors like waste management companies and potential users of recycled materials. Several aspects need to be covered if environmentally friendly and functional materials is desired.

First, recycling of the material would need to be implemented and functional. Principles of circular economy are met but only fairly if material is composted and not at all if it ends up incinerated. Focus should be paid on achieving closed loop and extended product service life to keep carbon in the product as long as possible but currently recycling or deposit systems for retrieval and utilization of used biocomposite does not exist as those processes related to aluminium and plastics do. Theoretically nothing would prevent products made of biocomposite being involved for example in Finland to country wide PALPA deposit network. Besides retrieving the material also effective recycling processes are required. Studies and projects relating to conventional composites (like glass fibre) have shown that recycling of the material is challenging. This is caused by the characteristics of the composites, but processing of bio composites may be easier especially in closed loop applications.

But to achieve efficient recycling, the second condition stands out: biocomposites should be widely used by the beverage industry and other fields of industry to enable sufficient volume for economically and environmentally acceptable recycling processes. Homogeneity of the material would be required between the manufactures or biocomposite grades would variate as currently plastics do. Numerous different variations caused by raw material selection may hinder efficient recycling compared to only few options.

Third, when renewable raw material is desired, sources for both fibre and matrix need to be obtained and selected from certified and verified sustainable sources. New renewable solution may not offspring with more problems and hence raw material selection needs throughout and wide perspective approach especially when current innovations differ from partly fossil-partly biological to fully biological raw materials also including options with recycled materials.

Fourth, more studies related to biocomposites are needed. Generally, fruitful field for further studies exist including for instance recycling options, utilization, and environmental effects. Theoretically biocomposites could be utilized on unlimited applications as alternative to conventional products not limited only to PET and aluminium. Also, interesting study subject would be transportation of the compared materials between the life cycle phases.

And five, the studied biocomposite was based on wood and corn. Wood is indeed a local material in the Nordics, but corn, as what comes to volume based, agriculture is not. Rather than making PLA from corn, possibilities for utilization of locally growing raw materials like sugar beet or potato should be considered. Using local materials would lead to minimized transportation caused environmental effects.

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APPENDIX I SELECTED INPUTS AND OUTPUTS FOR ALUMINIUM CAN LIFE CYCLE

INPUT OR OUTPUT	**Bauxite mining**	**Alumina production**	**Electrolysis** incl. anode production	**Primary ingot casting**	**Sheet production**	**Can production**	**Recycling**	**Remelting and casting**	**TOTAL**	**UNIT**
WATER										
Water consumption (m^3) *including surface and sea water*	3	15	9	0	2	5		2	**36**	**m^3**
Waste water (m^3)	3	10	12		3	3		2	**33**	**m^3**
ENERGY										
Electric power (MJ)	36	857	41975	253	1662	4625	31	1022	**50461**	**MJ**
Fuel energy (MJ) *including diesel, kerosene, gasoline, heavy fuel oil, natural gas and hard coal*	379	18881	1193	1295	4094	4193	281	1940	**32255**	**MJ**
Coke (kg)			345						**345**	**kg**
WASTE										
Overburden (kg)	530								**530**	**kg**
Red mud (kg)		2187							**2187**	**kg**
Other waste including dross and sludge (kg)		76		4	10	1584	57	46	**1777**	**kg**
Hazardous waste (kg)			29		3	45	3		**79**	**kg**
EMISSIONS TO AIR										
CO_2 (kg)	7	615	1359	1035	128				**3144**	**kg**
CF_4 (kg)			0,11						**0,11**	**kg**
C_2F_4 (kg)			0,01						**0,01**	**kg**
ACIDS AND CAUSTICS										
Acids and caustics (kg)		172			1	12		1	**186**	**kg**

APPENDIX II SELECTED OUTPUTS AND INPUTS FOR PET BOTTLE LIFE CYCLE

INPUT OR OUTPUT	Oil extraction	Oil desalting	Petroleum distillation	Ethylene glycol production	Pure terephtalic acid production	PET production	Injection moulding	Recycling	TOTAL	UNIT
WATER										
Water (m^3)	790	65	4	734	471	13		3	**2080**	**m^3**
Waste water (m^3)	1000		0						**1000**	**m^3**
ENERGY										
Energy (MJ)	3980	0	14	1861	1732	19397	6500	1152	**34636**	**MJ**
WASTE										
Waste, municipal and polymer (kg)	1					13			**14**	**kg**
EMISSIONS TO AIR										
CO_2 (kg)	97		31			2330			**2458**	**kg**
Methane (kg)	11							20	**30**	**kg**

APPENDIX III SELECTED INPUTS AND OUTPUTS FOR WOOD-BASED BIOCOMPOSITE MANUFACTURING

INPUT OR OUTPUT	Agriculture	PLA production	Silviculture	Pulping	Biocomposite manufacturing including injection moulding	TOTAL	UNIT
WATER							
Water (m^3)				186		**186**	**m^3**
Waste water (m^3)				35		**35**	**m^3**
ENERGY							
Energy (MJ)		23 420	2 733	1 564		**27 717**	**MJ**
Electricity (MJ)		6 680		4 770	37 440	**48 890**	**MJ**
WASTE							
***Waste** including sludge*				90	20	**90**	**kg**
EMISSIONS TO AIR							
CO_2 (kg)			146	2 790	1130	**4066**	**kg**
ACIDS AND CAUSTICS							
Acids(kg)		250		111		**361**	**kg**
OTHER							
Ethanol (kg)				60		**60**	**kg**