DTU Environment

LCA of Single Use Plastic Products in Denmark

Brief report

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Preface

This study provides an environmental Life Cycle Assessment (LCA) of the production of Single Use Plastic Products (SUP) and the production of alternative Single Use Non Plastic Products (SUNP) and their waste management in Denmark, in 2018.

The commissioner of this study is the Danish Environmental Protection Agency (Miljøstyrelsen) and the study was conducted by DTU (Danmarks Tekniske Universitet) Environment in the period August to October 2018.

The LCA was modelled using EASETECH, a software developed at DTU Environment for the environmental assessment of waste management systems.

The LCA has been conducted according to the requirements outlined in DS/EN ISO International Standards 14040 and 14044; however, the report is not intended to strictly comply with the standard.

The report was prepared by Vasiliki Takou, Alessio Boldrin, Thomas F. Astrup, Anders Damgaard

DTU Environment, October 2018

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Executive Summary

Conceptual framework

This study provides an environmental Life Cycle Assessment (LCA) for the production and waste management of Single Use Plastic Products (SUP) and Single Use Non Plastic Products (SUNP) in Denmark, in 2018. It was carried out by DTU Environment in the period August to October 2018 and was commissioned by the Danish Environmental Protection Agency (Miljøstyrelsen).

The study was commissioned in order to assess a proposal by the European Commission (EC, 2018a), which aims to develop policies that could reduce marine littering in Europe. The proposal recommends the ban of specific SUP products, which role will instead be fulfilled by alternative SUNP products.

The SUP products proposed to be banned and their alternatives can be seen in Table A

Table A: SUP products proposed to be banned, and their SUNP alternatives

Product	SUP Material to be banned	SUNP Alternative Material
Cotton Buds	Polypropylene (PP)	Paper
Cutlery	Polypropylene (PP)	Wood
Food containers (plates / clamshell)	Polystyrene (PS)	Paper
Straws	Polypropylene (PP)	Paper
Beverage Stirrers	Polypropylene (PP)	Wood

The Danish Environmental Protection Agency has commissioned this study in order to assess the environmental impacts associated with the production and waste management of the SUP and SUNP products presented Table A in order to identify any problematic environmental impacts that the implementation of the policy could involve. The report is intended for internal decision support to the Danish Environmental Protection Agency.

The study assesses a range of environmental impacts by practicing an LCA. The report focuses on single use items, as the assumption is that multi-use items always will be better for the environment. The report does not address any functional differences between the products arising from the material type used. The report also does not consider biodegradable plastics as they are excluded in the EC proposal. Finally the report does not consider effects from littering etc. as this are the reason for the suggested ban on the material and therefore already considered.

The LCA has been conducted following the principles outlined in DS/EN ISO International Standards 14040 and 14044; however, the report is not intended to strictly comply with the standard.

Methodological framework

An LCA is an ISO standardized method for quantifying the environmental impact of a product or a system during its lifespan, from “cradle” to “grave” (ISO, 2006a, 2006b). In the present study, the LCA focuses on the production and the disposal stage of the life cycle of the product. The LCA determines the environmental impact of the chosen

disposal options taking into account all the resources (material and energy) required for running the processes, as well as the emissions that those entail.
All input and output flows, as well as the results are calculated based on the *Functional Unit* (FU) of the study, which is the following:

Production of 1 Single Use Plastic product and its Single Use Non Plastic product alternative globally, and their waste management in Denmark, in 2018 “

The boundaries of the studied system are illustrated with a dashed line in Figure A. A consequential approach is used for the modelling of the system.

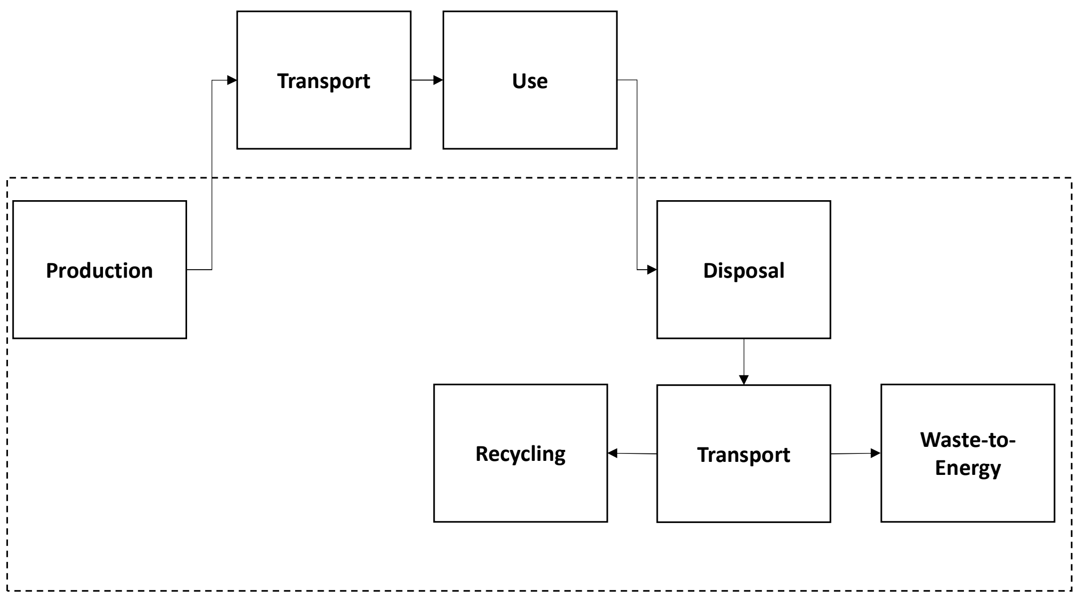


Figure A: SUP products proposed to be banned, and their SUNP alternatives

With regards to end-of-life scenarios, the options indicated by EC (EC, 2018a) were used for plastic, whereas, for paper and wood, it was assumed that the products are incinerated entirely. Paper and wood is assumed to be contaminated (e.g. with food leftovers) and not suitable for cleaning and recycling.

The modelling and the results generation was carried out using EASETECH, which is software developed at DTU Environment for the environmental assessment of waste management systems and technologies.

The processes used for modelling the products (extraction of materials and manufacturing of the products) represent global market processes, extracted from Ecoinvent v3.4 database, and are in line with the processes used in the report by the European Commission report (EC, 2018b).

The disposal phase is modelled using average processes from EASETECH, tailored to Danish conditions.

The Life Cycle Impact Assessment (LCIA) was carried out using the International reference Life Cycle Data system (ILCD) recommended impacts (EC-JRC, 2011).

Findings and Conclusions

The study identified, on basis of normalized impacts, that the categories with the largest potential impacts were climate change, particulate matter formation, fossil resource depletion and element resource depletion. Considering those categories, the results lead to the following conclusions:

- **Cotton Buds**: Paper cotton buds (SUNP) performed in average better than plastic cotton buds made out of polypropylene (SUP) in the baseline scenario, as well as in all sensitivity scenarios, with the exception of scenario S4. In scenario S4, which considered the indirect land use changes (iLUC) from paper production, the polypropylene option performed better.
- **Cutlery**: Wooden cutlery (SUNP) performed in average better or at least at the same level as plastic cutlery (SUP) made out of polypropylene in the baseline scenario, as well as in all the sensitivity scenarios, with the exception of scenario S4. In scenario S4, which considered the iLUC from wood production, the preferable option depended on the weight of the products. Nevertheless, for an average weight, the non-plastic option was preferable.
- **Food Containers**: For food containers (plates or clamshell), the paper option (SUNP) was found to perform worse or at best the same as the polystyrene option (SUP) considering all the sensitivity scenarios assessed.
- **Straws**: The paper straws (SUNP option) were found to perform better or on the same level with polypropylene (PP) straw, in all the scenarios tested.
- **Stirrers**: The wooden stirrers performed in average better or at least the same as plastic stirrers (SUP) made out of polypropylene in the baseline scenario, as well as in all the sensitivity scenarios, with the exception of scenario S4. In this scenario S4, which considered the iLUC from wood production, the preferable option depended on the weight of the products. Nevertheless, for an average weight, the non-plastic option was preferable.

Based on the abovementioned, it can be concluded that the weight can play an important role. Therefore, the design of the SUP might matter more than the shift to SUNP, and it is important that a shift to SUNP will be to lighter SUNP products. To assess the proposed change further an overview of the market of SUP products in Denmark, and whether heavy duty or light duty products have the greater shares could give more robust results. Furthermore it should be considered that functionality might change between SUP and SUNP products, and if this should lead to additional consumption of SUNP products to make up for this difference it could reverse the findings.

Moreover, it is important to keep in mind, that using biomass as raw material for the SUNP products can also have environmental impacts, due to the indirect land use changes that their procurement can include. This stresses the fact that non-plastic options can be problematic as well.

List of Abbriviations

Impact Categories

CC	Climate change
OD	Ozone depletion
HTC	Human toxicity, cancer effects
HTNC	Human toxicity, non-cancer effects
POF	Photochemical ozone formation
IR	Ionizing radiation
PM	Particulate matter
TA	Terrestrial acidification
TE	Terrestrial eutrophication
EM	Marine eutrophication
FE	Freshwater eutrophication
ET	Freshwater Ecotoxicity
RD fos	Resource depletion, fossil
RD ele	Resource depletion, abiotic

General

EOL	End-of-life (as: “treatment”, “waste management” or “disposal”)
EC	European Commission
FU	Functional Unit
iLUC	Indirect Land Use Changes
EC-JRC	European Commission-Joint Research Program
ILCD	International reference Life Cycle Data system
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle impact Assessment
SUP	Singe Use Plastic
SUNP	Single Use Non Plastic
WtE	Waste-to-Energy
WM	Waste Management

1. Introduction

This study was commissioned by the Danish Environmental Protection Agency (Miljøstyrelsen) in order to assess the environmental impacts of the production and disposal of a range of Single Use Plastic Products (SUP) and their Single Use Non Plastic (SUNP) alternatives.

1.1 Background

The study was commissioned in order to assess a proposal by the European Commission (EC) (EC, 2018a), which aims to develop policies that could assist the reduction of marine littering in Europe. The proposal recommends the ban of specific SUP products, for which their role and spot in the market will instead be fulfilled by alternative SUNP products.

1.2 Objectives

The objective of this study is to assess the environmental impacts associated with the production and disposal of both the SUP products, which are proposed to be banned, and their SUNP alternatives. This is done to preventively identify any problematic environmental impacts that could arise with the increased use of the alternative products. To achieve that, the study assesses a range of potential environmental impacts by performing a Life Cycle Assessment (LCA).

1.3 LCA

An LCA is an ISO standardized method for quantifying the environmental impact of a product or a system during its lifespan, from “cradle” to “grave” (ISO, 2006a, 2006b). In the present study, the LCA focused on the *Production* and *Disposal Phase* of the life cycle of the product, excluding their *Use Phase* and *Transport* to the consumers. This exclusion is justified with the fact that significant impacts are not expected to occur during the *Use Phase* of these particular products. *Transport* to the consumer is not included, as it as determining these logistics[1] for each product would be associated with large uncertainty. The importance of these parameters will instead be examined in the sensitivity analysis.

The LCA will determine the environmental impact of all the products of interest, taking into account all the resources (material and energy) required for running the processes, as well as the emissions that those entail. In cases where resources are recovered (e.g. waste to energy and recycling), the system is credited for the saved impacts that those resources would involve, in case they had to be produced in a conventional way.

The LCA modelling was carried out in EASETECH, which is software for conducting LCAs, developed at the Technical University of Denmark (DTU) (Clavreul et al., 2014).

[1] The term logistics is intended here as the market of the supplying countries, the means of transportation and the distances of the transport for each of the products.

2. SUP Products & SUNP Alternative Products

The study assessed 5 SUP products and their 5 SUNP alternatives. The products studied as well as data describing materials and weights are indicated in an unpublished report by EC (2018b). Table 1 presents the SUP products and the proposed, non-plastic, replacement material.

Table 1: SUP products proposed to be banned, and their SUNP alternatives

Product	SUP material, proposed to banned	SUNP alternative material
Cotton Buds	Polypropylene (PP)	Paper
Cutlery	Polypropylene (PP)	Wood
Plates / Food Packaging Clamshell	Polystyrene (PS)	Paper
Straws	Polypropylene (PP)	Paper
Beverage Stirrers	Polypropylene (PP)	Wood

3. LCA Methodology

3.1 Goal Definition

The goal of this LCA is to provide the Danish Environmental Protection Agency with a quantitative overview of the potential changes in environmental impact that might arise with the replacement of SUP products by SUNP products. This involves identifying: 1) the impact categories that have significant impacts; 2) the impact categories where the SUNP alternatives are performing worse than SUP; 3) the processes that contribute to these impacts; and 4) key sensitivity parameters that can influence the findings in points 1-3.

3.2 Functional Unit

The functional unit is an important starting point of an LCA study and it represents the reference unit of the study. It defines the function of the studied system and it is used as a reference for the inputs and outputs of the study. This means that all inputs should be inserted to the model relative to the functional unit and subsequently the outputs are given per functional unit (ISO, 2006a). The geographical scope and the reference year of the study should also be included in the functional unit, as they are factors that could affect the results of a study.

The scope of the present study is to assess the impacts of 1 item of each of the single use products listed in Table 1produced in the global market and disposed in Denmark. Accounting for all the above, the Functional Unit (FU) is defined as:

"Production of 1 Single Use Plastic product and its Single Use Non Plastic product alternative globally, and their disposal in Denmark, in 2018 "

It is important to be aware that the weight of SUP and SUNP products is not the same, meaning that the results can only be compared on a functional unit basis and not on a weight basis.

3.3 System Boundaries & Modelling Approach

As already mentioned in the functional unit section (i.e. 3.2), the geographical scope of the study is the global market for the production, and Denmark for the disposal. The temporal scope is year 2018. The time horizon of the impacts in this LCA was 100 years

As far as the stages of the life cycle of the product are concerned, this study includes only the impacts from the production and the disposal or End-of-Life (EoL) phases. Neither the transport nor the use phases are included in the assessment: both phases are tacitly assumed to remain unaffected by the potential change from SUP to SUNP; as such, no changes in impacts are expected. While it is not expected that significant impacts are associated with the use phase, estimation of transport logistics and associated impacts are considered uncertain and beyond the scope of this project. A sensitivity scenario employing different transport distances will be presented in the sensitivity analysis section to consider the importance of this phase.

Figure 1 presents the life cycle stages of the products. The system boundaries of the study, meaning the limits of the processes included in the study, are indicated with a dashed line.

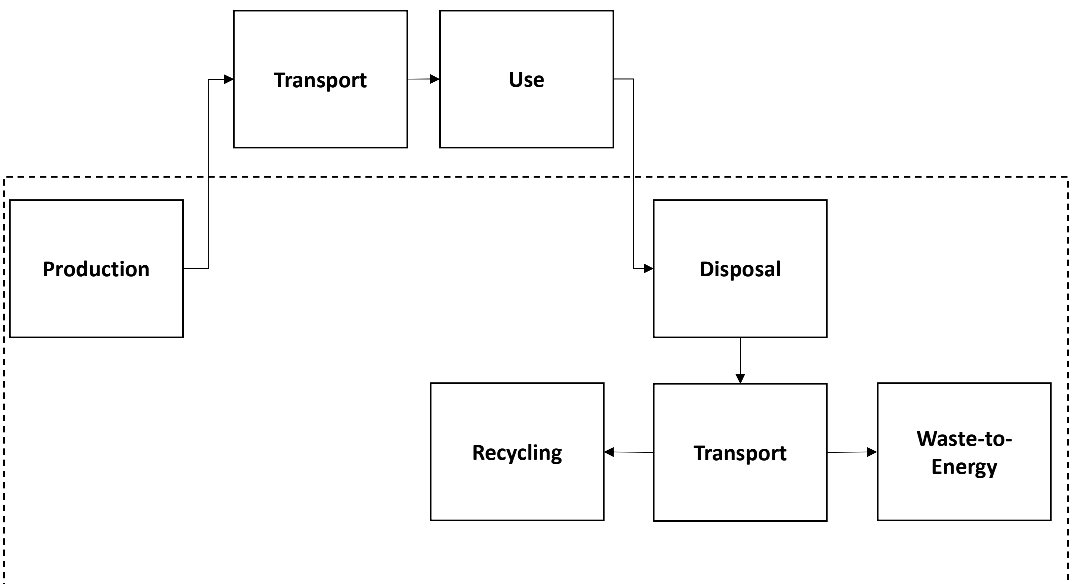


Figure 1: System boundaries. The dashed line indicates the processes included in the system

The multi-functionality of the system was addressed by using system expansion and most specifically the avoided burden approach (Finnveden et al., 2009). This means that secondary functions, i.e. functions generated in addition to the main functions of the studied systems, are assumed to displace conventional ways to produce the function in question. Thereby, the avoided burden of those processes is credited to the system as savings. A common example is the production of energy from a waste to energy plant. The main function is the waste treatment and the secondary function is the energy recovery. The energy recovered is displacing other means of energy production and therefore the avoided burdens from these means are subtracted from the impacts of the waste-to-energy plant.

This report uses a consequential approach for the modelling of the system, which is the same approach as the EC (2018) study, however results for attributional modelling will presented as a sensitivity analysis.

A consequential LCA, attempts to model a generic supply-chain based on how the market would theoretically respond to a decision (EC-JRC, 2010). In other words, the LCA models the changes in demand or supply of a technology/resource, as a result of a decision.

An attributional LCA on the other hand models a specific or average supply-chain and EoL value chain for the entire life cycle of a product in a static technosphere (EC-JRC, 2010). This means that this type of modelling tries to quantify the impacts of a life cycle of a product, by artificially isolating it from the rest of the economy, assuming it does not interact with other process. In addition, it means that it uses either producer specific data or mean market mix for the background processes (EC-JRC, 2010).

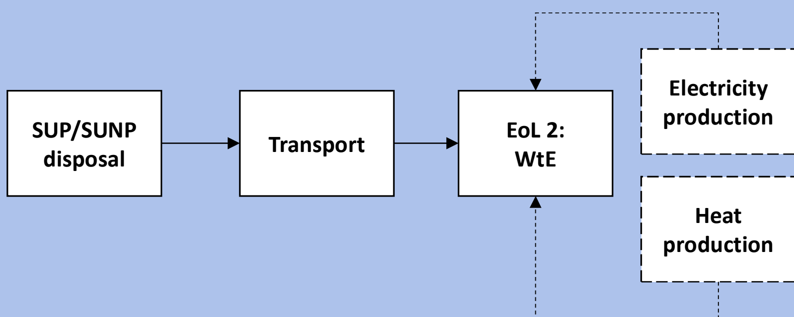
3.4 End-of-Life Scenarios

This study investigates two EoL scenarios, one based on recycling and the other based on Waste–to-Energy (i.e. Incineration). The description of the 2 scenarios is given below.

EOL 1: Recycling

EOL 2: Waste to Energy (WtE)

In this scenario, the SUP/SUNP products are disposed in the residual waste, which is then transported to a WtE facility. The electricity and heat produced during combustion substitute electricity production that would have been produced from other resources.



The EoL management scenarios for SUP products and their SUNP alternatives proposed in the EC report (EC, 2018b) are given in Table 2.

Table 2: Waste management options assumed by the EC (2018b) for the SUP products and their SUNP replacement.

MATERIAL	EOL	COTTON BUDS	CUTLERY	PLATES	STRAWS	STIRRERS
SUP	RECYCLING	1%	1%	5%	1%	0%
SUP	INCINERATION	99%	99%	95%	99%	100%
SUNP	RECYCLING	0%	90%	10%	10%	10%
SUNP	INCINERATION	100%	10%	90%	90%	90%

Compared to data provided by EC (2018b), some modifications were made in agreement with the commissioner. While for the SUP products, the values provided by EC were kept (same values as in Table 2), for SUNP products it is was assumed that they are sent for incineration entirely, as these products are currently not collected for recycling in Denmark. The reason for this is that, the EoL paper/wood products in this study (straws, plates) would most likely be contaminated with food/beverage residues and therefore not suitable for recycling. Therefore, it is assumed that SUNP are disposed in the residual waste, and thereby incinerated (

Table 3). The importance of the assumption that some plastics were recycled, were included in a sensitivity assessment where all plastics were sent for incineration.

Table 3: Waste management options assumed by this study for the SUP products and their SUNP replacement.

MATERIAL	EOL	COTTON BUDS	CUTLERY	PLATES	STRAWS	STIRRERS
SUP	RECYCLING	1%	1%	5%	0.6%	0%
SUP	INCINERATION	99%	99%	95%	99%	100%
SUNP	RECYCLING	0%	0%	0%	0%	0%
SUNP	INCINERATION	100%	100%	100%	100%	100%

3.5 Sensitivity Analysis

To investigate the importance of some of the assumptions decided with the commissioner on key parameters, six scenario sensitivity analyses were carried out. They aim to investigate variations in the results that could emerge from the alteration of specific scenario parameters. The changes were relevant to processes with high influence identified in the results chapter, or they are used to investigate extreme values for parameters that were uncertain. The scenario alterations are summarized below.

Scenario Sensitivity 1 (S1a to S1c): *Inclusion of transport of the products to the consumers*

In this scenario, we included transport of the products to the consumers for three different distances. Scenario ***S1a*** assumes a 100 kilometres transport distance, scenario ***S1b*** assumes 1000 kilometres and finally ***S1c*** assumes 5000 kilometres. For S1a and S1b road transfer is assumed while, for ***S1c*** we assumed transport via seaways.

Scenario Sensitivity 2 (S2a to S1c): *Extreme Energy Mix*

The energy substitution is proven to play an important role in scenarios where WtE is the management option, and thus it was considered potentially relevant also in this study. The first alteration concerned the electricity substitution. Instead of substituting the market for electricity in Denmark, we assume substitution of two extreme electricity mixes. In ***S2a***, we assume a marginal electricity which consists entirely of coal, and in ***S2b*** a mix that consists entirely of wind power. Scenario ***S2c*** concerns marginal heat. In this scenario, a marginal mix based entirely on wood biomass was assumed.

Scenario Sensitivity 3 (S3): *Attributional modeling approach*

This scenario models the system using the attributional LCA approach instead of the consequential.

Scenario Sensitivity 4 (S4): *Inclusion of indirect Land Use Changes (iLUC)*

This scenario models the system which included the iLUC caused by the use of biomass in the production of wood and paper products. The modelling of this alternative was based on Tonini et al. (2016)

Scenario Sensitivity 5 (S5): Clamshell as example of food container

This scenario models a five inch sandwich clamshell instead of a plate, as an example of a food container chosen in the EC (2018b) analysis. This scenario is modelled in two ways. Once, using an LCI based on data from Franklin and Associates (2006) as used in the EC (2018b) report, and once using processes from Ecoinvent v3.4 database. The SUP option for the clamshell is expandable PS, whereas the SUNP is paperboard.

Scenario Sensitivity 6 (S6): 100% Incineration of SUP products.
This scenario assumes all the SUP products are incinerated entirely i.e. the recycling rates are set to zero.

3.6 Modelling Tool

The modelling and calculation of the impacts in this study were carried out using EASETECH, a modelling tool developed at the environmental engineering department at DTU. EASETECH allows modelling of heterogeneous waste flows based on the physicochemical composition and gives the user the ability to keep track of mass and substances flow through the different processes, from the waste generation to their release to the environment (Clavreul et al., 2014). The user can modify all the processes parameters (e.g. plant efficiencies, emissions etc.) and physicochemical properties of the waste (heating value, heavy metal content etc.) in order to create a model that is tailored specifically to the studied system. Finally, it allows calculation of impacts based on standardized impact assessment methods that can be showed in regards to the substances or the processes of the system that contribute to them.

3.7 Data Requirements

It was beyond the scope of the project to collect, organize, and evaluate new data not readily available in existing databases. The commissioner requested that basis was taken in the EC (2018a and 2018b) reports, and readily available data for Danish waste management conditions.

The inventory data required for the LCA included:

- production of the raw materials that constitute the studied products;
- energy and emissions related to the manufacturing of the products themselves;
- average weights of individual products, as different masses are needed to obtain the same functionality from two items made from different raw material
- energy and emissions stemming from the waste management options. This aspect will, in some cases, be a function of the weight of individual items (see previous point).

In accordance with the EC (2018b) report, the study used data available in the Ecoinvent database, version 3.4.(Ecoinvent, 2018). For the manufacturing of the products, global market processes were used, whenever available, as it is assumed that products used in Denmark could be produced globally and not necessarily locally. The consequential version of the database was used; a detailed list of the inventory datasets can be found in Table 17 on Appendix A.

Data on the weight of products were obtained from the EC (2018b) report and from the online sources (Appendix B). The values from the EC report and data - on minimum, maximum and average weight calculated - can be found in Table 18 through Table 21 in Appendix A. Additional data on the material composition and on the waste management technologies were obtained from the library of the modelling tool, EASETECH or scientific articles, as specified in Table 16 in Appendix A. The models representing the EoL scenarios were also obtained from EASETECH; details can be found in Table 25.

3.8 Data Representativeness

The geographical scope of this study is Denmark; hence, data for energy requirements and EoL technologies representing the Danish situation were used. This excludes plastic recycling, which is assumed to take place in Germany, due to lack of plastic recycling facilities in Denmark. As far as the manufacturing of the products is concerned, global datasets were used, owing to the global nature of their procurement.

The most recent data available were used in order to increase the temporal representativeness of the study. Processes from Ecoinvent database represent 2018 data, and the newest EASETECH data for Denmark available were used.

3.9 Life Cycle Impact Assessment Methodology and Impact Categories

The impacts that will be calculated in this study are the International reference Life Cycle Data system (ILCD) recommended impacts (EC-JRC, 2011). The normalization references to be used are global based on the PROSUITE project (Laurent et al., 2013). The normalization references are provided in Person Equivalent (PE) at a global scale, which should be understood as a way to “translate” to the average impact induced by one person in the world.

Table 4 provides an overview of the different impact categories, their characterization model and their normalization reference.

Based on the results found, an assessment will be made of which impact categories that “stands out” as important. Importance will be determined as categories that clearly have values in person equivalents larger than zero, while also having impacts where there are clear differences between results for SUP and SUNP products.

Considering the toxicity categories it is recommended only to consider them if there are order of differences in magnitude between the results (Rosenbaum et al., 2008). The reason is that the characterization factors used to calculate the score of these impact categories are associated with significant uncertainty, meaning that it is typically advised to make conclusions only in those cases where differences of at least an order of magnitude between scenarios are estimated. They will therefore only be discussed if this is the case.

Table 4: Impact categories (EC-JRC, 2011) and normalization references (Laurent et al., 2013)of the chosen Life Cycle Impact Assessment (LCIA) method

Impact category	Acronyms	Characterization model	Indicator	Normalization Reference Global	Unit for NR
Climate change	CC	Baseline model of 100 years of the IPCC (Forster et al., 2007). Modelled as in Recipe 2008.	Radiative forcing as global warming potential (GWP100)	8.10E+03	kg CO2 eq./PE/year
Stratospheric ozone depletion	OD	Steady-state ODPs from the WMO assessment (latest WMO published ODP equivalents)	Ozone depletion potential (ODP)	4.14E-02	kg CFC-11 eq. /PE/year
Human toxicity, cancer effects	HTC	USEtox model v.1.01 (Rosenbaum et al., 2008)	Comparative toxic unit for humans (CTUh)	5.42E-05	CTUh/PE/year
Human toxicity, non-cancer effects	HTNC	USEtox model v.1.01 (Rosenbaum et al., 2008)	Comparative toxic unit for humans (CTUh)	1.10E-03	CTUh/PE/year
Particulate matter/respiratory inorganics	PM	Compilation in Humbert, 2009 based on Rabl and Spadaro, 2004 and Greco et al., 2007	Intake fraction for fine particles (kg PM2.5-eq/kg) – PM2.5eq	2.76E+00	kg PM2.5 eq. /PE/year
Ionizing radiation, human health	IR	Human health effect model as developed by Dreicer et al. (1995) (ref. Frischknecht et al. 2000) Modelled as in Recipe 2008	Human exposure efficiency relative to U235	1.33E+03	kBq U235 eq. (to air) /PE/year
Photochemical ozone formation	POF	LOTOS-EUROS (van Zelm et al., 2008) as applied in ReCiPe 2008 v 1.05	Tropospheric ozone concentration increase	5.67E+01	kg NMVOC eq. /PE/year
Acidification	TA	Accumulated exceedance (Posch et al., 2008; Seppälä et al., 2006)	Accumulated exceedance (AE)	4.96E+01	mol H+ eq. /PE/year
Eutrophication, terrestrial	TE	Accumulated exceedance (Posch et al., 2008; Seppälä et al., 2006)	Accumulated exceedance (AE)	1.15E+02	mol N eq. /PE/year
Eutrophication, freshwater	FE	EUTREND model as implemented in ReCiPe.	Residence time of P in freshwater end compartment	6.20E-01	kg P eq. /PE/year
Eutrophication, marine	ME	EUTREND model as implemented in ReCiPe	Residence time of N in marine end compartment	9.38E+00	kg N eq. /PE/year
Freshwater Ecotoxicity	ET	USEtox model v.1.01 (Rosenbaum et al., 2008)	Comparative toxic unit for ecosystems (CTUe)	6.65E+02	CTUe/PE/year
Resource depletion, fossil	RDfos	(van Oers et al., 2002)	Scarcity (MJ)	6.24E+04	MJ/PE/year
Resource depletion, mineral	RDele	(van Oers et al., 2002)	Scarcity (kg Sb eq.)	0.0343	kg Sb eq. /PE/year

3.10 Assumptions and Cut-offs

As a pre-requisite for the project, a range of assumptions and cut-offs were decided and applied to the project. The present study employs the following assumptions and cut-offs:

Assumptions in common with EC (2018b)***:***

- The study only addresses differences in materials used for the product, and does not consider changes in functionality or customer preferences between SUP and SUNP products.
- For the manufacturing of the products, global market processes were used whenever possible, and they were sourced from Ecoinvent v 3.4 database (Ecoinvent, 2018). The processes were chosen in accordance with the EC report and are global, market processes. A detailed list of inventory datasets is provided in Table 17 in the Appendix.
- Biodegradable plastics were excluded as the conditions of for their complete biodegradability might not be met in a marine environment, and avoiding the generation of microplastics is included in the scope of the proposal, (EC, 2018b).

Other specific assumptions:

- Multi-use (MU) products are always considered environmentally better than single-use products, and they are hence not included in the results. A rough screening was included to consider this in Appendix C.
- The marginal electricity for the various EOL technologies in Denmark was retrieved from Ecoinvent v 3.4 database (Ecoinvent, 2018). The process represents the market for high voltage electricity for Denmark. The marginal heat is on the other hand not available in Ecoinvent, and was therefore sourced from Miljøprojekt 1458 (Jensen et al., 2013). Details about the specific datasets are provided in Table 26 in Appendix A.
- Physicochemical properties (e.g. heating value, carbon content) for the various materials were acquired from the literature (Götze et al., 2016).
- "Food containers" was stated among the products proposed to be banned in the EC proposal (EC, 2018a). As example, this category included plates and clamshells. In this study we used plates as a baseline, and considered clamshells in the sensitivity analysis.
- ***Cut-offs:***
  As this is a comparative LCA, processes that are identical across all scenarios can be excluded. More specifically, in this report:
    - For cotton buds, we do not include cotton, as this would have the same impact independently of the material used as a support.
    - Collection of the waste is not included, as it often does not depend on the weight of the waste, but more on the waste type, collection scheme and truck type (Larsen et al., 2009). Assuming that the SUP and SUNP are similar and with comparable EoL collection schemes, the resulting potential impacts from this stage are supposed to be similar, thereby not significantly influencing the comparison and ranking of scenarios.

4. Results and Interpretation

The normalized potential impacts, expressed in person equivalent, for all the products and all impact categories mentioned in

Table 4 are illustrated in Figure 2 through Figure 6.

Based on the results illustrated in Figures 2-6, and the assessment approach described in section 3.9 the following impact categories were identified as relevant for further discussion: Climate Change (CC), Particular Matter formation (PM), Resource Depletion fossil (RD fos), Resource Depletion Elements (RD el).

Human Toxicity Cancer (HTC), Human Toxicity non Cancer (HTNC) and Ecotoxicity (ET) was not included due to the high uncertainty as described in section 3.9.

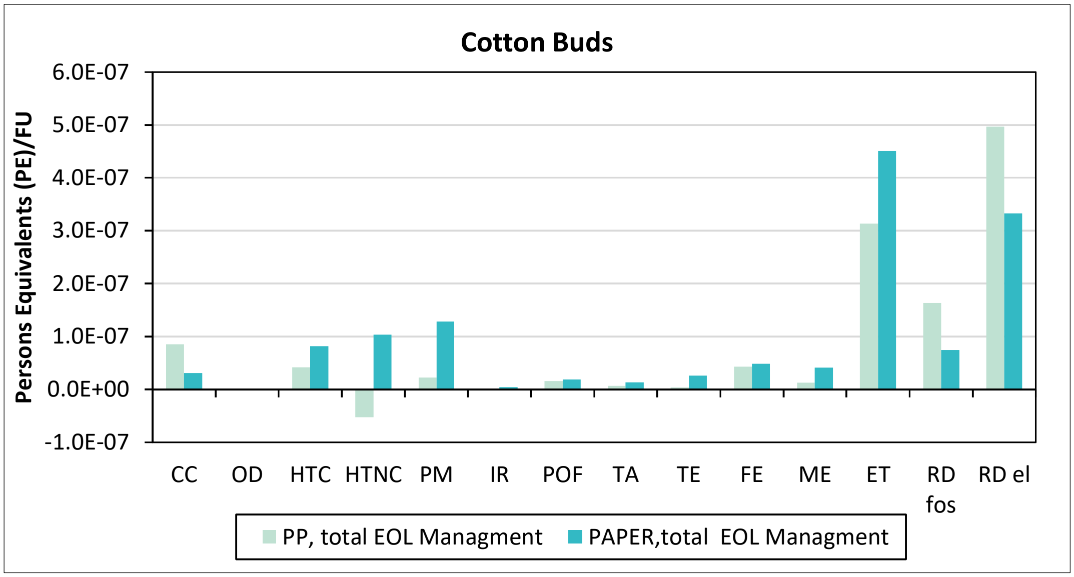


Figure 2: Normalized potential impacts for one average weight cotton bud made out of PP (SUP) and one from paper (SUNP). Acronyms for impact categories are explained in

Table 4.

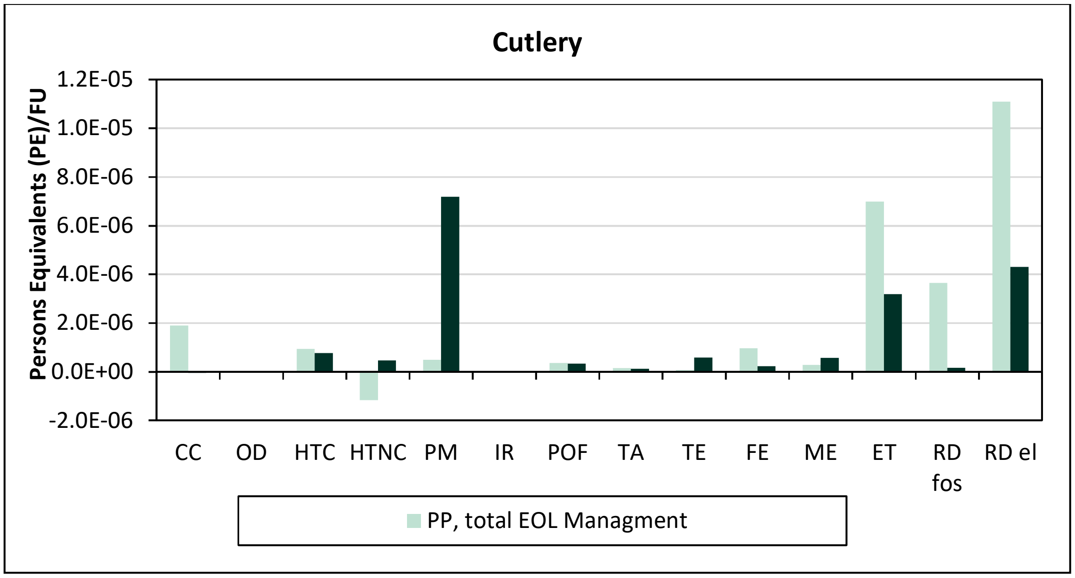


Figure 3: Normalized potential impacts for one average weight cutlery made out of PP (SUP) and one from wood (SUNP). Acronyms for impact categories are explained in

Table 4.

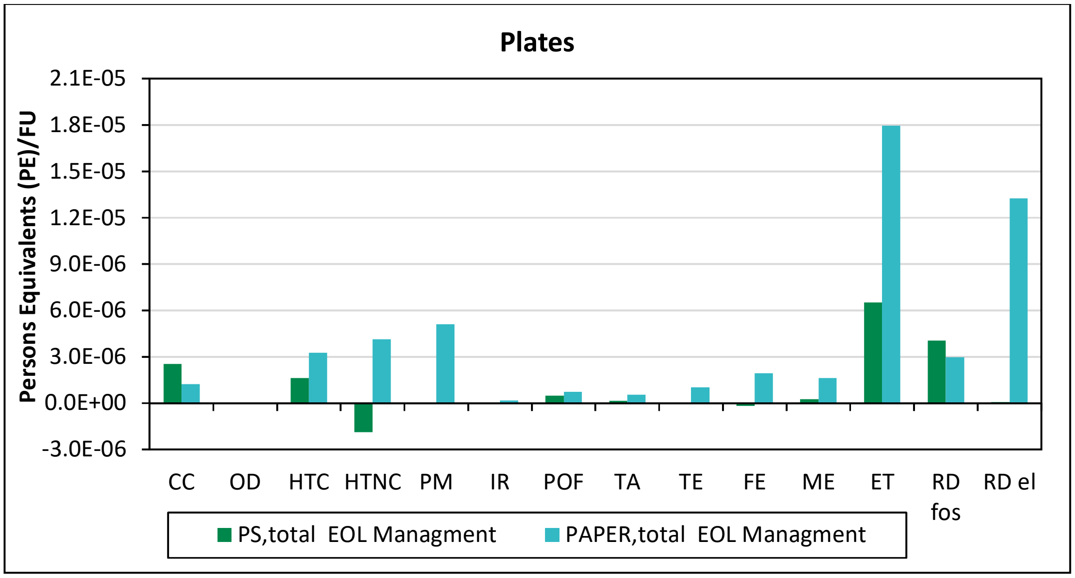


Figure 4: Normalized potential impacts for one average weight plate made out of PS (SUP) and one from paper (SUNP). Acronyms for impact categories are explained in

Table 4.

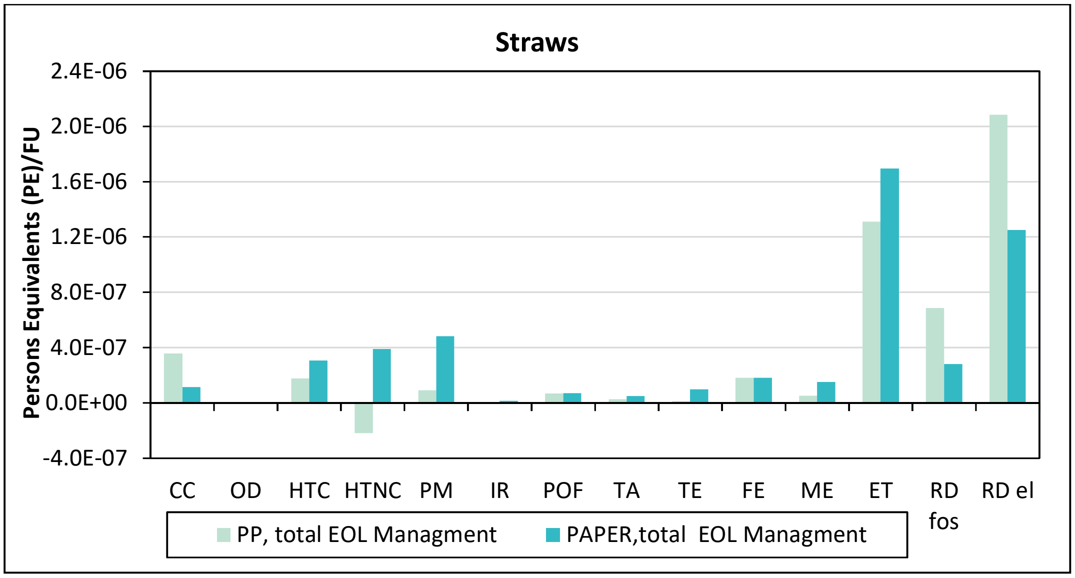


Figure 5: Normalized potential impacts for one average weight straw made out of PP (SUP) and one from paper (SUNP). Acronyms for impact categories are explained in

Table 4.

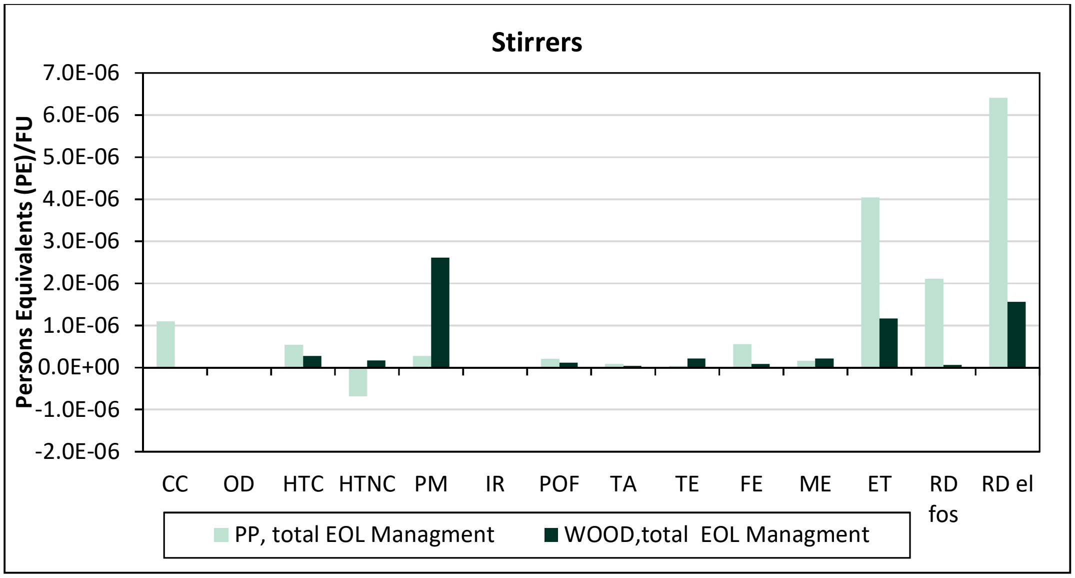


Figure 6: Normalized potential impacts for one average weight stirrer made out of PP (SUP) and one from wood (SUNP). Acronyms for impact categories are explained in

Table 4.

The characterized results for all the products and for all the impact categories are presented in Table 5.

The results are presented for four different weights, in relation to the fact that the weight of the different products is uncertain (due to high variability within each product type) yet critical for the results' outcomes. The results presented are for the maximum (MAX), minimum (MIN), and average (AVERAGE) weight, calculated from data available, as well as the weight indicated by the European Commission (EC, 2018b).

The average SUP and SUNP option of each product are color-coded red or green, within each impact category. Green indicates the preferable option, while red indicates the least preferable option. For example, for cotton buds in Climate Change (CC), the average SUP option is red and the average SUNP option is green. This indicates that the SUNP option has lower impacts (or better environmental performance), and is therefore preferable for CC. The light grey shaded areas are categories that were not analyzed in-depth depth as explained above the figures.

Table 5: Characterized results per FU, for all products and all impact categories for the maximum (MAX), minimum (MIN), average weight (AVERAGE), EC given weight. The light grey impact categories are those not analyzed in depth. The average SUP an SUNP option of each product is color-coded red or green, within each impact category. Green indicates the preferable option, while red indicates the least preferable option. Acronyms for impact categories are explained in

Table 4.

WEIGHT	CC kg CO2 eq	OD kg CFC11 eq	HTC CTUh	HTNC CTUh	PM kgPM2.5 eq	IR kBq U235 eq	POF kg NMVOC	TA mol H+ eq	TE mol N eq	FE kg P eq	ME kg N eq	ET CTUe	RD fos MJ	RD kg Sb eq
COTTON BUDS,SUP														
MIN	6.7E-04	-8.6E-12	2.2E-12	-5.6E-11	5.8E-08	-1.5E-06	8.8E-07	3.1E-07	3.8E-07	2.6E-08	1.1E-07	2.0E-04	9.8E-03	1.6E-08
MAX	7.1E-04	-9.2E-12	2.3E-12	-5.9E-11	6.2E-08	-1.6E-06	9.4E-07	3.3E-07	4.1E-07	2.8E-08	1.2E-07	2.1E-04	1.1E-02	1.8E-08
AVERAGE	6.9E-04	-8.9E-12	2.3E-12	-5.7E-11	6.0E-08	-1.5E-06	9.1E-07	3.2E-07	4.0E-07	2.7E-08	1.2E-07	2.1E-04	1.0E-02	1.7E-08
EC	7.6E-04	-9.8E-12	2.5E-12	-6.3E-11	6.6E-08	-1.7E-06	1.0E-06	3.5E-07	4.3E-07	2.9E-08	1.3E-07	2.3E-04	1.1E-02	1.9E-08
COTTON BUDS,SUNP														
MIN	1.5E-04	2.0E-11	2.7E-12	6.9E-11	2.1E-07	3.3E-06	6.4E-07	4.0E-07	1.8E-06	1.8E-08	2.3E-07	1.8E-04	2.8E-03	6.9E-09
MAX	2.8E-04	3.8E-11	5.0E-12	1.3E-10	4.0E-07	6.3E-06	1.2E-06	7.5E-07	3.4E-06	3.4E-08	4.3E-07	3.4E-04	5.2E-03	1.3E-08
AVERAGE	2.5E-04	3.3E-11	4.4E-12	1.1E-10	3.5E-07	5.6E-06	1.1E-06	6.7E-07	3.0E-06	3.0E-08	3.8E-07	3.0E-04	4.7E-03	1.1E-08
EC	1.3E-04	1.8E-11	2.4E-12	6.1E-11	1.9E-07	3.0E-06	5.7E-07	3.6E-07	1.6E-06	1.6E-08	2.1E-07	1.6E-04	2.5E-03	6.1E-09
CUTLERY, SUP														
MIN	4.6E-03	-5.9E-11	1.5E-11	-3.8E-10	4.0E-07	-1.0E-05	6.1E-06	2.1E-06	2.6E-06	1.8E-07	7.8E-07	1.4E-03	6.8E-02	1.1E-07
MAX	5.2E-02	-6.8E-10	1.7E-10	-4.4E-09	4.6E-06	-1.1E-04	6.9E-05	2.4E-05	3.0E-05	2.0E-06	8.9E-06	1.6E-02	7.7E-01	1.3E-06
AVERAGE	1.5E-02	-2.0E-10	5.1E-11	-1.3E-09	1.3E-06	-3.4E-05	2.0E-05	7.2E-06	8.8E-06	6.0E-07	2.6E-06	4.7E-03	2.3E-01	3.8E-07
EC	1.2E-02	-1.5E-10	3.8E-11	-9.6E-10	1.0E-06	-2.5E-05	1.5E-05	5.4E-06	6.6E-06	4.5E-07	2.0E-06	3.5E-03	1.7E-01	2.9E-07
CUTLERY, SUNP														
MIN	-1.9E-04	-2.0E-11	1.7E-11	2.1E-10	8.2E-06	-1.6E-05	7.6E-06	2.4E-06	2.8E-05	6.0E-08	2.2E-06	8.7E-04	4.2E-03	6.1E-08
MAX	-6.6E-04	-6.6E-11	5.7E-11	7.0E-10	2.7E-05	-5.2E-05	2.5E-05	7.9E-06	9.3E-05	2.0E-07	7.4E-06	2.9E-03	1.4E-02	2.0E-07
AVERAGE	-4.7E-04	-4.8E-11	4.2E-11	5.1E-10	2.0E-05	-3.8E-05	1.9E-05	5.8E-06	6.8E-05	1.5E-07	5.4E-06	2.1E-03	1.0E-02	1.5E-07
EC	-5.4E-04	-5.5E-11	4.8E-11	5.9E-10	2.3E-05	-4.4E-05	2.1E-05	6.7E-06	7.8E-05	1.7E-07	6.2E-06	2.4E-03	1.2E-02	1.7E-07

Table 5 (continued): Characterized results per FU, for all products and all impact categories for the maximum (MAX), minimum (MIN), average weight (AVERAGE), EC given weight. The light grey impact categories are those not analyzed in depth. The average SUP an SUNP option of each product has been color-coded red or green, within each impact category. Green indicates the preferable option, while red indicates the least preferable option. Acronyms for impact categories are explained in

Table 4.

WEIGHT	CC kg CO2 eq	OD kg CFC11 eq	HTC CTUh	HTNC CTUh	PM kgPM2.5 eq	IR kBq U235 eq	POF kg NMVOC	TA mol H+ eq	TE mol N eq	FE kg P eq	ME kg N eq	ET CTUe	RD fos MJ	RD kg Sb eq
PLATES, SUP														
MIN	3.6E-03	-4.7E-11	1.2E-11	-3.0E-10	3.0E-07	-8.1E-06	4.7E-06	1.6E-06	2.0E-06	1.4E-07	6.0E-07	1.1E-03	5.3E-02	8.8E-08
MAX	2.2E-02	-2.9E-10	7.3E-11	-1.9E-09	1.9E-06	-5.0E-05	2.9E-05	1.0E-05	1.2E-05	8.6E-07	3.7E-06	6.7E-03	3.3E-01	5.5E-07
AVERAGE	8.9E-03	-1.2E-10	2.9E-11	-7.5E-10	7.6E-07	-2.0E-05	1.2E-05	4.0E-06	4.9E-06	3.4E-07	1.5E-06	2.7E-03	1.3E-01	2.2E-07
EC	2.7E-03	-3.5E-11	8.8E-12	-2.3E-10	2.3E-07	-6.0E-06	3.5E-06	1.2E-06	1.5E-06	1.0E-07	4.5E-07	8.1E-04	4.0E-02	6.6E-08
PLATES, SUNP														
MIN	-8.0E-05	-8.3E-12	7.1E-12	8.8E-11	3.4E-06	-6.5E-06	3.2E-06	9.9E-07	1.2E-05	2.5E-08	9.3E-07	3.6E-04	1.7E-03	2.5E-08
MAX	-2.6E-04	-2.6E-11	2.2E-11	2.7E-10	1.1E-05	-2.0E-05	9.9E-06	3.1E-06	3.6E-05	7.8E-08	2.9E-06	1.1E-03	5.4E-03	7.9E-08
AVERAGE	-1.7E-04	-1.8E-11	1.5E-11	1.9E-10	7.2E-06	-1.4E-05	6.7E-06	2.1E-06	2.5E-05	5.3E-08	2.0E-06	7.7E-04	3.7E-03	5.4E-08
EC	-3.4E-04	-3.5E-11	3.0E-11	3.7E-10	1.4E-05	-2.8E-05	1.3E-05	4.2E-06	4.9E-05	1.1E-07	4.0E-06	1.5E-03	7.4E-03	1.1E-07
STRAWS, SUP														
MIN	2.2E-03	-2.9E-11	7.2E-12	-1.9E-10	1.9E-07	-5.0E-06	2.9E-06	9.9E-07	1.2E-06	8.5E-08	3.7E-07	6.6E-04	3.2E-02	5.4E-08
MAX	4.3E-03	-5.6E-11	1.4E-11	-3.6E-10	3.7E-07	-9.7E-06	5.7E-06	1.9E-06	2.4E-06	1.7E-07	7.2E-07	1.3E-03	6.3E-02	1.1E-07
AVERAGE	2.9E-03	-3.8E-11	9.5E-12	-2.4E-10	2.5E-07	-6.4E-06	3.8E-06	1.3E-06	1.6E-06	1.1E-07	4.9E-07	8.7E-04	4.3E-02	7.1E-08
EC	1.8E-03	-2.3E-11	5.9E-12	-1.5E-10	1.5E-07	-4.0E-06	2.4E-06	8.1E-07	9.8E-07	6.9E-08	3.0E-07	5.4E-04	2.6E-02	4.4E-08
STRAWS, SUNP														
MIN	9.1E-04	1.2E-10	1.6E-11	4.1E-10	1.3E-06	2.0E-05	3.9E-06	2.4E-06	1.1E-05	1.1E-07	1.4E-06	1.1E-03	1.7E-02	4.1E-08
MAX	9.7E-04	1.3E-10	1.7E-11	4.4E-10	1.4E-06	2.1E-05	4.1E-06	2.6E-06	1.2E-05	1.2E-07	1.5E-06	1.2E-03	1.8E-02	4.4E-08
AVERAGE	9.4E-04	1.3E-10	1.7E-11	4.3E-10	1.3E-06	2.1E-05	4.0E-06	2.5E-06	1.1E-05	1.1E-07	1.4E-06	1.1E-03	1.8E-02	4.3E-08
EC	6.3E-04	8.5E-11	1.1E-11	2.9E-10	9.0E-07	1.4E-05	2.7E-06	1.7E-06	7.6E-06	7.6E-08	9.7E-07	7.6E-04	1.2E-02	2.9E-08

Table 5 (continued): Characterized results per FU, for all products and all impact categories for the maximum (MAX), minimum (MIN), average weight (AVERAGE), EC given weight. The light grey impact categories are those not analyzed in depth. The average SUP an SUNP option of each product has been color-coded red or green, within each impact category. Green indicates the preferable option while red indicates the least preferable option. Acronyms for impact categories are explained in

Table 4.

WEIGHT	CC kg CO2 eq	OD kg CFC11 eq	HTC CTUh	HTNC CTUh	PM kgPM2.5 eq	IR kBq U235 eq	POF kg NMVOC	TA mol H+ eq	TE mol N eq	FE kg P eq	ME kg N eq	ET CTUe	RD fos MJ	RD kg Sb eq
STIRRERS, SUP														
MIN	3.6E-03	-4.7E-11	1.2E-11	-3.0E-10	3.0E-07	-8.1E-06	4.7E-06	1.6E-06	2.0E-06	1.4E-07	6.0E-07	1.1E-03	5.3E-02	8.8E-08
MAX	2.2E-02	-2.9E-10	7.3E-11	-1.9E-09	1.9E-06	-5.0E-05	2.9E-05	1.0E-05	1.2E-05	8.6E-07	3.7E-06	6.7E-03	3.3E-01	5.5E-07
AVERAGE	8.9E-03	-1.2E-10	2.9E-11	-7.5E-10	7.6E-07	-2.0E-05	1.2E-05	4.0E-06	4.9E-06	3.4E-07	1.5E-06	2.7E-03	1.3E-01	2.2E-07
EC	2.7E-03	-3.5E-11	8.8E-12	-2.3E-10	2.3E-07	-6.0E-06	3.5E-06	1.2E-06	1.5E-06	1.0E-07	4.5E-07	8.1E-04	4.0E-02	6.6E-08
STIRRERS, SUNP														
MIN	-8.0E-05	-8.3E-12	7.1E-12	8.8E-11	3.4E-06	-6.5E-06	3.2E-06	9.9E-07	1.2E-05	2.5E-08	9.3E-07	3.6E-04	1.7E-03	2.5E-08
MAX	-2.6E-04	-2.6E-11	2.2E-11	2.7E-10	1.1E-05	-2.0E-05	9.9E-06	3.1E-06	3.6E-05	7.8E-08	2.9E-06	1.1E-03	5.4E-03	7.9E-08
AVERAGE	-1.7E-04	-1.8E-11	1.5E-11	1.9E-10	7.2E-06	-1.4E-05	6.7E-06	2.1E-06	2.5E-05	5.3E-08	2.0E-06	7.7E-04	3.7E-03	5.4E-08
EC	-3.4E-04	-3.5E-11	3.0E-11	3.7E-10	1.4E-05	-2.8E-05	1.3E-05	4.2E-06	4.9E-05	1.1E-07	4.0E-06	1.5E-03	7.4E-03	1.1E-07

For the impact categories analyzed in depth, a visual representation of the results containing error bars for the maximum and minimum potential impact (based on the minimum and maximum weigh), can be seen in Appendix A.

A summary of the results for individual products is provided in Table 6 through Table 10. Only the impact categories chosen to be examined further are included in these tables. The second column states whether the most preferable option is the plastic based (SUP) or the non-plastic based (SUNP).

Considering the results for the full range of weights for each product (Table 5), in some cases, the SUNP and SUP results overlap, meaning that both products could be the best option, depending on their weight. When the results overlap (e.g. for cutlery, Table 7), both SUNP and SUP are given. The first product (in black) is indicating the best option considering the average weight of the products. The second product (in red after a slash) represents the case where the choice of a different weight combination could lead to the opposite conclusion (e.g. minimum weight for SUP and maximum weight for SUNP). If the results do not overlap, and one alternative is clearly better than the other independently of the weight range, only one option is stated. The last two columns present extreme cases, by choosing min/max weights so either SUP or SUNP becomes the best option if possible. This is done in order to highlight that the weight can determine if one product is better than the other. So across the impact categories we identified the cases where choosing another weight than the average (min or max) would change the preferred product.

Based on these results, some main conclusions can be drawn:

- For cotton buds, the SUNP option performs better in comparison to SUP in all cases (Table 6). Hence, replacement of this product is advisable.
- For cutlery, the SUNP option performs better or at least the same in comparison to SUP in all cases (Table 7). Hence, replacement of this product is advisable.
- For plates, the SUP option is preferable or at least comparable to the SUNP option (Table 8. Therefore, replacement of plates is not the best option.
- For straws, the SUNP option performs better in comparison to SUP (Table 9). Hence, replacement this product is advisable.
- For Stirrers, the SUNP option performs better in comparison to SUP (Table 10). Hence, replacement of this product is advisable.

Table 6: Summary of results for cotton buds.

COTTON BUDS RESULTS SUMMARY				
	PREFERABLE	**MATERIAL**	**SUNP BEST CASE**	**SUNP WORST CASE**
CLIMATE CHANGE	SUNP	PAPER	SUNP	SUNP
PARTICULAR MATTER FORMATION	SUP	PP	SUP	SUP
RESOURCE DEPLETION FOSSIL	SUNP	PAPER	SUNP	SUNP
RESOURCE DEPLETION ELEMENTS	SUNP	PAPER	SUNP	SUNP
PREFERABLE OVERALL	**SUNP***	**PAPER**	**SUNP**	**SUNP**

* performs the same or better for all weights

Table 7: Summary of results for cutlery.

CUTLERY RESULTS SUMMARY				
	PREFERABLE	**MATERIAL**	**SUNP BEST CASE**	**SUNP WORST CASE**
CLIMATE CHANGE	SUNP	WOOD	SUNP	SUNP
PARTICULAR MATTER FORMATION	SUP/SUNP	PP/WOOD	SUNP	SUP
RESOURCE DEPLETION FOSSIL	SUNP	WOOD	SUNP	SUNP
RESOURCE DEPLETION ELEMENTS	SUNP/SUP	WOOD/PP	SUNP	SUP
PREFERABLE OVERALL	**SUNP***	**WOOD**	**SUNP**	**SAME**

* performs the same or better for all weights

Table 8: Summary of results for plates.

PLATES RESULTS SUMMARY				
	PREFERABLE	**MATERIAL**	**SUNP BEST CASE**	**SUNP WORST CASE**
CLIMATE CHANGE	SUNP/SUP	PAPER/PS	SUNP	SUP
PARTICULAR MATTER FORMATION	SUP	PS	SUP	SUP
RESOURCE DEPLETION FOSSIL	SUNP/SUP	PAPER/PS	SUNP	SUP
RESOURCE DEPLETION ELEMENTS	SUP	PS	SUP	SUP
PREFERABLE OVERALL	SUP*	PS	SAME	SUP

* performs the same or better for all weights

Table 9: Summary of results for straws.

STRAWS RESULTS SUMMARY				
	PREFERABLE	**MATERIAL**	**SUNP BEST CASE**	**SUNP WORST CASE**
CLIMATE CHANGE	SUNP	PAPER	SUNP	SUNP
PARTICULAR MATTER FORMATION	SUP	PP	SUP	SUP
RESOURCE DEPLETION FOSSIL	SUNP	PAPER	SUNP	SUNP
RESOURCE DEPLETION ELEMENTS	SUNP	PAPER	SUNP	SUNP
PREFERABLE OVERALL	SUNP*	PAPER	SUNP	SUNP

* performs the same or better for all weights

Table 10: Summary of results for stirrers.

STIRRERS RESULTS SUMMARY				
	PREFERABLE	**MATERIAL**	**SUNP BEST CASE**	**SUNP WORST CASE**
CLIMATE CHANGE	SUNP	WOOD	SUNP	SUNP
PARTICULAR MATTER FORMATION	SUP	PP	SUP	SUP
RESOURCE DEPLETION FOSSIL	SUNP	WOOD	SUNP	SUNP
RESOURCE DEPLETION ELEMENTS	SUNP	WOOD	SUNP	SUNP
PREFERABLE OVERALL	SUNP*	WOOD	SUNP	SUNP

* performs the same or better for all weights

5. Sensitivity Analysis

In the following sections, the results of the sensitivity analysis are described. It should be noted that only the cases where the results are influenced significantly and/or the ranking between SUP and SUNP was changed are presented.

5.1 Scenario Sensitivity 1

In this sensitivity scenario, the transport of the products to the final user was included. The addition of the transportation increased the total impacts of the products. Nonetheless, in none of the cases (i.e. 100, 1000 or 5000 kilometers transport distance) this addition resulted in a shift of the ranking between SUP and SUNP alternatives. This means that the inclusion of transportation in the calculation does not affect the conclusions for any of products and for any of the impact categories. The results for each of the scenarios S1a, S1b and S1c are presented in Table 27 through Table 29 in Appendix A.3.

5.2 Scenario Sensitivity 2

In Scenario S2a, the electricity mix was changed to 100% wind power. The change in electricity mix influenced the ranking for only 2 products, namely cutlery and stirrers. For cutlery (Figure 7), a change in ranking is seen for the impact categories Ionizing Radiation (IR), Photochemical Ozone Formation (POF) and Terrestrial Acidification (TA), where now SUP products are more favorable than SUNP. For stirrers (Figure 8), the ranking of Photochemical Ozone Formation (POF) and Terrestrial Acidification (TA) shifted to favor SUP as well. The values for these impact categories affected by the change in electricity mix are relatively low compared to the rest of the categories, while no change in ranking was seen for the impact categories with relatively high values. Hence, the overall recommendation of SUNP being preferable therefore does not change.

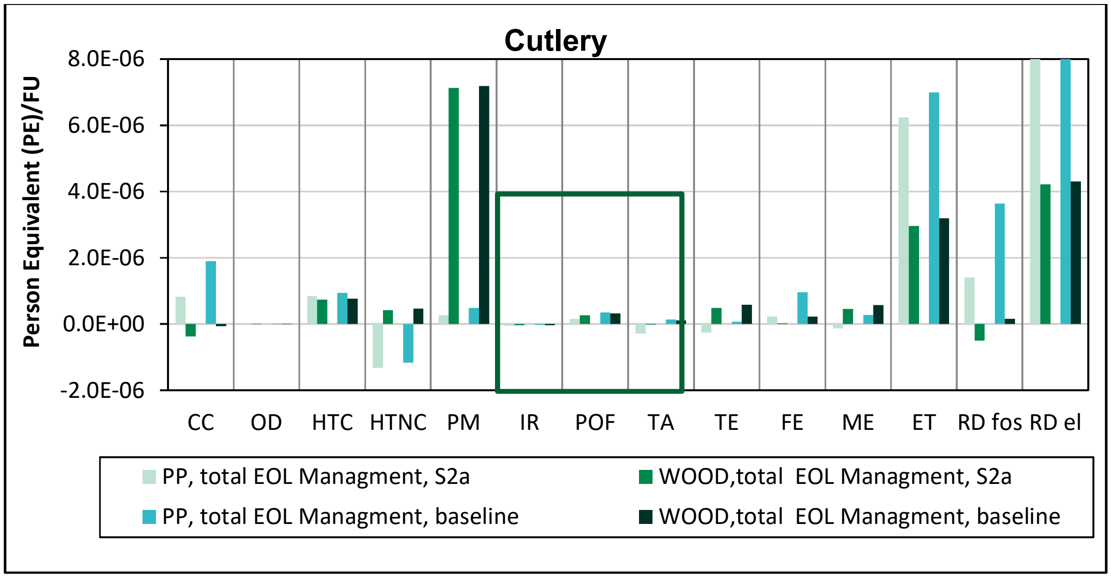


Figure 7: Normalized potential impacts for Scenario Sensitivity S2a (i.e. 100% electricity from wind) for *Cutlery*, in comparison to baseline results.

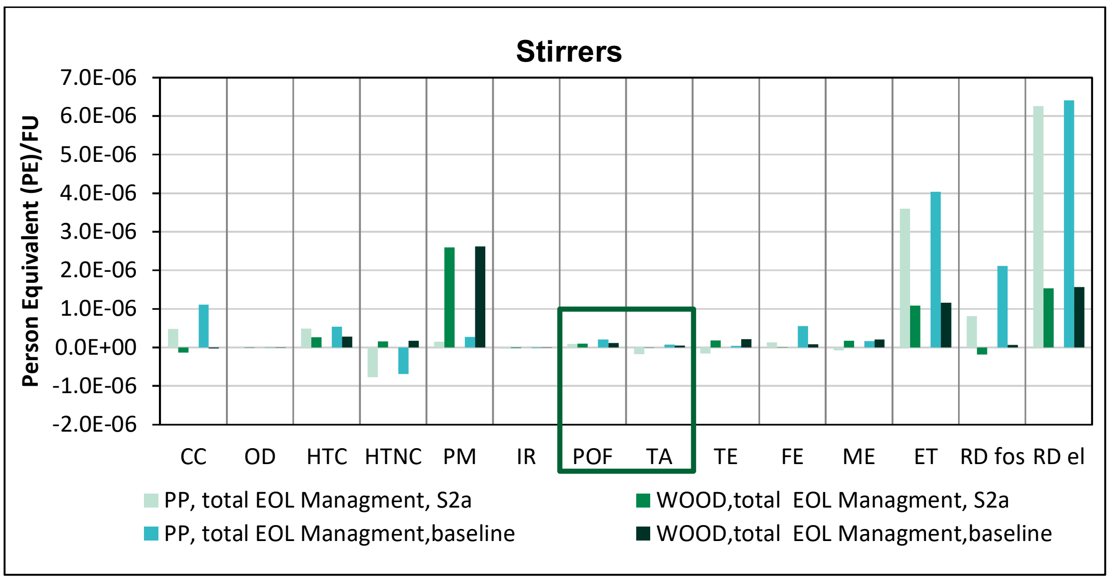


Figure 8: Normalized potential impacts for Scenario Sensitivity S2a (i.e. 100% electricity from wind) for *Stirrers*, in comparison to baseline results.

In S2b, the electricity mix was changed to consist of 100% electricity produced from hard coal. This resulted in a shift in the ranking only for straws and stirrers. For straws (Figure 9), the impact categories affected were Photochemical Ozone Formation (POF) and Freshwater Eutrophication (FE); the ranking was shifted to favor the SUNP option. For stirrers (Figure 10), the only impact category where shift in ranking was observed was Marine Eutrophication (ME), where the SUNP is now preferable to SUP. Hence, the overall recommendation of SUNP being preferable does not change.

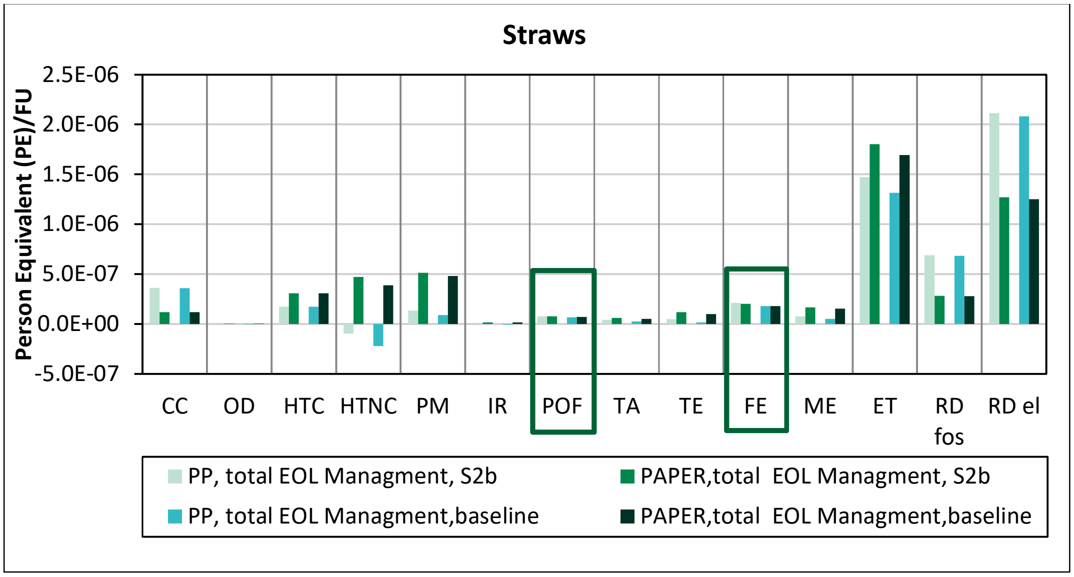


Figure 9: Normalized potential impacts for Scenario Sensitivity S2b (i.e. 100% electricity from hard coal) for *Straws*, in comparison to baseline results.

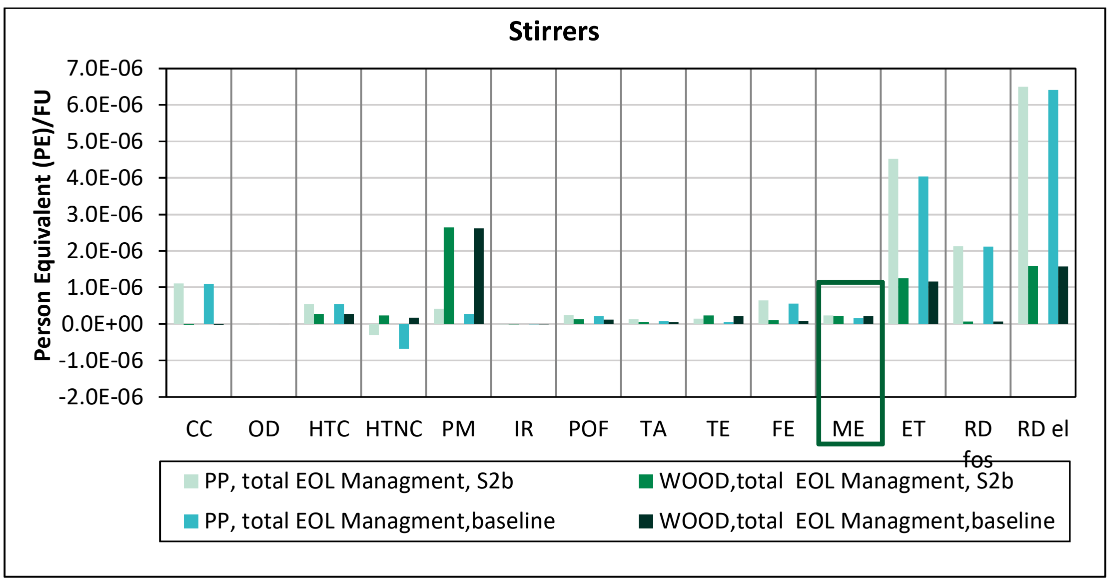


Figure 10: Normalized potential impacts for Scenario Sensitivity S2b (i.e. 100% electricity from hard coal) for *Stirrers*, in comparison to baseline results.

In scenario S2c, where the heat was assumed to be based 100% on wood, the ranking shifted for cutlery, straws and, stirrers. For cutlery (Figure 11), Ozone Depletion (OD) shifted to favor SUNP, while Human Toxicity Cancer (HTC), Ionizing Radiation (IR), and Ecotoxicity (ET) shifted to favor the SUP option. For straws (Figure 12) Ozone Formation (POF) and Terrestrial Acidification (TA), shifted to favor SUNP. For stirrers (Figure 13), Ozone Depletion (OD) and Marine Eutrophication (ME) shifted to favor SUNP, while for Human Toxicity Cancer (HTC) and Ecotoxicity (ET) SUP performs better. Hence, the overall recommendation of SUNP being preferable does not change.

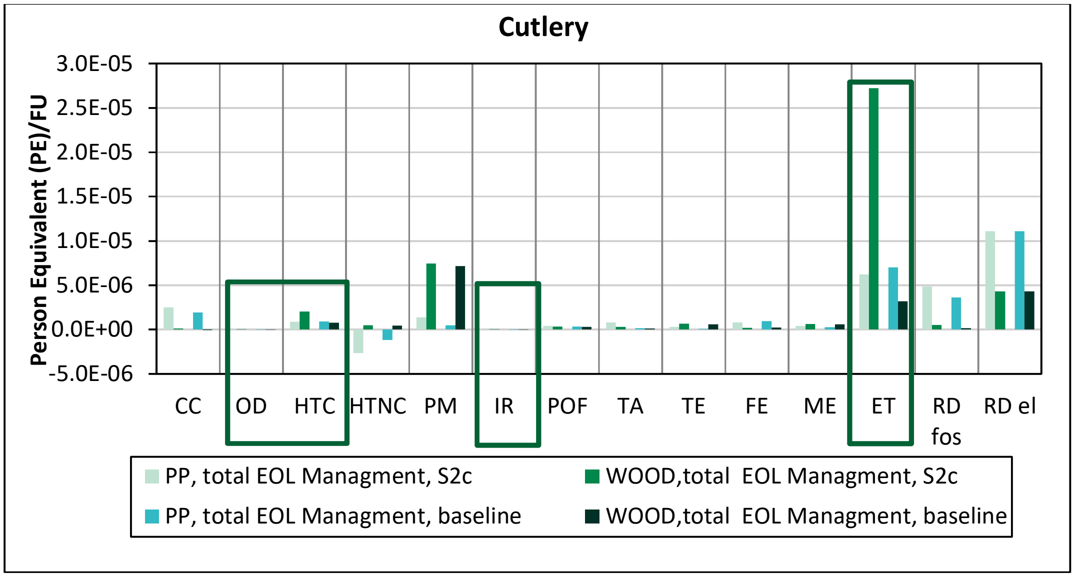


Figure 11: Normalized potential impacts for Scenario Sensitivity S2c (i.e. 100% heat from wood) for *Cutlery*, in comparison to baseline results.

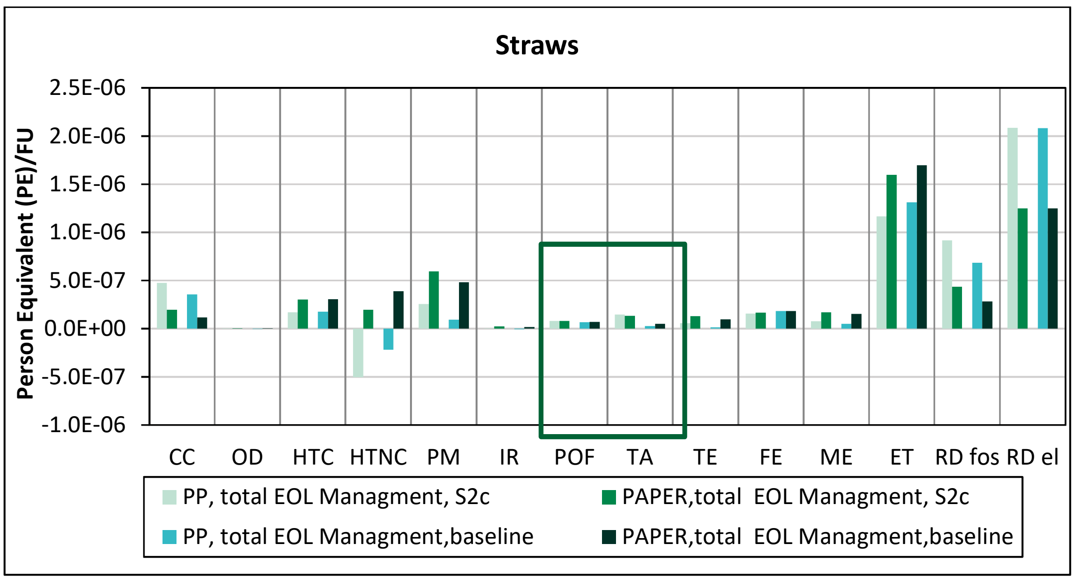


Figure 12: Normalized potential impacts for Scenario Sensitivity S2c (i.e. 100% heat from wood) for *Straws*, in comparison to baseline results.

The results for each of the scenarios S2a, S2b and S2c are presented in Table 30 through Table 32Table 29 in Appendix A.3

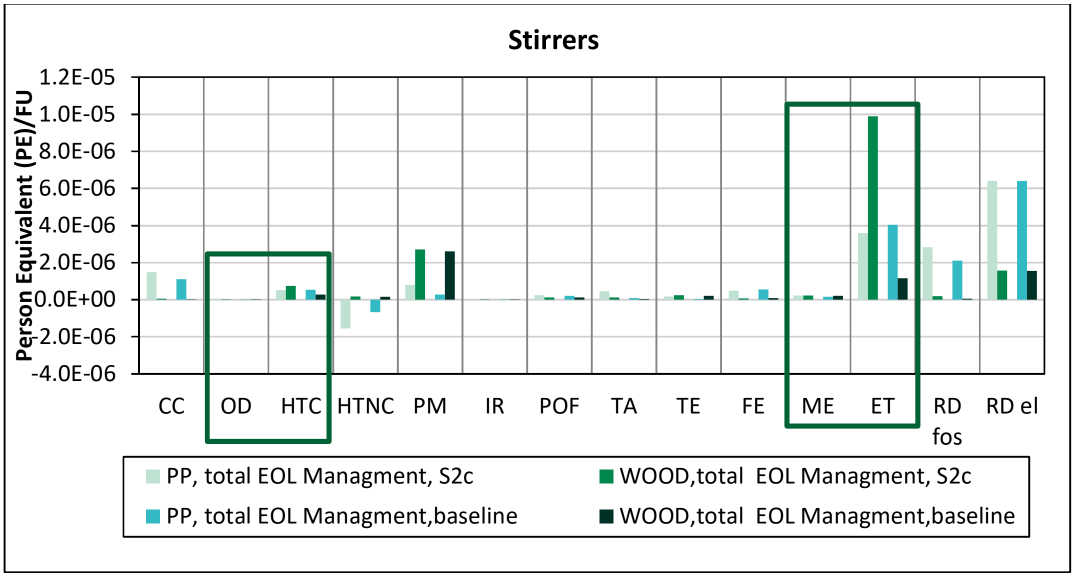


Figure 13: Normalized potential impacts for Scenario Sensitivity S2c (i.e. 100% heat from wood) for S*tirrers*, in comparison to baseline results.

5.3 Scenario Sensitivity 3

In scenario S3 all results were recalculated using an attributional modelling approach. For the average weight, a ranking shift occurred only for cutlery and stirrers. For cutlery, Ionizing Radiation (IR) shifted to favor the SUP option while for stirrers Marine Eutrophication (ME), shifted to favor the SUNP option. It should be mentioned though that final results are very close to each other, so the two options (i.e. SUP and SUNP) are practically identical for both IR and ME. When also considering the uncertainty related to the weight of the products, it was seen that the ranking of the products did not change for any of the assessed impact categories. Hence, the overall recommendation of SUNP being preferable does not change. The results are presented in Table 33Table 29 in Appendix A.3

5.4 Scenario Sensitivity 4

Scenario S4 included the impacts related to the indirect Land Use Changes (iLUC) occurring as a result of the procurement of the biomass needed for the production of wood and paper SUNP materials. The results of the Sensitivity Scenario 4 can be summarized as follows:

- For cotton buds (Table 11), there was a shift in ranking for three impact categories, namely, Climate Change, Resource Depletion fossil (RDfos) and Resource Depletion elements (RDel). Including the burdens from the iLUC for paper makes the SUP option more preferable in these categories.
- For cutlery (Table 12), the ranking is shifted in Human Toxicity Cancer (HTC), Ionizing Radiation (IR), Photochemical Ozone Formation (POF), Terrestrial Acidification (TA), where the SUP option is now more favorable.
- For plates (Table 13), the ranking is shifted for Climate Change (CC) and Resource Depletion, fossil (RDfos), where the SUP option is now more preferable.

- For straws (Table 14), there was a shift in ranking for Climate Change (CC), Resource Depletion, fossil (RDfos) and Resource Depletion, elements (RDel) categories, where SUP is now a more favorable option.
- For stirrers (Table 15), only Terrestrial Acidification (TA) and Photochemical Ozone Formation (POF) were influenced by the iLUC addition; for these categories, SUP is now more favorable than SUNP.

The above mentioned shifts were observed when comparing the average weight of the products. For the categories with relatively high impact, a comparison was performed accounting also for the weight uncertainty. The results of the sensitivity analysis including the weight uncertainty are summarized in Table 11 to Table 15, under "SUNP best case" and "SUNP worst case".

Table 11: Summary of results for cotton buds in scenario S4.

Cotton Buds, Scenario S4				
	PREFERABLE	**MATERIAL**	**SUNP BEST CASE**	**SUNP WORST CASE**
CLIMATE CHANGE	SUP/SUNP	PAPER	SUNP	SUP
PARTICULAR MATTER FORMATIO	SUP	PP	SUP	SUP
RESOURCE DEPLETION FOSSIL	SUNP	PAPER	SUNP	SUNP
RESOURCE DEPLETION ELEMENTS	SUP/SUNP	PP/PAPER	SUNP	SUP
PREFERABLE OVERALL	SUP**	PP	SUNP	SUP

**only for average weights

Table 12: Summary of results for cutlery in scenario S4.

Cutlery, Scenario S4				
	PREFERABLE	**MATERIAL**	**SUNP BEST CASE**	**SUNP WORST CASE**
CLIMATE CHANGE	SUNP/SUP	WOOD/PP	SUNP	SUP
PARTICULAR MATTER FORMATIO	SUP	PP	SUP	SUP
RESOURCE DEPLETION FOSSIL	SUNP	WOOD	SUNP	SUNP
RESOURCE DEPLETION ELEMENTS	SUNP/SUP	WOOD	SUNP	SUP
PREFERABLE OVERALL	SUNP**	WOOD	SUNP	SUP

**only for average weights

Table 13: Summary of results for plates in scenario S4.

Plates, Scenario S4				
	PREFERABLE	**MATERIAL**	**SUNP BEST CASE**	**SUNP WORST CASE**
CLIMATE CHANGE	SUP/SUNP	PS/PAPER	SUNP	SUNP
PARTICULAR MATTER FORMATIO	SUP	PS	SUP	SUP
RESOURCE DEPLETION FOSSIL	SUP/SUNP	PS/PAPER	SUNP	SUP
RESOURCE DEPLETION ELEMENTS	SUP	PS	SUP	SUP
PREFERABLE OVERALL	SUP**	PS	SAME	SUP

**only for average weights

Table 14: Summary of results for straws in scenario S4.

Straws, Scenario S4				
	PREFERABLE	**MATERIAL**	**SUNP BEST CASE**	**SUNP WORST CASE**
CLIMATE CHANGE	SUP/SUNP	PP	SUNP	SUNP
PARTICULAR MATTER FORMATIO	SUP	PP	SUP	SUP
RESOURCE DEPLETION FOSSIL	SUNP	PAPER	SUNP	SUNP
RESOURCE DEPLETION ELEMENTS	SUNP-SUP	PAPER-PP	SUNP	SUP
PREFERABLE OVERALL	SAME**	PAPER	SUNP	SAME

**only for average weights

Table 15: Results summary for stirrers in scenario S4.

STIRRERS, S4 SUMMARY RESULTS				
	PREFERABLE	**MATERIAL**	**SUNP BEST CASE**	**SUNP WORST CASE**
CLIMATE CHANGE	SUNP/SUP	WOOD	SUNP	SUP
PARTICULAR MATTER FORMATIO	SUP	PP	SUP	SUP
RESOURCE DEPLETION FOSSIL	SUNP	WOOD	SUNP	SUNP
RESOURCE DEPLETION ELEMENTS	SUNP/SUP	WOOD	SUNP	SUNP
PREFERABLE OVERALL	SUNP**	WOOD	SUNP	SUP

**only for average weights

From the results presented in the Table 11 through Table 15, when considering iLUC, it can be concluded that:

- For cotton buds, the SUP option becomes preferable, while in the baseline scenario the SUNP option was better, for all the weights.
- For straws, the SUNP option performs better or the same as the SUP option independently of weight.
- For plates, the conclusion remains the same for these categories, SUP is the preferred option.
- For cutlery and stirrers, SUNP is preferable, but only based on the average weight, while in the baseline the SUNP option was better or the same compared to the SUP throughout the whole weight range.

This highlights the importance of the sourcing of the biomass used for the SUNP products, and that they should if possible be based on residual biomass that currently is not used for anything.

The detailed results are presented in Table 34 in Appendix A.3.

5.5 Scenario Sensitivity 5

In the case of the five-inch clamshell sandwich packaging both modelling approaches (Ecoinvent and EC LCI) lead to the same conclusion: the SUP option is preferable to the SUNP option when considering either all impact categories or, only the ones with the highest relative impacts (CC, PM, ET, RD fos, RD ele). This is also in accordance with the conclusion for the average weight PS plates.

The outcomes are actually different when compared to the results in the EC (2018b) The difference in results between the two studies, could be due to the inclusion of the transportation of the products to the consumer. However, the values and processes associated with the transportation were not mentioned in the EC report (2018b), meaning that a further analysis is not possible.

The detailed results are presented in Table 35 in Appendix A.3.

5.6 Scenario Sensitivity 6

In this sensitivity scenario, the SUP all assumed to be incinerated entirely, instead of using the assumptions of

Table 3. Nonetheless, in none of the cases did this alteration result in a shift of the ranking between SUP and SUNP alternatives. This means that assuming plastics are not recycled is not affecting the conclusions. This was expected as the recycling rate was any way very low. The results for scenario S6 are presented in in Table 36 in Appendix A.3.

6. Conclusion

The study identified, on basis of normalized impacts, that the categories with the largest potential impacts were climate change, particulate matter formation, fossil resource depletion and element resource depletion. Considering those categories, the results lead to the following conclusions:

- **Cotton Buds**: Paper cotton buds (SUNP) performed in average better than plastic cotton buds made out of polypropylene (SUP) in the baseline scenario, as well as in all sensitivity scenarios, with the exception of scenario S4. In scenario S4, which considered the indirect land use changes (iLUC) from paper production, the polypropylene option performed better.
- **Cutlery**: Wooden cutlery (SUNP) performed in average better or at least at the same level as plastic cutlery (SUP) made out of polypropylene in the baseline scenario, as well as in all the sensitivity scenarios, with the exception of scenario S4. In scenario S4, which considered the iLUC from wood production, the preferable option depended on the weight of the products. Nevertheless, for an average weight, the non-plastic option was preferable.
- **Food Containers**: For food containers (plates or clamshell), the paper option (SUNP) was found to perform worse or at best the same as the polystyrene option (SUP) considering all the sensitivity scenarios assessed.
- **Straws**: The paper straws (SUNP option) were found to perform better or on the same level with polypropylene (PP) straw, in all the scenarios tested.
- **Stirrers**: The wooden stirrers performed in average better or at least the same as plastic stirrers (SUP) made out of polypropylene in the baseline scenario, as well as in all the sensitivity scenarios, with the exception of scenario S4. In this scenario S4, which considered the iLUC from wood production, the preferable option depended on the weight of the products. Nevertheless, for an average weight, the non-plastic option was preferable.

Based on the abovementioned, it can be concluded that the weight can play an important role. Therefore, the design of the SUP might matter more than the shift to SUNP, and it is important that a shift to SUNP will be to lighter SUNP products. To assess the proposed change further an overview of the market of SUP products in Denmark, and whether heavy duty or light duty products have the greater shares could give more robust results. Furthermore it should be considered that functionality might change between SUP and SUNP products, and if this should lead to additional consumption of SUNP products to make up for this difference it could reverse the findings.

Moreover, it is important to keep in mind, that using biomass as raw material for the SUNP products can also have environmental impacts, due to the indirect land use changes that their procurement can include. This stresses the fact that non-plastic options can be problematic as well.

7. References

Clavreul, J., Baumeister, H., Christensen, T.H., Damgaard, A., 2014. An environmental assessment system for environmental technologies. Environ. Model. Softw. 60, 18–30. https://doi.org/10.1016/j.envsoft.2014.06.007

COWI og Miljøstyrelsen, 2018. På Vej - Mod øget genanvendelse af husholdningaffald. Unpublished.

EC-JRC, 2011. International Reference Life Cycle Data System (ILCD) Handbook- Recommendations for Life Cycle Impact Assessment in the European context. Publications Office of the European Union, Luxemburg. https://doi.org/10.278/33030

EC-JRC, 2010. International Reference Life Cycle Data System (ILCD) Handbook -- General guide for Life Cycle Assessment -- Detailed guidance, Constraints. https://doi.org/10.2788/38479

EC, 2018a. Reducing Marine Litter: action on single use plastics and fishing gear Accompanying the document Proposal for a Directive of the European Parliament and of the Council on the reduction of the impact of certain plastic products on the environment.

EC, 2018b. Life Cycle Inventories of Single Use Plastic Products and their Alternatives Part of "Study to explore links between production, the environment and environmental policy". Unpublished.

Ecoinvent, 2018. Ecoinvent Version 3 [WWW Document]. URL https://www.ecoinvent.org/database/database.html

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Dorland, R. Van, 2007. Changes in Atmospheric Constituents and in Radiative Forcing., in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1103/PhysRevB.77.220407

Franklin and Assosiates, 2006. Foam, Life Cycle Inventory Of Polystyrene Bleached Paperboard, And Corrugated Paperboard Foodservice Products.

Götze, R., Pivnenko, K., Boldrin, A., Scheutz, C., Astrup, T.F., 2016. Physico-chemical characterisation of material fractions in residual and source-segregated household waste in Denmark. Waste Manag. 54, 13–26. https://doi.org/10.1016/j.wasman.2016.05.009

Greco, S.L., Wilson, A.M., Spengler, J.D., Levy, J.I., 2007. Spatial patterns of mobile source particulate matter emissions-to-exposure relationships across the United States. Atmos. Environ. 41, 1011–1025. https://doi.org/10.1016/j.atmosenv.2006.09.025

Humbert, S., 2009. Geographically Differentiated Life-cycle Impact Assessment of Human Health. University of California, Berkeley, Berkeley, California, USA.

ISO, 2006a. Environmental management - Life cycle assessment - Principles and framework -

ISO 14040.

ISO, 2006b. Environmental management - Life cycle assessment - Requirements and guidelines - ISO 14044.

Jensen, M.B., Kromann, M., Lund Neidel, T., Bjørn Jakobsen, J., Møller, J., 2013. Miljø- og samfundsøkonomisk vurdering af muligheder for øget genanvendelse af papir, pap, plast, metal og organisk affald fra dagrenovation, Miljøprojekt nr. 1458. https://doi.org/978-87-92903-80-8

Larsen, A.W., Vrgoc, M., Christensen, T.H., Lieberknecht, P., 2009. Diesel consumption in waste collection and transport and its environmental significance. Waste Manag. Res. 27, 652–659. https://doi.org/10.1177/0734242X08097636

Laurent, A., Hauschild, M.Z., Golsteijn, L., Simas, M., And, J.F., Wood, R., 2013. Deliverable 5.2: Normalisation factors for environmental, economic and socio-economic indicators. PROJECT: Development and application of a standardized methodology for the PROspective SUstaInability assessment of TEchnologies. Copenhagen, Denmark.

Montzka, S., Fraser, P., 1999. Controlled substances and other source gases. Chapter 2 in scientific assessment of ozone depletion: 1998, Global Ozone Research and Monitoring Project— report no. 44.

Posch, M., Seppälä, J., Hettelingh, J.P., Johansson, M., Margni, M., Jolliet, O., 2008. The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. Int. J. Life Cycle Assess. 13, 477–486. https://doi.org/10.1007/s11367-008-0025-9

Rabl, A., Spadaro, J., 2004. The RiskPoll software, version is 1.051 (dated August 2004).

Rosenbaum, R.K., Bachmann, T.M., Gold, L.S., Huijbregts, M.A.J., Jolliet, O., Juraske, R., Koehler, A., Larsen, H.F., MacLeod, M., Margni, M., McKone, T.E., Payet, J., Schuhmacher, M., Van De Meent, D., Hauschild, M.Z., 2008. USEtox - The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int. J. Life Cycle Assess. 13, 532–546. https://doi.org/10.1007/s11367-008-0038-4

Seppälä, J., Posch, M., Johansson, M., Hettelingh, J.-P., 2006. Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator. Int. J. Life Cycle Assess. 11, 403–416. https://doi.org/10.1065/lca2005.06.215

Tonini, D., Hamelin, L., Astrup, T.F., 2016. Environmental implications of the use of agro-industrial residues for biorefineries: application of a deterministic model for indirect land-use changes. GCB Bioenergy 8, 690–706. https://doi.org/10.1111/gcbb.12290

van Oers, L., Koning, A. De, Guinée, J.B., Huppes, G., 2002. Abiotic resource depletion in LCA, Road and Hydraulic Engineering Institute, Ministry of Transport and Water. Amsterdam.

van Zelm, R., Huijbregts, M.A.J., den Hollander, H.A., van Jaarsveld, H.A., Sauter, F.J., Struijs, J., van Wijnen, H.J., van de Meent, D., 2008. European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. Atmos. Environ. 42, 441–453. https://doi.org/10.1016/j.atmosenv.2007.09.072

8. Appendices

8.1 Appendix A

A.1. Life Cycle Inventory

This section provides the data and corresponding references utilized for the present LCA study.

Material Generation

The waste generation fractions used are shown in Table 16.

Table 16: Waste fraction used for the modelling of the products when they are disposed.

MATERIAL	MATERIAL NAME	DATABASE	COTTON BUDS	CUTLERY	PLATES	STRAWS	STIRRERS
PP	plastic packaging-PP	(Götze et al., 2016)	X	X		X	
PS	plastic packaging-PS	(Götze et al., 2016)			X		
WOOD	wood	EASETECH; modified for bamboo heating value		X			X
PAPER	Other clean paper	EASETECH	X		X		

For the manufacturing of the products, global market processes were used where possible, and they were sourced from Ecoinvent v 3.4 database (Ecoinvent, 2018). The processes were chosen in accordance with the EC report (2018b) and are presented in Table 17 below.

Table 17: Processes used for the manufacturing of the SUP products and their SUNP alternatives.

PROCESS	ECOINVENT NAME	COMMENT
PP Manufacturing	polyethylene pipe production, DN 200, SDR 41; GLO, consequential	Changed polyethylene input in the process to polypropylene input, and assumed the rest processes are the same.
Wood Manufacturing	market for plywood, for indoor use; RER, consequential	It is assumed that the process of making plywood is similar to the production of cutlery and stirrers. An average bamboo density (450kg/m3) is assumed for converting volume to weight of plywood.
PS Manufacturing	market for polystyrene, expandable; GLO, consequential	In the EC report the LCI from a report from Franklin and Associates (2006) was used. This is examined in the sensitivity analysis

The weight of the products as reported in the EC report (2018b) is shown in Table 18.

Table 18: Product weight reported by the EC report (2018b).

MATERIAL	COTTON BUDS	CUTLERY	CLAMSHELL	STRAWS	STIRRERS
PP	0.00017	0.0026	N/A	0.00040	0.0006
PS	N/A	0.0000	0.005	N/A	N/A
WOOD	N/A	0.0030	N/A	N/A	0.0019
PAPER	0.00017	N/A	0.0100	0.00080	N/A

Material weight found in commercially available data in Amazon or Alibaba, are shown in Table 19 to Table 21, which show the minimum weight found, the maximum and the average weight respectively.

Table 19: Minimum product weight found.

MATERIAL	COTTON BUDS	CUTLERY	PLATES	STRAWS	STIRRERS
PP	0.00015	0.0010	N/A	0.00049	0.0008
PS	N/A	0.0010	1.65E-03	N/A	0.0008
WOOD	N/A	0.0011	N/A	N/A	0.0004
PAPER	0.000190	N/A	6.53E-03	0.00115	N/A

Table 20: Maximum product weight found.

MATERIAL	COTTON BUDS	CUTLERY	PLATES	STRAWS	STIRRERS
PP	0.00016	0.0118	N/A	0.00096	0.0050
PS	N/A	0.0118	6.27E-03	N/A	0.0050
WOOD	0.000185	0.0036	N/A	N/A	0.0014
PAPER	0.000355	N/A	3.45E-02	0.00122	N/A

Table 21: Average calculated product weight.

MATERIAL	COTTON BUDS	CUTLERY	PLATES	STRAWS	STIRRERS
PP	0.000155	0.0035	2.10E-02	0.00065	0.0020
PS	N/A	0.0035	4.17E-03	N/A	0.0020
WOOD	0.00019	0.0026	N/A	N/A	0.0009
PAPER	0.000316	N/A	1.26E-02	0.00119	N/A

Transport

Table 22 presents the data associated with the transport.

Table 22: Processes and distances used for transport

	EXTERNAL PROCESS	VALUE	UNIT	REFERENCE
To sorting facility	Road, Long haul truck, Euro3, 25t, Generic, 2006	50	km	WRAP (2008)
To WtE facility	Road, Long haul truck, Euro3, 25t, Generic, 2006	50	km	WRAP (2008)
to Recycling/ash backfilling in Germany	Road, Long haul truck, Euro3, 25t, Generic, 2006	300	km	google maps

Plastic Recycling

Table 23 and Table 24 present the data associated with the plastic recycling.

Table 23: Processes and efficiencies used for sorting of plastic.

PLASTIC SORTING	SORTED (%)	RESIDUES (%)	REFERENCE
PP	85.5	14.5	(COWI og Miljøstyrelsen, 2018)
PS	85.5	14.5	(COWI og Miljøstyrelsen,

Table 24: Processes and substitution ratios for the recycling of plastics.

PLASTIC RECYCLING	TECHNICAL SUBSTITUTION RATIO (A) (%)	MARKET SUBSTITUTION RATIO (B) (%)	TOTAL SUBSTITUTION	SUBSTITUTED PROCESS (ECOINVENT v3.4)	REFERENCE
PP	90.3	-90	-81.27	market for polypropylene, granulate; GLO, consequential.	[1]EASETECH Process: -Plastic (PP) to granulate, DK, 2000
PS	75.5	-90	-67.95	market for polystyrene, general purpose; GLO,	[1,2]Plastic (PP) to granulate, DK, 2000,

1 Modified for German data, instead of Danish.

2 Modified A, B factors to be the same as process “PET recycling, Europe based on Rigamonti”, as it is assumed that PS will be of lower quality than PP.

End- of -Life Modules in EASETECH

The following processes from EASETECH were used for modelling the EoL scenarios:

Table 25: EASETECH modules used for the recycling of plastics.

PROCESS	EASETECH NAME	SUBSTITUTED MATERIAL (ECOINVENT V3.4)	COMMENT
PP Recycling	Plastic (PP) to granulate, DK, 2000	market for polypropylene, granulate; GLO	Modified for German data, instead of Danish.
PS Recycling	Plastic (PP) to granulate, DK, 2000,	market for polystyrene, general purpose; GLO	1. Modified for German data, instead of Danish. 2. Modified A, B factors to be the same as process "PET recycling, Europe based on Rigamonti", as it is assumed that PS will be of lower quality than PP
Waste to energy Incineration	Waste to energy plant, generic, DK, 2012	Marginal heat Marginal Electricity	The process models a generic Danish incinerator. The energy contained in the waste, after subtracting the energy required for water evaporation, is converted to heat and electricity with efficiencies 73% and 22% respectively

Energy for EOL management in Denmark

The marginal electricity for the various EOL technologies in Denmark was retrieved from Ecoinvent v 3.4 database (Ecoinvent, 2018). The process represents the market for high voltage electricity for Denmark. The marginal heat is on the other hand not available in Ecoinvent, and was therefore sourced from Miljøprojekt 1458 (Jensen et al., 2013).

Table 26: Processes used for the marginal electricity and heat mixes.

PROCESS	ECOINVENT NAME	COMMENT
Marginal Electricity	Market for electricity, high voltage, DK, consequential	
Miljøprojekt 1458 (Jensen et al., 2013)	heat production, hardwood chips from forest, at furnace 5000kW, state-of-the-art 2014; CH, consequential	39% of the marginal heat mix
	heat production, natural gas, at boiler modulating >100kW; Europe without Switzerland, consequential	26% of the marginal heat mix
	heat production, at hard coal industrial furnace 1-10MW; Europe without Switzerland, consequential	20% of the marginal heat mix
	heat production, heavy fuel oil, at industrial furnace 1MW; CH, consequential	9% of the marginal heat mix
	heat and power co-generation, biogas, gas engine; DK, allocation at the point of substitution	6% of the marginal heat mix

The processes shown in Table 26 above are substituted in the case of WtE management option, as the energy is recovered.

A.2. Additional Results for Baseline Results

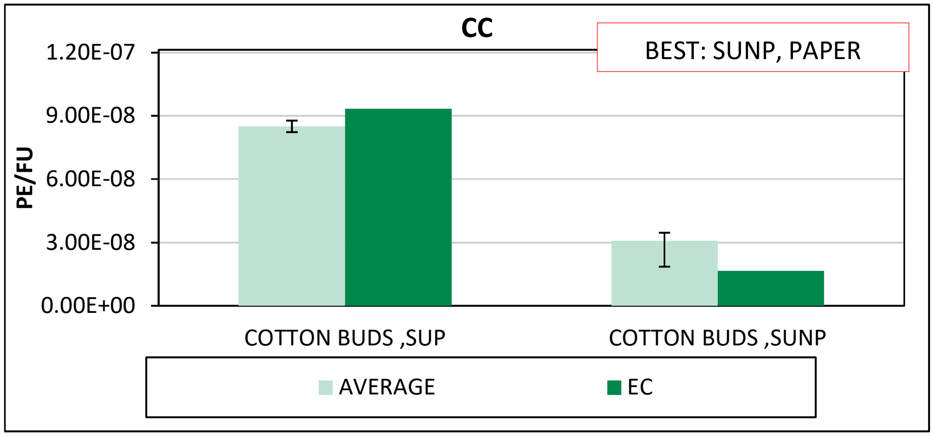


Figure 14: Normalized results for CC with weight uncertainty bars for cotton buds.

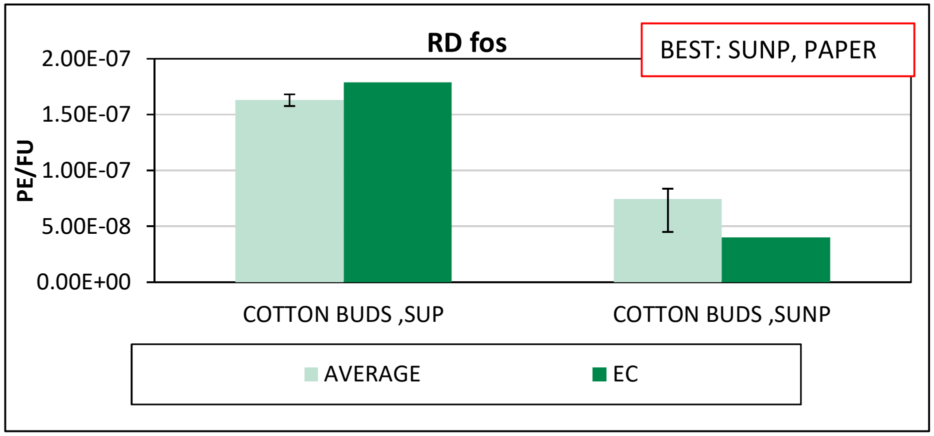


Figure 15: Normalized results for RD fos with weight uncertainty bars for cotton buds.

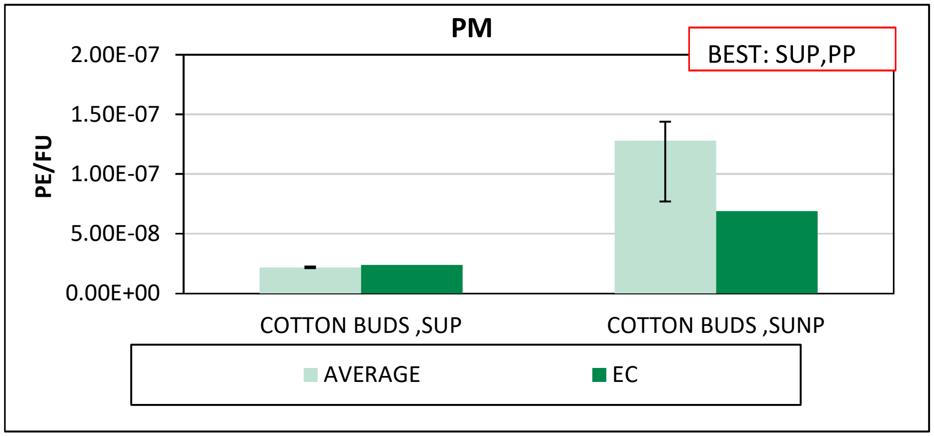


Figure 16: Normalized results for PM with weight uncertainty bars for cotton buds.

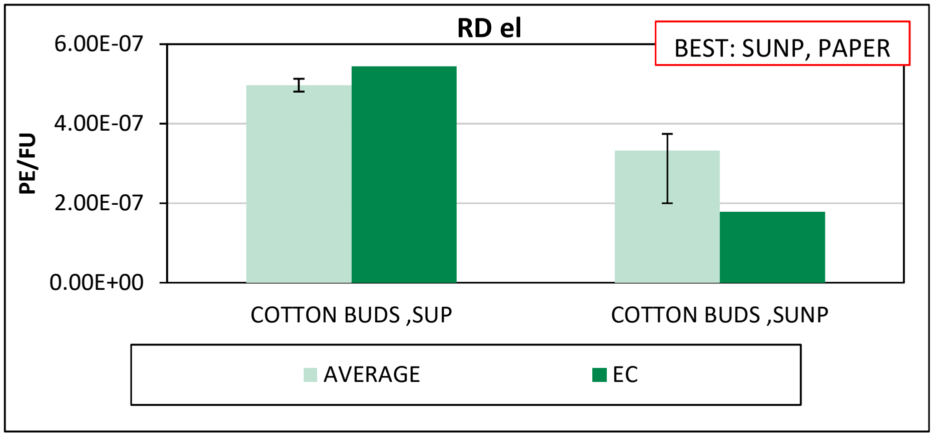


Figure 17: Normalized results for RD el with weight uncertainty bars for cotton buds.

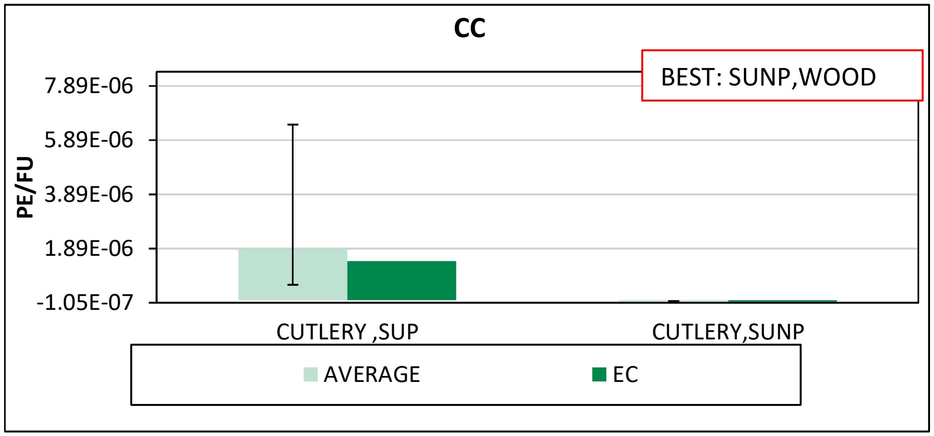


Figure 18: Normalized results for CC with weight uncertainty bars for cutlery.

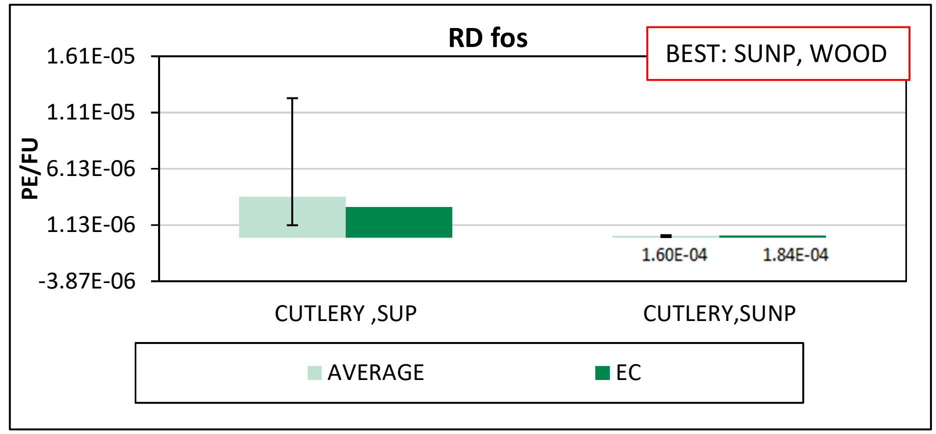


Figure 21: Normalized results for RD fos with weight uncertainty bars for cutlery.

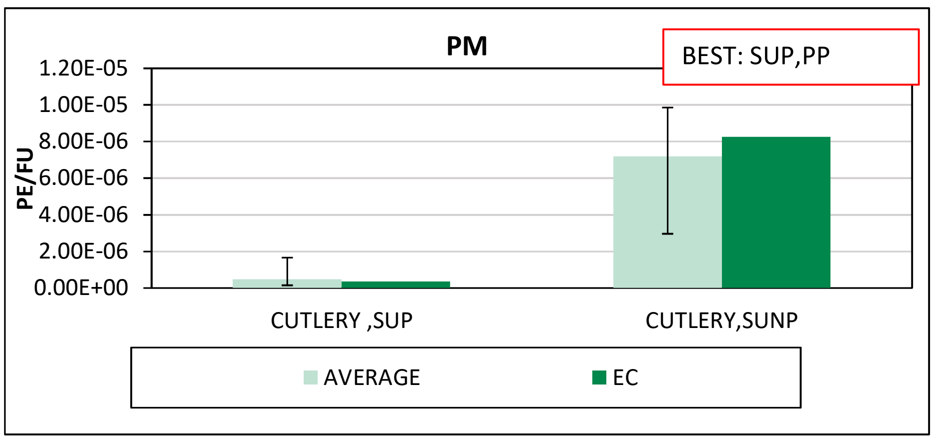


Figure 20: Normalized results for PM with weight uncertainty bars for cutlery.

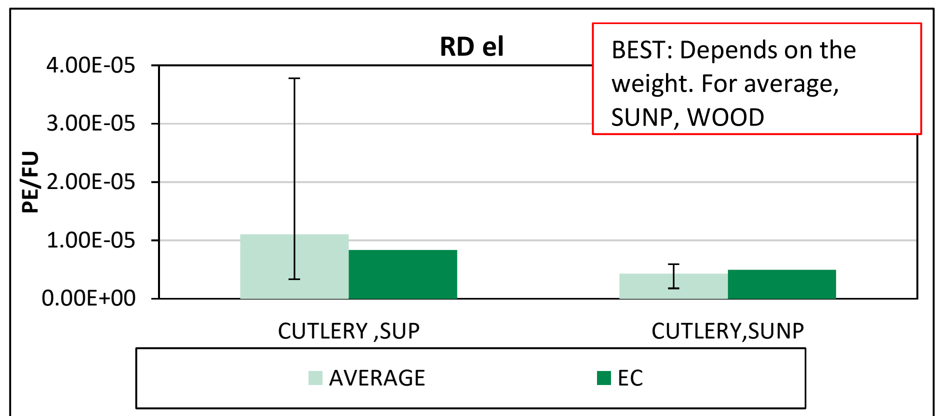


Figure 19: Normalized results for RD el with weight uncertainty bars for cutlery.

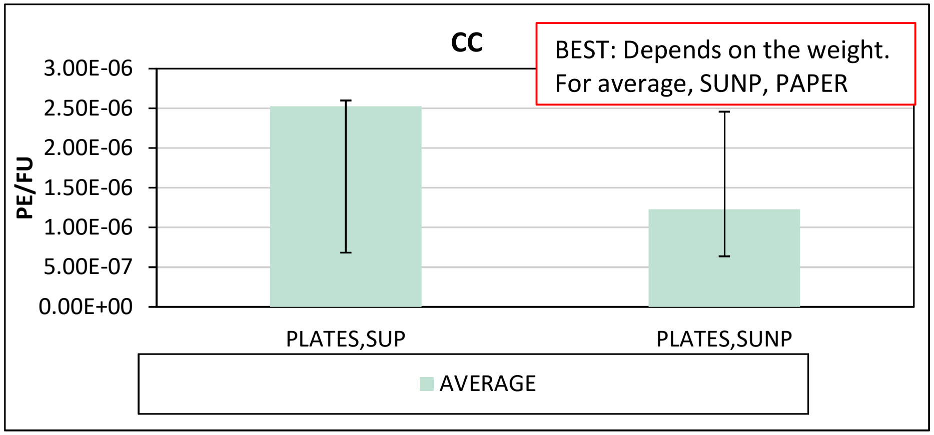


Figure 22: Normalized results for CC with weight uncertainty bars for plates.

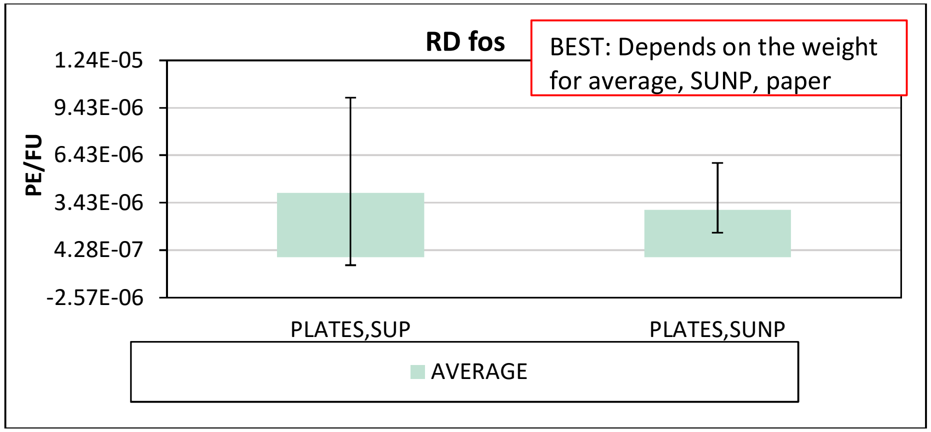


Figure 24: Normalized results for RD fos with weight uncertainty bars for plates.

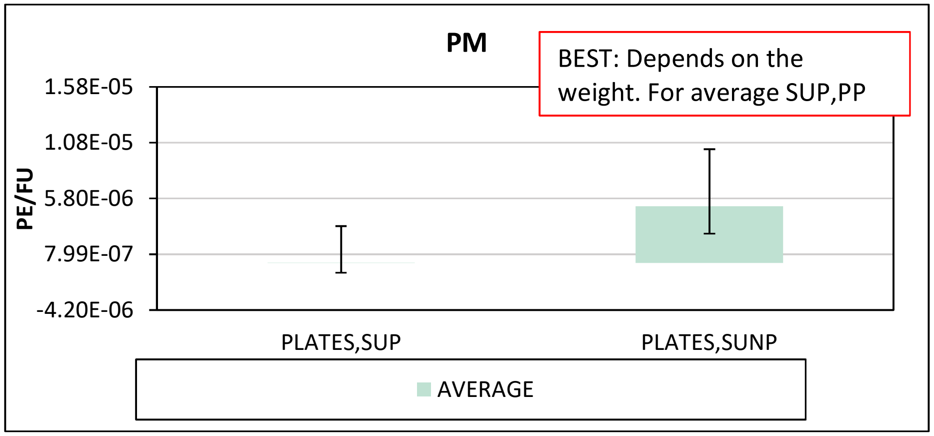


Figure 23: Normalized results for PM with weight uncertainty bars for plates.

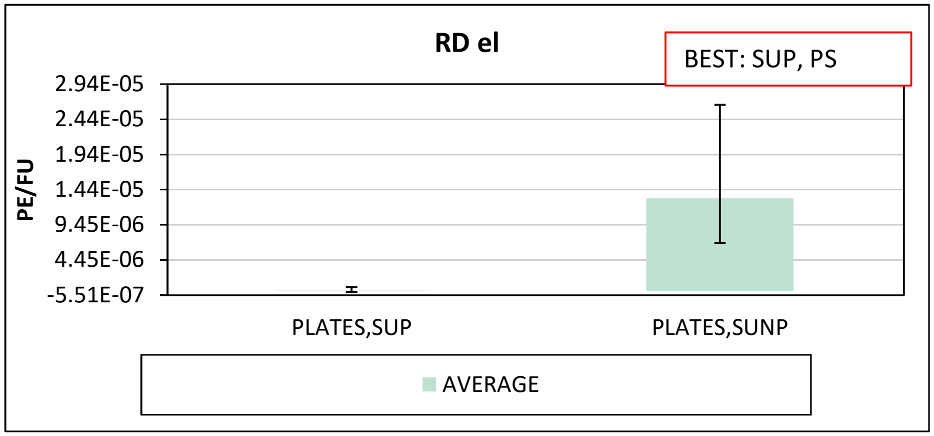


Figure 25: Normalized results for RD el with weight uncertainty bars for plates.

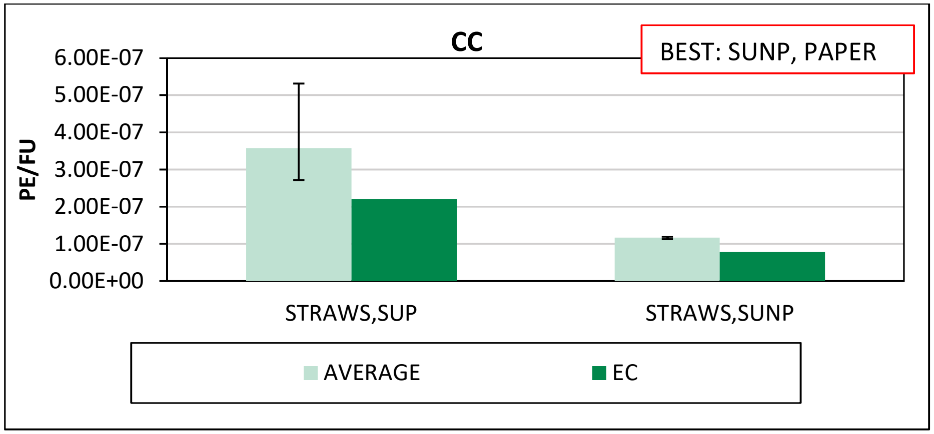


Figure 26: Normalized results for CC with weight uncertainty bars for straws.

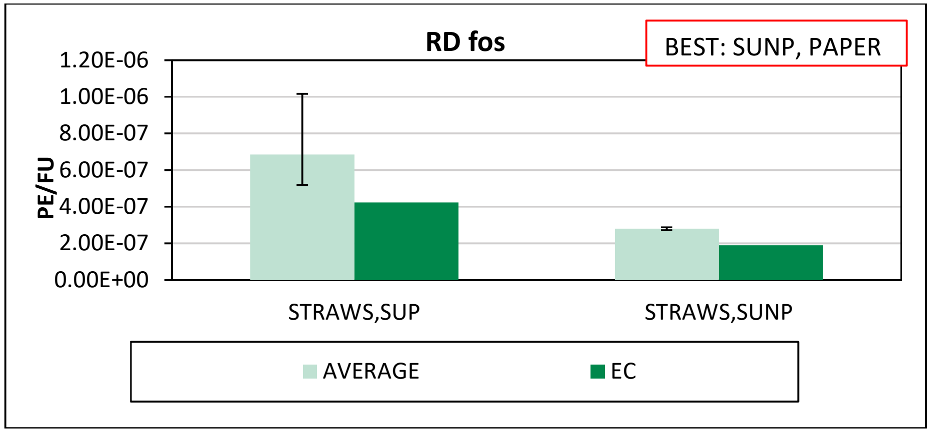


Figure 28: Normalized results for RD fos with weight uncertainty bars for straws.

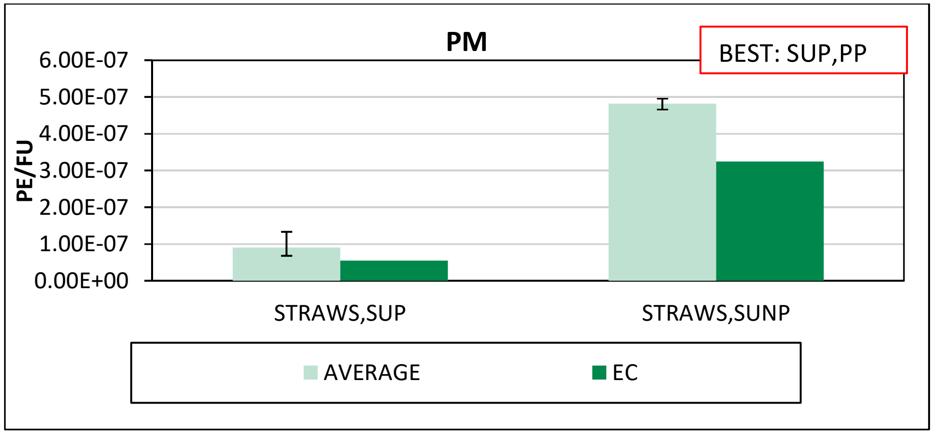


Figure 27: Normalized results for PM with weight uncertainty bars for straws.

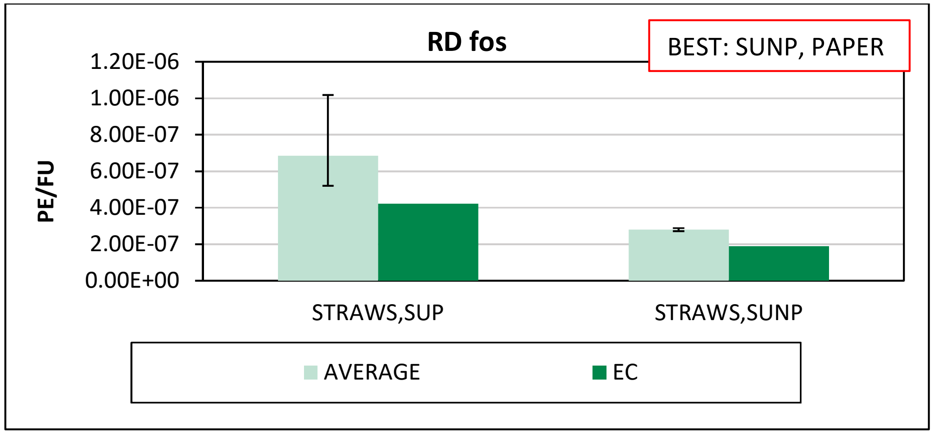


Figure 29: Normalized results for RD el with weight uncertainty bars for straws.

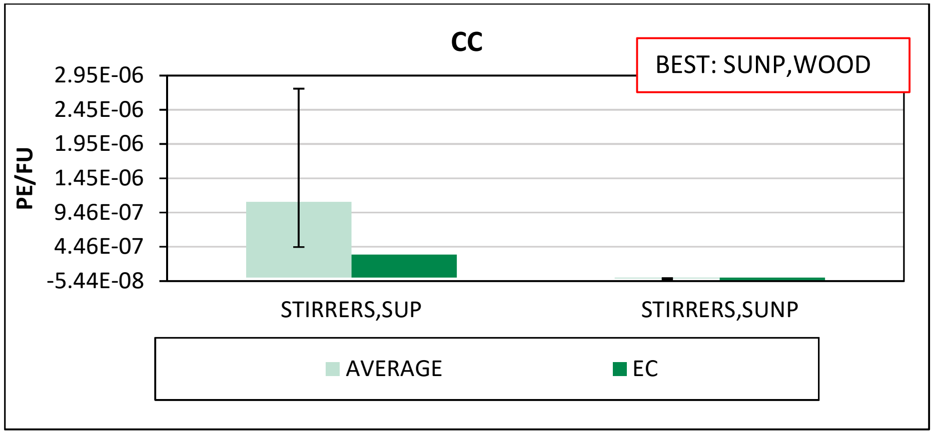


Figure 30: Normalized results for CC with weight uncertainty bars for stirrers.

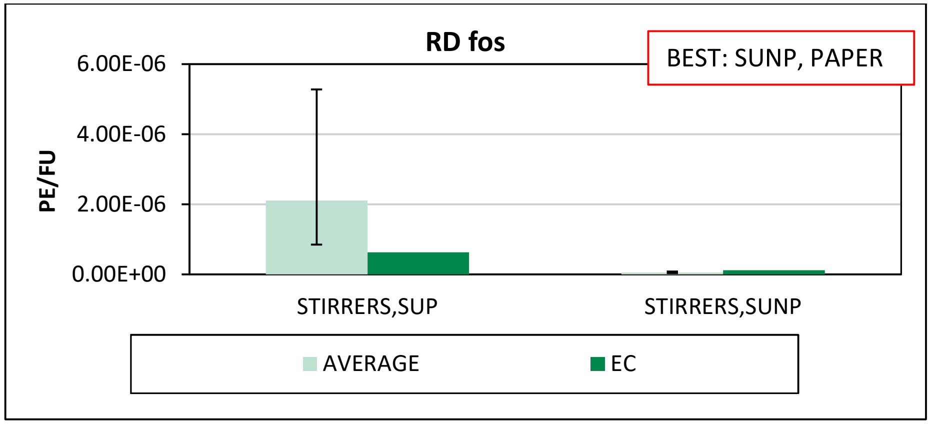


Figure 32: Normalized results for RD fos with weight uncertainty bars for stirrers.

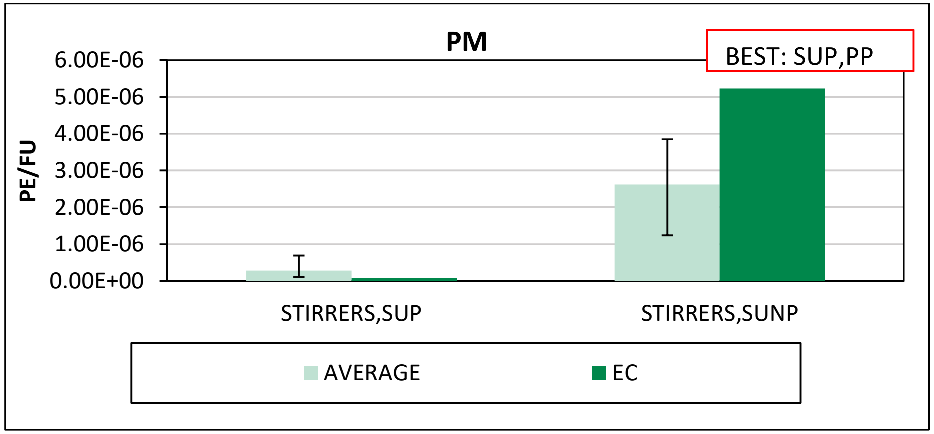


Figure 31: Normalized results for PM with weight uncertainty bars for stirrers.

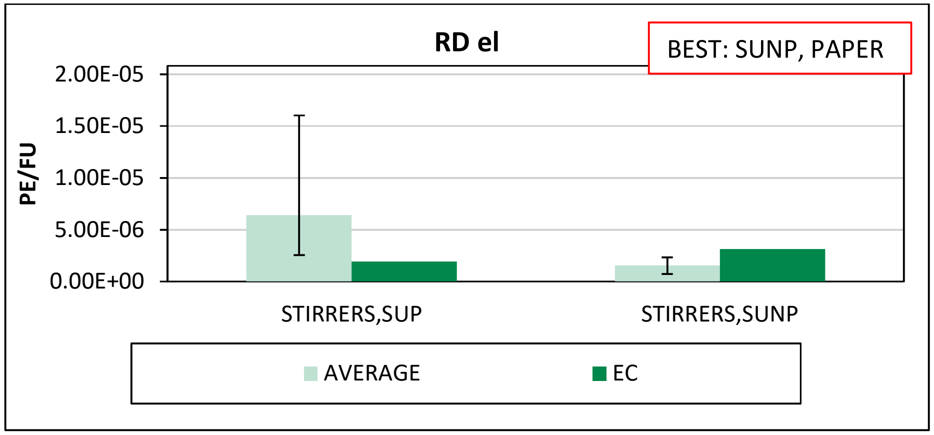


Figure 33: Normalized results for RD el with weight uncertainty bars for stirrers.

A.3. Sensitivity Analysis Results

Table 27: Characterized results for scenario sensitivity S1a.

SCENARIO	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD el
	kg CO2 eq	kg CFC11 eq	CTUh	CTUh	kgPM2.5 eq	kBq U235 eq	kg NMVOC	mol H+ eq	mol N eq	kg P eq	kg N eq	CTUe	MJ	kg Sb eq
COTTON BUDS														
PP, total EOL Management, S1a	1.05E-11	-5.19E-09	7.75E-04	-4.72E-05	7.96E-09	-8.50E-13	2.87E-10	1.34E-10	3.33E-11	6.97E-08	1.37E-09	4.71E-10	2.62E-12	1.45E-05
PAPER,total EOL Management, S1a	3.85E-12	1.95E-08	1.51E-03	9.46E-05	4.65E-08	3.14E-12	3.38E-10	2.79E-10	2.33E-10	7.77E-08	4.43E-09	6.78E-10	1.21E-12	9.69E-06
CUTLERY														
PP, total EOL Management, S1a	2.35E-10	-1.16E-07	1.73E-02	-1.06E-03	1.78E-07	-1.90E-11	6.41E-09	3.00E-09	7.43E-10	1.56E-06	3.07E-08	1.05E-08	5.85E-11	3.24E-04
WOOD, total EOL Management, S1a	-6.75E-12	-2.81E-08	1.42E-02	4.26E-04	2.61E-06	-2.16E-11	5.82E-09	2.42E-09	5.18E-09	3.78E-07	6.26E-08	4.81E-09	2.70E-12	1.26E-04
PLATES														
PS, total EOL Management, S1a	3.13E-10	-1.10E-07	3.00E-02	-1.69E-03	1.84E-08	-3.51E-11	8.55E-09	3.23E-09	9.35E-11	-2.87E-07	2.85E-08	9.82E-09	6.50E-11	2.52E-06
PAPER, total EOL Management, S1a	1.53E-10	7.78E-07	6.00E-02	3.77E-03	1.85E-06	1.25E-10	1.35E-08	1.11E-08	9.28E-09	3.10E-06	1.76E-07	2.70E-08	4.80E-11	3.86E-04
STRAWS														
PP, total EOL Management, S1a	4.42E-11	-2.19E-08	3.25E-03	-1.99E-04	3.31E-08	-3.62E-12	1.20E-09	5.57E-10	1.37E-10	2.92E-07	5.74E-09	1.98E-09	1.10E-11	6.07E-05
PAPER, total EOL Management, S1a	1.45E-11	7.34E-08	5.67E-03	3.56E-04	1.75E-07	1.18E-11	1.27E-09	1.05E-09	8.76E-10	2.92E-07	1.66E-08	2.55E-09	4.54E-12	3.65E-05
STIRRERS														
PP, total EOL Management, S1a	1.36E-10	-6.83E-08	9.98E-03	-6.18E-04	1.01E-07	-1.14E-11	3.71E-09	1.69E-09	4.13E-10	8.96E-07	1.76E-08	6.07E-09	3.39E-11	1.87E-04
WOOD, total EOL Management, S1a	-2.45E-12	-1.02E-08	5.15E-03	1.55E-04	9.48E-07	-7.84E-12	2.12E-09	8.79E-10	1.88E-09	1.38E-07	2.28E-08	1.75E-09	9.80E-13	4.57E-05

Table 28: Characterized results for scenario sensitivity S1b.

SCENARIO	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD el
	kg CO2 eq	kg CFC11 eq	CTUh	CTUh	kgPM2.5 eq	kBq U235 eq	kg NMVOC	mol H+ eq	mol N eq	kg P eq	kg N eq	CTUe	MJ	kg Sb eq
COTTON BUDS														
PP, total EOL Management, S1b	1.07E-11	-5.18E-09	7.81E-04	-4.51E-05	8.44E-09	-8.40E-13	3.18E-10	1.66E-10	6.33E-11	6.97E-08	1.78E-09	4.74E-10	2.66E-12	1.45E-05
PAPER, total EOL Management, S1b	4.25E-12	1.95E-08	1.52E-03	9.89E-05	4.75E-08	3.17E-12	4.01E-10	3.44E-10	2.94E-10	7.78E-08	5.25E-09	6.85E-10	1.30E-12	9.71E-06
CUTLERY														
PP, total EOL Management, S1b	2.39E-10	-1.16E-07	1.75E-02	-1.01E-03	1.89E-07	-1.88E-11	7.10E-09	3.71E-09	1.41E-09	1.56E-06	3.97E-08	1.06E-08	5.95E-11	3.24E-04
WOOD, total EOL Management, S1b	-3.50E-12	-2.80E-08	1.43E-02	4.61E-04	2.61E-06	-2.14E-11	6.35E-09	2.96E-09	5.69E-09	3.79E-07	6.94E-08	4.86E-09	3.44E-12	1.26E-04
PLATES														
PS, total EOL Management, S1b	3.18E-10	-1.10E-07	3.02E-02	-1.63E-03	3.15E-08	-3.48E-11	9.38E-09	4.10E-09	8.99E-10	-2.86E-07	3.93E-08	9.91E-09	6.62E-11	2.75E-06
PAPER, total EOL Management, S1b	1.69E-10	7.78E-07	6.05E-02	3.94E-03	1.89E-06	1.26E-10	1.60E-08	1.37E-08	1.17E-08	3.10E-06	2.09E-07	2.73E-08	5.16E-11	3.87E-04
STRAWS														
PP, total EOL Management, S1b	4.50E-11	-2.19E-08	3.27E-03	-1.90E-04	3.52E-08	-3.58E-12	1.33E-09	6.92E-10	2.63E-10	2.92E-07	7.43E-09	1.99E-09	1.12E-11	6.08E-05
PAPER, total EOL Management, S1b	1.60E-11	7.34E-08	5.71E-03	3.72E-04	1.79E-07	1.19E-11	1.51E-09	1.29E-09	1.11E-09	2.93E-07	1.97E-08	2.58E-09	4.88E-12	3.65E-05
STIRRERS														
PP, total EOL Management, S1b	1.39E-10	-6.82E-08	1.01E-02	-5.91E-04	1.07E-07	-1.12E-11	4.11E-09	2.10E-09	7.99E-10	8.96E-07	2.28E-08	6.12E-09	3.45E-11	1.87E-04
WOOD, total EOL Management, S1b	-1.27E-12	-1.02E-08	5.18E-03	1.68E-04	9.51E-07	-7.78E-12	2.31E-09	1.08E-09	2.07E-09	1.38E-07	2.52E-08	1.77E-09	1.25E-12	4.58E-05

Table 29: Characterized results for scenario sensitivity S1c.

SCENARIO	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD el
	kg CO2 eq	kg CFC11 eq	CTUh	CTUh	kgPM2.5 eq	kBq U235 eq	kg NMVOC	mol H+ eq	mol N eq	kg P eq	kg N eq	CTUe	MJ	kg Sb eq
COTTON BUDS														
PP, total EOL Management, S1c	1.05E-11	-5.19E-09	7.75E-04	-4.75E-05	8.24E-09	-8.49E-13	2.99E-10	1.62E-10	4.45E-11	6.97E-08	1.53E-09	4.71E-10	2.62E-12	1.45E-05
PAPER, total EOL Management, S1c	3.87E-12	1.95E-08	1.51E-03	9.41E-05	4.71E-08	3.15E-12	3.62E-10	3.35E-10	2.56E-10	7.77E-08	4.74E-09	6.78E-10	1.21E-12	9.69E-06
CUTLERY														
PP, total EOL Management, S1c	2.35E-10	-1.16E-07	1.73E-02	-1.06E-03	1.84E-07	-1.90E-11	6.68E-09	3.61E-09	9.94E-10	1.56E-06	3.41E-08	1.05E-08	5.85E-11	3.24E-04
WOOD, total EOL Management, S1c	-6.62E-12	-2.81E-08	1.42E-02	4.22E-04	2.61E-06	-2.15E-11	6.03E-09	2.88E-09	5.37E-09	3.79E-07	6.52E-08	4.80E-09	2.71E-12	1.26E-04
PLATES														
PS, total EOL Management, S1c	3.13E-10	-1.10E-07	3.00E-02	-1.70E-03	2.62E-08	-3.50E-11	8.87E-09	3.98E-09	3.95E-10	-2.86E-07	3.26E-08	9.82E-09	6.50E-11	2.50E-06
PAPER, total EOL Management, S1c	1.54E-10	7.78E-07	6.00E-02	3.75E-03	1.88E-06	1.25E-10	1.44E-08	1.33E-08	1.02E-08	3.10E-06	1.89E-07	2.70E-08	4.81E-11	3.86E-04
STRAWS														
PP, total EOL Management, S1c	4.42E-11	-2.19E-08	3.25E-03	-2.00E-04	3.43E-08	-3.62E-12	1.25E-09	6.73E-10	1.84E-10	2.92E-07	6.39E-09	1.97E-09	1.10E-11	6.07E-05
PAPER, total EOL Management, S1c	1.45E-11	7.34E-08	5.67E-03	3.54E-04	1.77E-07	1.18E-11	1.36E-09	1.26E-09	9.62E-10	2.92E-07	1.78E-08	2.55E-09	4.54E-12	3.65E-05
STIRRERS														
PP, total EOL Management, S1c	1.36E-10	-6.82E-08	9.98E-03	-6.21E-04	1.04E-07	-1.14E-11	3.86E-09	2.04E-09	5.57E-10	8.96E-07	1.96E-08	6.07E-09	3.39E-11	1.87E-04
WOOD, total EOL Management, S1c	-2.41E-12	-1.02E-08	5.15E-03	1.53E-04	9.49E-07	-7.83E-12	2.19E-09	1.05E-09	1.95E-09	1.38E-07	2.37E-08	1.75E-09	9.87E-13	4.57E-05

Table 30: Characterized results for scenario sensitivity S2a.

SCENARIO	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD el
	kg CO2 eq	kg CFC11 eq	CTUh	CTUh	kgPM2.5 eq	kBq U235 eq	kg NMVOC	mol H+ eq	mol N eq	kg P eq	kg N eq	CTUe	MJ	kg Sb eq
								COTTON BUDS						
PP, total EOL Management, S2a	4.61E-12	-7.18E-09	6.98E-04	-5.37E-05	4.30E-09	-1.74E-12	1.27E-10	-2.60E-10	-1.01E-10	1.70E-08	-6.33E-10	4.20E-10	1.01E-12	1.41E-05
PAPER, total EOL Management, S2a	-6.56E-13	1.80E-08	1.44E-03	8.93E-05	4.39E-08	2.47E-12	2.12E-10	-2.35E-11	1.27E-10	3.82E-08	2.87E-09	6.39E-10	-1.77E-14	9.39E-06
								CUTLERY						
PP, total EOL Management, S2a	1.03E-10	-1.60E-07	1.56E-02	-1.20E-03	9.61E-08	-3.89E-11	2.84E-09	-5.80E-09	-2.25E-09	3.79E-07	-1.41E-08	9.38E-09	2.26E-11	3.16E-04
WOOD, total EOL Management, S2a	-4.59E-11	-4.10E-08	1.36E-02	3.81E-04	2.58E-06	-2.74E-11	4.74E-09	-2.10E-10	4.26E-09	3.76E-08	4.90E-08	4.47E-09	-7.93E-12	1.23E-04
								PLATES						
PS, total EOL Management, S2a	1.71E-10	-1.58E-07	2.81E-02	-1.85E-03	-7.30E-08	-5.64E-11	4.70E-09	-6.21E-09	-3.13E-09	-1.53E-06	-1.92E-08	8.60E-09	2.65E-11	-6.73E-06
PAPER, total EOL Management, S2a	-2.61E-11	7.15E-07	5.74E-02	3.56E-03	1.75E-06	9.83E-11	8.46E-09	-9.37E-10	5.06E-09	1.52E-06	1.14E-07	2.55E-08	-7.07E-13	3.74E-04
								STRAWS						
PP, total EOL Management, S2a	1.93E-11	-3.03E-08	2.93E-03	-2.27E-04	1.77E-08	-7.37E-12	5.31E-10	-1.10E-09	-4.27E-10	7.00E-08	-2.70E-09	1.76E-09	4.24E-12	5.93E-05
PAPER, total EOL Management, S2a	-2.47E-12	6.75E-08	5.42E-03	3.36E-04	1.65E-07	9.28E-12	7.99E-10	-8.84E-11	4.78E-10	1.44E-07	1.08E-08	2.40E-09	-6.67E-14	3.53E-05
								STIRRERS						
PP, total EOL Management, S2a	5.95E-11	-9.42E-08	8.98E-03	-7.02E-04	5.31E-08	-2.30E-11	1.63E-09	-3.43E-09	-1.33E-09	2.10E-07	-8.48E-09	5.41E-09	1.30E-11	1.82E-04
WOOD, total EOL Management, S2a	-1.67E-11	-1.49E-08	4.95E-03	1.39E-04	9.39E-07	-9.98E-12	1.72E-09	-7.62E-11	1.55E-09	1.37E-08	1.78E-08	1.62E-09	-2.88E-12	4.48E-05

Table 31: Characterized results for scenario sensitivity S1b.

SCENARIO	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD el
	kg CO2 eq	kg CFC11 eq	CTUh	CTUh	kgPM2.5 eq	kBq U235 eq	kg NMVOC	mol H+ eq	mol N eq	kg P eq	kg N eq	CTUe	MJ	kg Sb eq
COTTON BUDS														
PP, total EOL Management, S2b	1.06E-11	-5.00E-09	7.74E-04	-2.12E-05	1.17E-08	-7.80E-13	3.34E-10	2.03E-10	9.99E-11	8.09E-08	1.95E-09	5.27E-10	2.63E-12	1.47E-05
PAPER, total EOL Management, S2b	3.86E-12	1.97E-08	1.51E-03	1.14E-04	4.94E-08	3.22E-12	3.69E-10	3.28E-10	2.80E-10	8.63E-08	4.81E-09	7.20E-10	1.20E-12	9.84E-06
CUTLERY														
PP, total EOL Management, S2b	2.37E-10	-1.12E-07	1.73E-02	-4.75E-04	2.62E-07	-1.74E-11	7.46E-09	4.54E-09	2.23E-09	1.81E-06	4.36E-08	1.18E-08	5.88E-11	3.28E-04
WOOD, total EOL Management, S2b	-6.66E-12	-2.62E-08	1.42E-02	5.97E-04	2.63E-06	-2.09E-11	6.09E-09	2.85E-09	5.59E-09	4.53E-07	6.60E-08	5.17E-09	2.69E-12	1.27E-04
PLATES														
PS, total EOL Management, S2b	3.14E-10	-1.03E-07	3.00E-02	-1.06E-03	1.12E-07	-3.26E-11	9.65E-09	4.94E-09	1.70E-09	-1.38E-08	4.23E-08	1.12E-08	6.51E-11	7.22E-06
PAPER, total EOL Management, S2b	1.54E-10	7.86E-07	6.00E-02	4.55E-03	1.97E-06	1.28E-10	1.47E-08	1.31E-08	1.11E-08	3.44E-06	1.92E-07	2.87E-08	4.80E-11	3.92E-04
STRAWS														
PP, total EOL Management, S2b	4.45E-11	-2.10E-08	3.25E-03	-8.91E-05	4.92E-08	-3.27E-12	1.40E-09	8.52E-10	4.19E-10	3.39E-07	8.18E-09	2.21E-09	1.10E-11	6.16E-05
PAPER, total EOL Management, S2b	1.45E-11	7.42E-08	5.67E-03	4.30E-04	1.86E-07	1.21E-11	1.39E-09	1.24E-09	1.05E-09	3.25E-07	1.81E-08	2.71E-09	4.53E-12	3.70E-05
STIRRERS														
PP, total EOL Management, S2b	1.37E-10	-6.45E-08	9.99E-03	-2.74E-04	1.51E-07	-1.01E-11	4.31E-09	2.62E-09	1.29E-09	1.04E-06	2.52E-08	6.80E-09	3.40E-11	1.89E-04
WOOD, total EOL Management, S2b	-2.42E-12	-9.51E-09	5.15E-03	2.17E-04	9.57E-07	-7.60E-12	2.22E-09	1.04E-09	2.03E-09	1.65E-07	2.40E-08	1.88E-09	9.77E-13	4.62E-05

Table 32: Characterized results for scenario sensitivity S2c

SCENARIO	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD el
	kg CO2 eq	kg CFC11 eq	CTUh	CTUh	kgPM2.5 eq	kBq U235 eq	kg NMVOC	mol H+ eq	mol N eq	kg P eq	kg N eq	CTUe	MJ	kg Sb eq
								COTTON BUDS						
PP, total EOL Management, S2c	1.40E-11	4.48E-09	7.53E-04	-1.09E-04	2.22E-08	8.13E-13	3.37E-10	7.07E-10	1.21E-10	6.10E-08	1.97E-09	4.19E-10	3.49E-12	1.45E-05
PAPER, total EOL Management, S2c	6.46E-12	2.68E-08	1.48E-03	4.75E-05	5.74E-08	4.40E-12	3.71E-10	7.08E-10	2.95E-10	7.10E-08	4.81E-09	6.38E-10	1.86E-12	9.69E-06
								CUTLERY						
PP, total EOL Management, S2c	3.13E-10	1.00E-07	1.68E-02	-2.43E-03	4.97E-07	1.82E-11	7.52E-09	1.58E-08	2.70E-09	1.36E-06	4.39E-08	9.35E-09	7.79E-11	3.24E-04
WOOD, total EOL Management, S2c	1.59E-11	3.60E-08	3.77E-02	4.48E-04	2.70E-06	3.25E-11	6.11E-09	6.15E-09	5.73E-09	3.22E-07	6.75E-08	4.09E-08	8.38E-12	1.26E-04
								PLATES						
PS, total EOL Management, S2c	3.96E-10	1.21E-07	2.94E-02	-3.17E-03	3.61E-07	4.82E-12	9.72E-09	1.70E-08	2.19E-09	-4.95E-07	4.26E-08	8.56E-09	8.58E-11	2.89E-06
PAPER, total EOL Management, S2c	2.57E-10	1.07E-06	5.91E-02	1.89E-03	2.29E-06	1.75E-10	1.48E-08	2.82E-08	1.18E-08	2.83E-06	1.91E-07	2.54E-08	7.41E-11	3.86E-04
								STRAWS						
PP, total EOL Management, S2c	5.89E-11	1.87E-08	3.16E-03	-4.59E-04	9.32E-08	3.38E-12	1.41E-09	2.97E-09	5.07E-10	2.55E-07	8.24E-09	1.75E-09	1.47E-11	6.08E-05
PAPER, total EOL Management, S2c	2.43E-11	1.01E-07	5.58E-03	1.79E-04	2.16E-07	1.66E-11	1.40E-09	2.66E-09	1.11E-09	2.67E-07	1.81E-08	2.40E-09	6.99E-12	3.65E-05
								STIRRERS						
PP, total EOL Management, S2c	1.82E-10	5.74E-08	9.70E-03	-1.42E-03	2.86E-07	1.03E-11	4.35E-09	9.13E-09	1.55E-09	7.83E-07	2.53E-08	5.39E-09	4.52E-11	1.87E-04
WOOD, total EOL Management, S2c	5.80E-12	1.31E-08	1.37E-02	1.63E-04	9.82E-07	1.18E-11	2.22E-09	2.24E-09	2.08E-09	1.17E-07	2.45E-08	1.49E-08	3.05E-12	4.57E-05

Table 33: Characterized results for scenario sensitivity S3.

SCENARIO	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD el
	kg CO2 eq	kg CFC11 eq	CTUh	CTUh	kgPM2.5 eq	kBq U235 eq	kg NMVOC	mol H+ eq	mol N eq	kg P eq	kg N eq	CTUe	MJ	kg Sb eq
COTTON BUDS														
PP, total EOL Management, S3	1.04E-11	-3.71E-09	7.49E-04	-5.51E-05	5.86E-09	2.89E-12	2.93E-10	1.53E-10	4.14E-11	2.82E-08	1.51E-09	4.49E-10	2.45E-12	1.86E-05
PAPER, total EOL Management, S3	3.12E-12	1.30E-08	1.53E-03	1.02E-04	5.82E-08	1.09E-11	3.73E-10	4.41E-10	2.97E-10	8.12E-08	5.39E-09	6.90E-10	9.21E-13	1.17E-05
CUTLERY														
PP, total EOL Management, S3	2.32E-10	-8.30E-08	1.67E-02	-1.23E-03	1.31E-07	6.47E-11	6.54E-09	3.42E-09	9.24E-10	6.30E-07	3.36E-08	1.00E-08	5.47E-11	4.15E-04
WOOD, total EOL Management, S3	9.64E-12	1.22E-07	1.22E-02	5.15E-04	1.73E-06	1.06E-10	4.47E-09	2.72E-09	3.16E-09	3.87E-07	3.90E-08	4.85E-09	5.01E-12	1.09E-04
PLATES														
PS, total EOL Management, S3	3.12E-10	-1.05E-07	3.03E-02	-1.70E-03	9.75E-09	-3.57E-11	8.60E-09	3.12E-09	1.11E-10	-3.13E-07	2.92E-08	9.93E-09	6.46E-11	1.27E-05
PAPER, total EOL Management, S3	1.24E-10	5.20E-07	6.08E-02	4.06E-03	2.32E-06	4.34E-10	1.49E-08	1.76E-08	1.18E-08	3.23E-06	2.15E-07	2.75E-08	3.67E-11	4.65E-04
STRAWS														
PP, total EOL Management, S3	4.37E-11	-1.61E-08	3.13E-03	-2.34E-04	2.39E-08	1.19E-11	1.23E-09	6.25E-10	1.67E-10	1.17E-07	6.27E-09	1.88E-09	1.03E-11	7.79E-05
PAPER, total EOL Management, S3	1.17E-11	4.91E-08	5.74E-03	3.83E-04	2.19E-07	4.10E-11	1.40E-09	1.66E-09	1.12E-09	3.05E-07	2.03E-08	2.60E-09	3.47E-12	4.39E-05
STIRRERS														
PP, total EOL Management, S3	1.34E-10	-4.94E-08	9.63E-03	-7.20E-04	7.36E-08	3.66E-11	3.78E-09	1.92E-09	5.14E-10	3.59E-07	1.93E-08	5.79E-09	3.17E-11	2.40E-04
WOOD, total EOL Management, S3	3.50E-12	4.44E-08	4.44E-03	1.87E-04	6.30E-07	3.87E-11	1.63E-09	9.90E-10	1.15E-09	1.41E-07	1.42E-08	1.76E-09	1.82E-12	3.96E-05

Table 34: Results of scenario sensitivity S4.

SCENARIO	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD el
	kg CO2 eq	kg CFC11 eq	CTUh	CTUh	kgPM2.5 eq	kBq U235 eq	kg NMVOC	mol H+ eq	mol N eq	kg P eq	kg N eq	CTUe	MJ	kg Sb eq
								COTTON BUDS						
PP, total EOL Management, S4	1.05E-11	-5.19E-09	7.75E-04	-4.75E-05	7.90E-09	-8.51E-13	2.84E-10	1.30E-10	2.99E-11	6.97E-08	1.33E-09	4.71E-10	2.61E-12	1.45E-05
PAPER, total EOL Management, S4	2.19E-11	5.68E-08	4.33E-03	2.59E-04	1.49E-07	9.21E-12	1.19E-09	2.43E-09	1.68E-09	2.39E-07	7.26E-08	1.87E-09	3.65E-12	2.62E-05
								CUTLERY						
PP, total EOL Management, S4	2.35E-10	-1.16E-07	1.73E-02	-1.06E-03	1.77E-07	-1.90E-11	6.34E-09	2.92E-09	6.69E-10	1.56E-06	2.97E-08	1.05E-08	5.84E-11	3.24E-04
WOOD, total EOL Management, S4	1.42E-10	8.62E-08	2.41E-02	5.41E-04	3.01E-06	-3.12E-12	1.18E-08	2.07E-08	1.99E-08	1.02E-06	8.81E-07	8.53E-09	9.69E-12	2.10E-04
								PLATES						
PS, total EOL Management, S4	3.12E-10	-1.10E-07	3.00E-02	-1.70E-03	1.70E-08	-3.51E-11	8.46E-09	3.14E-09	3.93E-12	-2.87E-07	2.73E-08	9.81E-09	6.49E-11	2.50E-06
PAPER, total EOL Management, S4	8.71E-10	2.26E-06	1.73E-01	1.03E-02	5.94E-06	3.67E-10	4.75E-08	9.68E-08	6.68E-08	9.54E-06	2.89E-06	7.45E-08	1.45E-10	1.04E-03
								STRAWS						
PP, total EOL Management, S4	4.41E-11	-2.19E-08	3.25E-03	-2.00E-04	3.29E-08	-3.62E-12	1.19E-09	5.42E-10	1.23E-10	2.92E-07	5.55E-09	1.97E-09	1.10E-11	6.07E-05
PAPER, total EOL Management, S4	8.23E-11	2.14E-07	1.63E-02	9.73E-04	5.60E-07	3.46E-11	4.49E-09	9.14E-09	6.31E-09	9.01E-07	2.73E-07	7.04E-09	1.37E-11	9.86E-05
								STIRRERS						
PP, total EOL Management, S4	1.36E-10	-6.83E-08	9.97E-03	-6.21E-04	1.00E-07	-1.14E-11	3.66E-09	1.64E-09	3.70E-10	8.96E-07	1.70E-08	6.07E-09	3.38E-11	1.87E-04
WOOD, total EOL Management, S4	5.15E-11	3.13E-08	8.77E-03	1.97E-04	1.09E-06	-1.14E-12	4.28E-09	7.51E-09	7.23E-09	3.71E-07	3.20E-07	3.10E-09	3.52E-12	7.63E-05

Table 35: Characterized results for scenario sensitivity S5.

SCENARIO	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD el
	kg CO2 eq	kg CFC11 eq	CTUh	CTUh	kgPM2.5 eq	kBq U235 eq	kg NMVOC	mol H+ eq	mol N eq	kg P eq	kg N eq	CTUe	MJ	kg Sb eq
							EC LCI							
PS, total EOL Management	1.64E+01	-5.11E-07	-3.03E-08	-2.55E-06	-7.49E-03	-9.57E-02	-2.52E-02	-5.79E-02	-1.13E-01	-4.84E-04	-7.59E-03	-3.86E+00	-1.20E+02	-1.24E-05
PAPER, total EOL Management	1.78E+01	-3.71E-07	-2.03E-09	-1.01E-06	-5.88E-03	-8.79E-02	-2.07E-03	-3.99E-02	-5.60E-02	8.59E-04	-2.41E-03	-2.65E+00	-8.94E+01	-1.02E-05
							Ecoinvent							
PS, total EOL Management	2.42E+01	-2.41E-07	9.89E-08	-2.47E-06	-2.27E-04	-7.56E-02	2.97E-02	5.91E-03	-5.58E-03	-1.50E-04	2.36E-03	4.76E+00	2.82E+02	2.73E-06
PAPER, total EOL Management	7.92E+00	1.06E-06	1.40E-07	3.61E-06	1.12E-02	1.76E-01	3.37E-02	2.11E-02	9.47E-02	9.46E-04	1.21E-02	9.49E+00	1.48E+02	3.61E-04

Table 36: Characterized results for scenario sensitivity S6

SCENARIO	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD el
	kg CO2 eq	kg CFC11 eq	CTUh	CTUh	kgPM2.5 eq	kBq U235 eq	kg NMVOC	mol H+ eq	mol N eq	kg P eq	kg N eq	CTUe	MJ	kg Sb eq
							COTTON BUDS							
PP, total EOL Management, S2a	4.61E-12	-7.18E-09	6.98E-04	-5.37E-05	4.30E-09	-1.74E-12	1.27E-10	-2.60E-10	-1.01E-10	1.70E-08	-6.33E-10	4.20E-10	1.01E-12	1.41E-05
PAPER, total EOL Management, S2a	-6.56E-13	1.80E-08	1.44E-03	8.93E-05	4.39E-08	2.47E-12	2.12E-10	-2.35E-11	1.27E-10	3.82E-08	2.87E-09	6.39E-10	-1.77E-14	9.39E-06
							CUTLERY							
PP, total EOL Management, S2a	1.03E-10	-1.60E-07	1.56E-02	-1.20E-03	9.61E-08	-3.89E-11	2.84E-09	-5.80E-09	-2.25E-09	3.79E-07	-1.41E-08	9.38E-09	2.26E-11	3.16E-04
WOOD, total EOL Management, S2a	-4.59E-11	-4.10E-08	1.36E-02	3.81E-04	2.58E-06	-2.74E-11	4.74E-09	-2.10E-10	4.26E-09	3.76E-08	4.90E-08	4.47E-09	-7.93E-12	1.23E-04
							PLATES							
PS, total EOL Management, S2a	1.71E-10	-1.58E-07	2.81E-02	-1.85E-03	-7.30E-08	-5.64E-11	4.70E-09	-6.21E-09	-3.13E-09	-1.53E-06	-1.92E-08	8.60E-09	2.65E-11	-6.73E-06
PAPER, total EOL Management, S2a	-2.61E-11	7.15E-07	5.74E-02	3.56E-03	1.75E-06	9.83E-11	8.46E-09	-9.37E-10	5.06E-09	1.52E-06	1.14E-07	2.55E-08	-7.07E-13	3.74E-04
							STRAWS							
PP, total EOL Management, S2a	1.93E-11	-3.03E-08	2.93E-03	-2.27E-04	1.77E-08	-7.37E-12	5.31E-10	-1.10E-09	-4.27E-10	7.00E-08	-2.70E-09	1.76E-09	4.24E-12	5.93E-05
PAPER, total EOL Management, S2a	-2.47E-12	6.75E-08	5.42E-03	3.36E-04	1.65E-07	9.28E-12	7.99E-10	-8.84E-11	4.78E-10	1.44E-07	1.08E-08	2.40E-09	-6.67E-14	3.53E-05
							STIRRERS							
PP, total EOL Management, S2a	5.95E-11	-9.42E-08	8.98E-03	-7.02E-04	5.31E-08	-2.30E-11	1.63E-09	-3.43E-09	-1.33E-09	2.10E-07	-8.48E-09	5.41E-09	1.30E-11	1.82E-04
WOOD, total EOL Management, S2a	-1.67E-11	-1.49E-08	4.95E-03	1.39E-04	9.39E-07	-9.98E-12	1.72E-09	-7.62E-11	1.55E-09	1.37E-08	1.78E-08	1.62E-09	-2.88E-12	4.48E-05

8.2 Appendix B

This appendix contain the online sources used to estimate the weight of the SUP and SUNP products

A.4. Cotton Buds

SUP: PP

Table 37: Online sources for defining the SUP option for cotton buds.

ITEM	WEIGHT (length ~75mm)	UNIT	NO OF ITEMS	REFERENCE
PP/LDPE COTTON BUD (without cotton)	0.16	g	1	Scaled in the lab
Plastic COTTON BUD (without cotton)	0.15	g	100	https://www.alibaba.com/product-detail/Facial-exfoliating-puritan-cosmetic-q-tips_60742467881.html?spm=a2700.7724838.2017115.160.67093ec1ZTP7W0&s=p
Plastic COTTON BUD (without cotton)	15.5	g	100	https://www.alibaba.com/product-detail/High-Quality-Plastic-Stick-Cotton-Buds_60147292978.html?spm=a2700.7724838.2017115.60.58b5154f85HzeZ

SUNP: Paper

Table 38: Online sources for defining the SUNP option for cotton buds.

ITEM (length ~75mm)	WEIGHT	UNIT	NO OF ITEMS	REFERENCE
Paper cotton bud (without cotton)	33.5	g	100	https://www.alibaba.com/product-detail/High-Quality-Plastic-Stick-Cotton-Buds_60147292978.html?spm=a2700.7724838.2017115.60.58b5154f85HzeZ
Paper cotton bud (without cotton)	32.5	g	100	https://www.alibaba.com/product-detail/High-Quality-Plastic-Stick-Cotton-Buds_60147292978.html?spm=a2700.7724838.2017115.60.58b5154f85HzeZ
Paper cotton bud (without cotton)	33.5	g	100	https://www.alibaba.com/product-detail/High-Quality-Plastic-Stick-Cotton-Buds_60147292978.html?spm=a2700.7724838.2017115.60.58b5154f85HzeZ
Paper cotton bud (without cotton)	33.5	g	100	https://www.alibaba.com/product-detail/High-Quality-Plastic-Stick-Cotton-Buds_60147292978.html?spm=a2700.7724838.2017115.60.58b5154f85HzeZ
Paper cotton bud (without cotton)	19	g	100	https://www.alibaba.com/product-detail/High-Quality-Plastic-Stick-Cotton-Buds_60147292978.html?spm=a2700.7724838.2017115.60.58b5154f85HzeZ
Paper cotton bud (without cotton)	34.5	g	100	https://www.alibaba.com/product-detail/Eco-Friendly-Paper-Stick-Cosmetic-Cotton_60761995803.html?spm=a2700.7724838.2017115.132.19251bc5c8Ccam
Paper cotton bud (without cotton)	30.5	g	100	https://www.alibaba.com/product-detail/200PCS-OEM-ODM-Design-Paper-Stick_60564452709.html?spm=a2700.7724838.2017115.398.19251bc5c8Ccam
Paper cotton bud (without cotton)	0.355		1	https://www.alibaba.com/product-detail/40pcs-OEM-design-paper-stick-make_60816257700.html?spm=a2700.7724838.2017115.435.19251bc5c8Ccam

*subtracting 4.5g/100 pieces, for cotton, as indicate in figure x.https://www.alibaba.com/product-detail/250-pcs-in-heart-box-wooden_60782646797.html

A.5. Cutlery

SUP: PP

Table 39: Online sources for defining the SUP option for cutlery.

ITEM	WEIGHT (size ~7")	UNIT	No of ITEMS	Quality	REFERENCE
PP spoon/knife/fork	3.4	lb	300	heavy duty	https://www.amazon.com/Count-Heavy-Clear-Plastic-Cutlery/dp/B077JJNRWZ/ref=sr_1_1_sspa?s=industrial&ie=UTF8&qid=1534491966&sr=1-1-spons&keywords=plastic+cutlery&psc=1
plastic	5	g	1	heavy duty	https://open.library.ubc.ca/cIRcle/collections/undergraduateresearch/18861/items/1.0108511
PP spoon/knife/fork	10.4	lb	1000	heavy duty	https://www.amazon.com/AmazonBasics-Heavy-Weight-Plastic-Spoons-000-Count/dp/B0758G4MQC/ref=sr_1_1_sspa?s=home-garden&ie=UTF8&qid=1534495568&sr=1-1-spons&keywords=plastic+fork&psc=1
PS fork/knife	7	g	1	heavy duty	lab measurement
PS fork/knife	11.8	kg	1000	N/A; assumed heavy duty	https://www.sciencedirect.com/science/article/pii/S0956053X0800295X?via%3Dihub
PP spoon/knife/fork	2.3	lb	400	medium duty	https://www.amazon.com/Plastic-Cutlery-Medium-Weight-Disposable/dp/B007WM0WHK/ref=sr_1_12?s=home-garden&ie=UTF8&qid=1534495568&sr=1-12&keywords=plastic+fork
plastic	2.6	g	1	light duty	https://open.library.ubc.ca/cIRcle/collections/undergraduateresearch/18861/items/1.0108511
PP spoon/knife/fork	5.95	lb	1000	light duty	https://www.amazon.com/AmazonBasics-Light-Weight-Plastic-Forks-000-Count/dp/B0758G4MNR/ref=sr_1_2_sspa?s=home-garden&ie=UTF8&qid=1534495568&sr=1-2-spons&keywords=plastic+fork&psc=1

SUNP: Wood

Table 40: Online sources for defining the SUNP option for cutlery

ITEM	WEIGHT (size ~6")	UNIT	No of ITEMS	REFERENCE
Birch spoon/knife/fork set	27.2	oz	300	https://www.amazon.com/Disposable-Wooden-Cutlery-Sets-Biodegradable/dp/B06XMRHGPW/ref=sr_1_6?s=home-garden&ie=UTF8&qid=1534431063&sr=1-6&keywords=disposable+cutlery+wooden+6%22&dpID=51VFivRHUrL&preST=_SX300_QL70_&dpSrc=srch
Birch spoon	8	Oz	100	https://www.amazon.com/dp/B01LY7Y5Y0/ref=psdc_15754771_t2_B002KIINCM
Birch spoon	3.2	oz	25	https://www.amazon.com/Wowlife-Length-Disposable-Cutlery-Silverware/dp/B00ZFWP3SW/ref=sr_1_6?s=home-garden&ie=UTF8&qid=1534427689&sr=1-6&keywords=birch+cutlery+6&dpID=41Z5VxbB7SL&preST=_SY300_QL70_&dpSrc=srch
Birch spoon	9.6	oz	250	https://www.amazon.com/dp/B01B4GC0WY/ref=psdc_15754771_t1_B00HZANN1G
Birch fork	16	oz	200	https://www.amazon.com/Perfect-Stix-Green-Fork-158-200ct/dp/B00T0NW0UG/ref=sr_1_24?s=home-garden&ie=UTF8&qid=1534430077&sr=1-24&keywords=disposable+wooden+cutlery+6%22
Birch knife	10.4	oz	100	https://www.amazon.com/Perfect-Stix-Disposable-Cutlery-100ct/dp/B00HZANQZE/ref=pd_bxgy_328_img_3?_encoding=UTF8&pd_rd_i=B00HZANQZE&pd_rd_r=C8SS1M8EJNKXQJ5E64WQ&pd_rd_w=eKUng&pd_rd_wg=p59Bp&psc=1&refRID=C8SS1M8EJNKXQJ5E64WQ&dpID=41uqglGwS7L&preST=_SX342_QL70_&dpSrc=detail
Birch spoon/knife/fork set	28.8	oz	300	https://www.amazon.com/dp/B075Q58NWZ/ref=sspa_dk_detail_19?psc=1&pd_rd_i=B075Q58NWZ&pd_rd_wg=KXrzq&pd_rd_r=MXP295M0TR39YEA48DHC&pd_rd_w=3YEjE
Birch fork	3	g	1	Lab measurement

A.6. Plates

SUP: PS

Table 41: Online sources for defining the SUP option for plates

ITEM	WEIGHT (size ~9")	UNIT	NO OF ITEMS	Quality	REFERENCE
PS foam plates	440	g	100		https://www.amazon.co.uk/Foam-Plates-Disposable-Polystyrene-products/dp/B0085OJJHI
PS foam plates	11.2	ounce	50		https://www.amazon.com/Nicole-Home-Collection-Dinnerware-3-Compartment/dp/B00J4JXEEW/ref=sr_1_9_s_it?s=hpc&ie=UTF8&qid=1537430778&sr=1-9&refinements=p_n_feature_keywords_five_browse-bin%3A6146354011
PS foam plates	11.8	lb	200		https://www.amazon.com/Multi-Purpose-Great-Value-Soak-Proof-Disposable/dp/B01DXYFOLO/ref=sr_1_16_s_it?s=hpc&ie=UTF8&qid=1537430461&sr=1-16&refinements=p_n_feature_keywords_five_browse-bin%3A6146354011
PS foam plates	15.5	ounce	100		https://www.amazon.com/Foam-Disposable-Polystyrene-products-Products/dp/B0085OJJHI

SUNP: Paper

Table 42: Online sources for defining the SUNP option for plates

ITEM	WEIGHT (9" diameter)	UNIT	NO OF ITEMS	REFERENCE
Paper plate	0.51	oz	1	https://www.amazon.com/Plates-inches-Disposable-Dinner-Classic/dp/B0771KDBRP/ref=sr_1_1_sspa?s=home-garden&ie=UTF8&qid=1534503268&sr=1-1-spons&keywords=paper+plate+9+inch&psc=1
Paper plate	1.49	lb	100	https://www.amazon.com/Nicole-Home-Collection-Everyday-Dinnerware/dp/B0053KORAQ/ref=sr_1_8?s=home-garden&ie=UTF8&qid=1534503268&sr=1-8&keywords=paper+plate+9+inch&dpID=41YrqOwIYML&preST=_SY300_QL70_&dpSrc=srch
Paper plate	2.45	lb	32	https://www.amazon.com/dp/B01F96791W/ref=sspa_dk_detail_11?psc=1&pd_rd_i=B01F96791W&pd_rd_wg=3bKVK&pd_rd_r=38WJNV9PPHAZVNWX5NKN&pd_rd_w=6021c
Paper plate	2.9	lb	200	https://www.amazon.com/Nicole-Home-Collection-Everyday-Dinnerware/dp/B00P2XTTS4/ref=pd_bxgy_328_img_2?_encoding=UTF8&pd_rd_i=B00P2XTTS4&pd_rd_r=729K2FF36Q8DDM1VA2QY&pd_rd_w=AcspL&pd_rd_wg=VtFFV&psc=1&refRID=729K2FF36Q8DDM1VA2QY&dpID=41JmI5jcuZL&preST=_SY300_QL70_&dpSrc=detail
Paper plate	16.3	lb	600	https://www.amazon.com/Daily-Chef-Heavy-Paper-600ct/dp/B0023XPX0E/ref=sr_1_2?s=home-garden&ie=UTF8&qid=1534504929&sr=8-2&keywords=Bakers+and+Chefs++Paper+Plates+9+inch&dpID=41EnxWVGN-L&preST=_SY300_QL70_&dpSrc=srch
Paper plate	3.39	lb	100	https://www.amazon.com/dp/B00D5YOQBW/ref=psdc_15750751_t4_B0771KDBRP
Paper plate	2.9	lb	100	https://www.amazon.com/Nicole-Home-Collection-Count-Heavy/dp/B01CFVR48W/ref=sr_1_8?s=industrial&ie=UTF8&qid=1534505560&sr=1-8&keywords=Paper+Plates+coated
Paper plate	8.47	g	1	LAB

A.7. Straws

SUP: PP

Table 43: Online sources for defining the SUP option for straws.

ITEM	WEIGHT (diam. ~22")	UNIT	NO OF ITEMS	REFERENCE
PP straw	5.4	oz	250	https://www.amazon.com/dp/B07B4JJ562/ref=psdc_15754801_t3_B01G43DKEY
straw	8.8	oz	500	https://www.amazon.com/dp/B07DPK6W15/ref=sspa_dk_detail_4?psc=1&pd_rd_i=B07DPK6W15&pd_rd_wg=5Y4Bo&pd_rd_r=Y38JSBB6QF70GYRKG82W&pd_rd_w=xI4tX
PP straw	8.6	oz	250	https://www.amazon.com/dp/B07BWK51SN/ref=sspa_dk_detail_3?psc=1&pd_rd_i=B07BWK51SN&pd_rd_wg=PTeWV&pd_rd_r=67V8MS4776H408E58H2D&pd_rd_w=jQt9B
PP straw	1.2	lb	1000	https://www.amazon.com/dp/B071ZNTBS3/ref=psdc_15754801_t5_B01G43DKEY?th=1

SUNP: Paper

Table 44: Online sources for defining the SUNP option for straws.

ITEM	WEIGHT (diam. ~23")	UNIT	NO OF ITEMS	REFERENCE
Paper Straw	10.6	oz	250	https://www.amazon.com/dp/B07DHM9LCC/ref=sspa_dk_detail_5?psc=1&pd_rd_i=B07DHM9LCC&pd_rd_wg=yFLnG&pd_rd_r=AZNSDM59A41P2N7RK543&pd_rd_w=ZcrNb
Paper Straw	8.2	oz	200	https://www.amazon.com/dp/B07D8TLQRG/ref=sspa_dk_detail_4?psc=1&pd_rd_i=B07D8TLQRG&pd_rd_wg=iM98m&pd_rd_r=NAJ29VSDT1R92BGA14Z5&pd_rd_w=Dn7VA
Paper Straw	9.8	oz	225	https://www.amazon.com/dp/B07CH3R3GF/ref=psdc_15754801_t4_B07CV8JG97
Paper Straw	6.4	oz	150	https://www.amazon.com/dp/B01N6P6AGK/ref=psdc_15754801_t4_B07CH3R3GF

A.8. Stirrers

SUP: PP

Table 45: Online sources for defining the SUP option for stirrers.

ITEM	WEIGHT (size ~7")	UNIT	NO OF ITEMS	REFERENCE
PS stirrer	5	g	1	https://www.alibaba.com/product-detail/Wholesale-transparent-disposable-plastic-stirrer-for_60743227911.html?spm=a2700.galleryofferlist.normalList.272.8d473748isivaS&s=p
PS stirrer	0.8	g	1	https://www.alibaba.com/product-detail/Manufacturer-directly-supply-custom-design-long_60747893707.html?spm=a2700.7724857.normalList.6.185959f2rw0rCF&s=p
PS stirrer	2.6	g	1	https://www.alibaba.com/product-detail/5-Hot-Drink-Mixer-disposable-Tea_60377317990.html?spm=a2700.7724857.normalList.1.185959f2rw0rCF&s=p
PS stirrer	12.6	kg	5000	https://www.alibaba.com/product-detail/Wholesale-transparent-disposable-plastic-stirrer-for_60743227911.html?spm=a2700.galleryofferlist.normalList.30.23212191X6spOB&s=p
PP stirrer	3	g	1	https://www.alibaba.com/product-detail/5-Hot-Drink-Mixer-disposable-Tea_60377317990.html?spm=a2700.7724857.normalList.1.185959f2rw0rCF&s=p
PP stirrer	1	g	1	https://www.alibaba.com/product-detail/5inch-130mm-PP-Disposable-Plastic-Coffee_60559226492.html?spm=a2700.7724857.normalList.65.185959f2rw0rCF

Table 46: Online sources for defining the SUNP option for stirrers.

ITEM	WEIGHT (size ~7")	UNIT	NO OF ITEMS	REFERENCE
birch wood stirrer	2.08	lb	1000	https://www.amazon.com/dp/B079L13R34/ref=psdc_2566784011_t2_B078NM1KKB
birch wood stirrer	5	oz	100	https://www.amazon.com/Disposable-Birchwood-Coffee-Sticks-Stirrers/dp/B077XB3HZT/ref=sr_1_5?s=home-garden&ie=UTF8&qid=1534515437&sr=1-5&keywords=Wooden+Stirrers+7%22&dpID=516TKxmjNaL&preST=_SX300_QL70_&dpSrc=srch
birch wood stirrer	1	lb	1000	https://www.amazon.com/Birch-Stirrers-coffee-sticks-7-Inch/dp/B00350J4GS/ref=sr_1_31_sspa?s=home-garden&ie=UTF8&qid=1534516804&sr=1-31-spons&keywords=wooden+stirrers+%26+birch&psc=1
birch wood stirrer	2.25	lb	1000	https://www.amazon.com/dp/B074YZCMDM/ref=psdc_2566784011_t1_B00350J4GS

8.3 Appendix C

This appendix presents the results for the comparison of Multi Use (MU) products compared to the Single Use Plastic (SUP) products. The material for the MU alternative for cutlery, stirrers and straws is stainless steel, while for cotton buds and clamshells is polyethylene (PE).

A.9. Modelling of MU Alternatives

In order to calculate the impact of the multi-use products, the *Use Phase* should be included, as in this case it is important. The use phase includes the washing of the product and to determine it, a process for the market for dishwashing had to be modelled.

Market for Dishwashing:

According to the EC (EC, 2018b) report the market for dishwashing in Europe comprises of 40% hand wash and 60% machine wash. The values for energy, water and detergent consumption for the market of dishwashing are presented in Table 47 and Table 48 for the best case scenario and the worst case scenario respectively, and they were taken from the EC (2018b). The values are given per item washed. Waste water treatment of the water used, is included as well.

Table 47: Processes for in the used for the modelling of the market of dishwashing (best case scenario)

Name	Amount/item	Unit	Comment
Domestic waste water treatment, 2003, EU-27, ELCD	0.07*0.6+0.319*0.4	kg	machine wash+hand wash
non-ionic surfactant production, ethylene oxide derivate; GLO	0.0002	kg	machine wash+hand wash total
tap water production, underground water without treatment; CH	0.07*0.6+0.319*0.4	kg	machine wash+hand wash
Electricity-DK	0.006*0.6+0.009*0.4	kWh	machine wash+hand wash

Table 48: Processes for in the used for the modelling of the market of dishwashing (worst case scenario)

Name	Amount	Unit	Comment
Domestic waste water treatment, 2003, EU-27, ELCD	0.115*0.6+1.181*0.4	kg	machine wash+hand wash
non-ionic surfactant production, ethylene oxide derivate; GLO	0.0005	kg	machine wash+hand wash total
tap water production, underground water without treatment; CH	0.115*0.6+1.181*0.4	kg	machine wash+hand wash
Electricity-DK	0.008*0.6+0.03*0.4	kWh	machine wash+hand wash

The report provided an estimation on the number of uses of each product during its life cycle and it is presented in

Table 49.

Table 49: Assumed no of uses for the MU alternatives of the products (EC, 2018b)

Product	No of uses
Cotton buds	734
Cutlery	4416
Food containers	515
Straws	5412
Stirrers	11274

The Impact from the dishwashing is multiplied with the impact from washing one item as follows:

$$Impact\ of\ washing, entire\ life\ cycle_i = impact\ of\ washing\ one\ item * No\ of\ uses\ of\ item_i\ (1)$$

Where *i* is indicating the product studied, *impact of washing one item* is the impact from the processes given in Table 47 and Table 48 and the *No of uses of item*$_i$ is given in

Table 49.

This Impact is added to the impact of the rest of the life cycle stages i.e. production, transport, disposal and total impact is divided by the number of uses of each product. This is to determine the impact corresponding to a single use of the MU products.
The above-mentioned can be expressed with formula (2):

$$Total\ impact\ of\ a\ single\ use\ of\ a\ MU\ product = \frac{Impact\ of\ the\ entire\ life\ cycle^{*}}{No\ of\ Uses} \quad (2)$$

*Including one time washing, multiplied by the number of uses.

The normalized impact of washing the items one time is given in Table 50 for the base case scenario and the worst case scenario:

Table 50: Normalized results for the market of dishwashing process. See

Table 4 or abbreviation explanation.

Name	CC	OD	HTC	HTNC	PM	IR	POF	TA	TE	FE	ME	ET	RD fos	RD el
	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE	PE
Washing burden per item (best case)	7.10E-07	2.01E-09	5.35E-07	8.40E-07	5.88E-07	2.72E-08	2.81E-07	4.09E-07	6.20E-07	2.80E-07	8.27E-07	9.30E-06	5.32E-07	1.03E-06
Washing burden per item (worst case)	2.18E-06	5.48E-09	1.30E-06	2.01E-06	1.53E-06	7.70E-08	8.19E-07	1.20E-06	1.77E-06	6.75E-07	2.36E-06	2.31E-05	1.50E-06	2.57E-06

The process contributing to the impacts for the dishwashing process are presented in Figure 34 Figure 35 for the best case and the worst case scenario respectively.

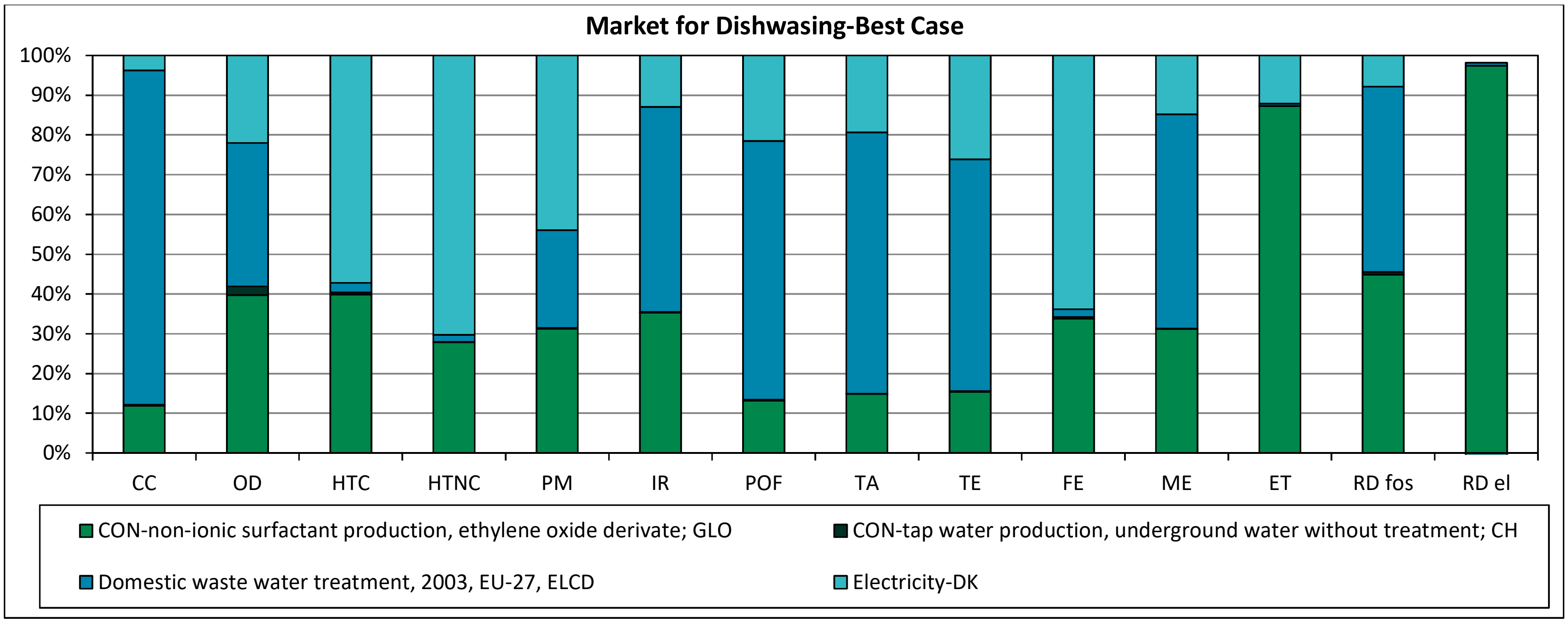


Figure 34: Process contribution for market for dishwasher, best case scenario.

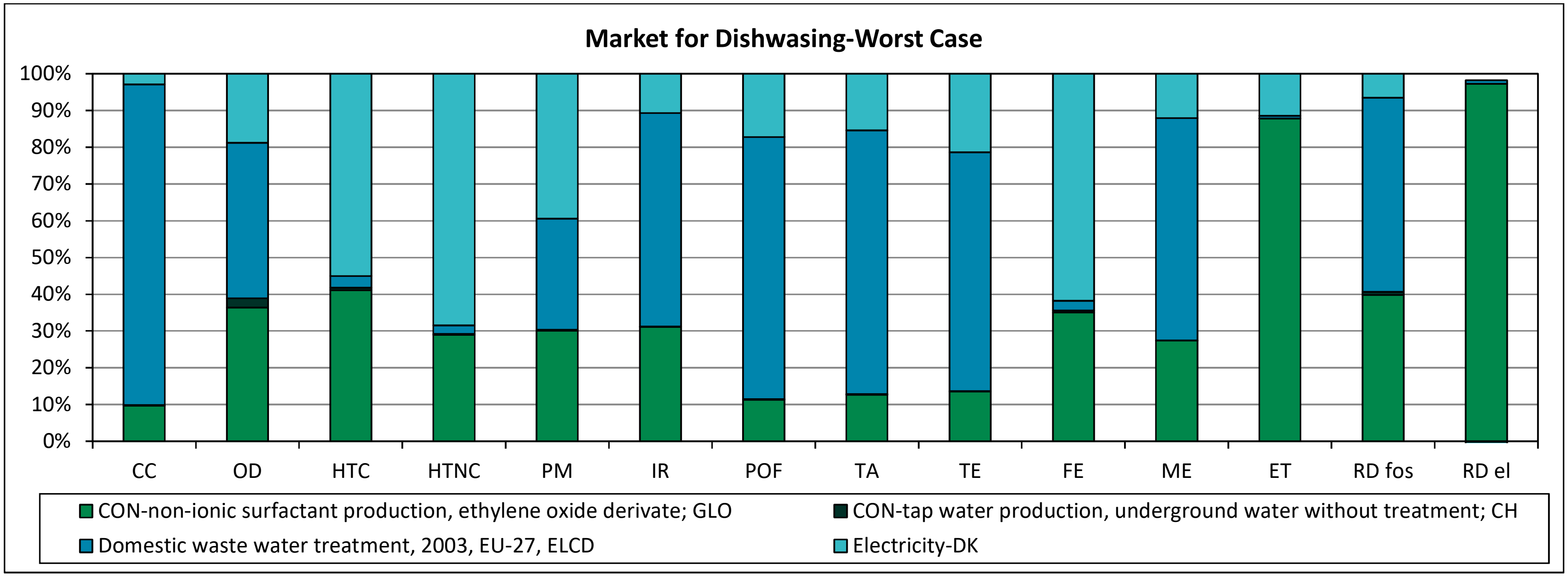


Figure 35: Process contribution for market for dishwasher, worst case scenario.

Results for Best Case Scenario

From Figure 36 to Figure 39 can be concluded that the MU option performs generally better than the SUP option for cutlery, clamshells and stirrers but not for cotton buds and straws, for the categories studied.

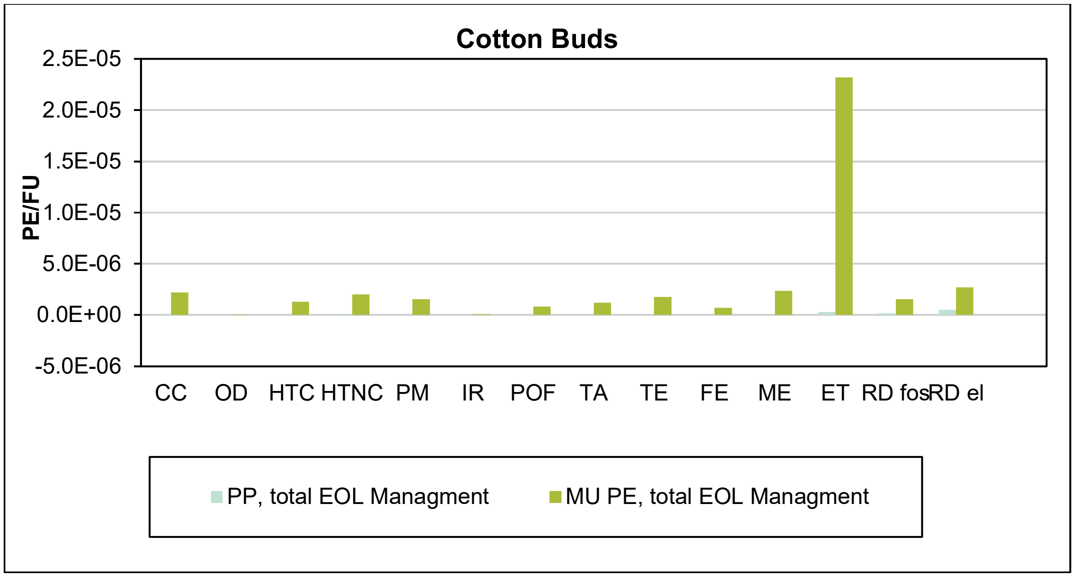


Figure 36: Normalized results for one SUP cotton bud and one MU cotton bud used one time, best case scenario. See

Table 4 or abbreviation explanation

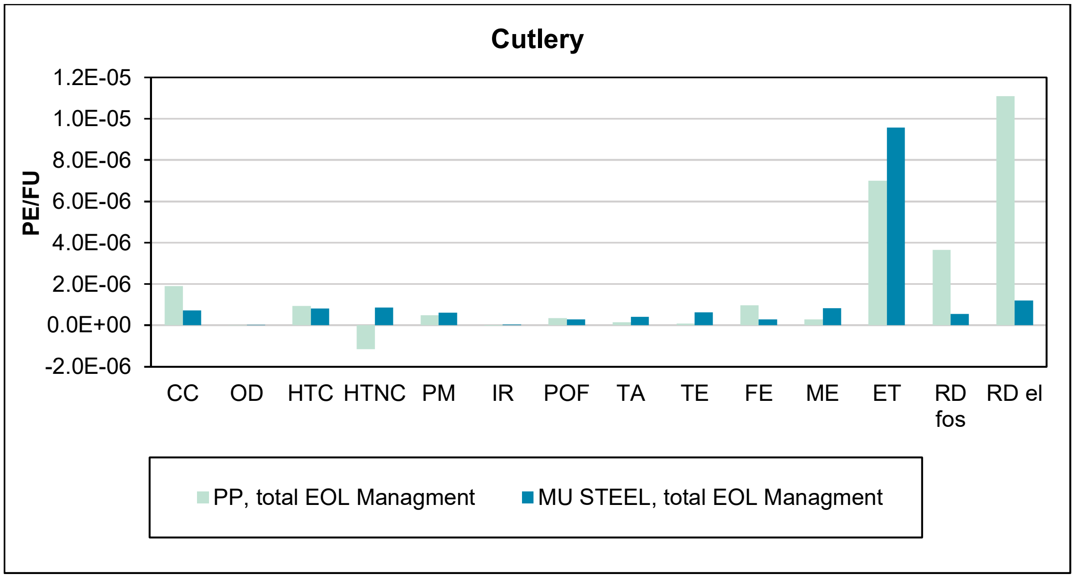


Figure 37: Normalized results for one SUP cutlery and one MU cutlery used one time, best case scenario. See

Table 4 or abbreviation explanation

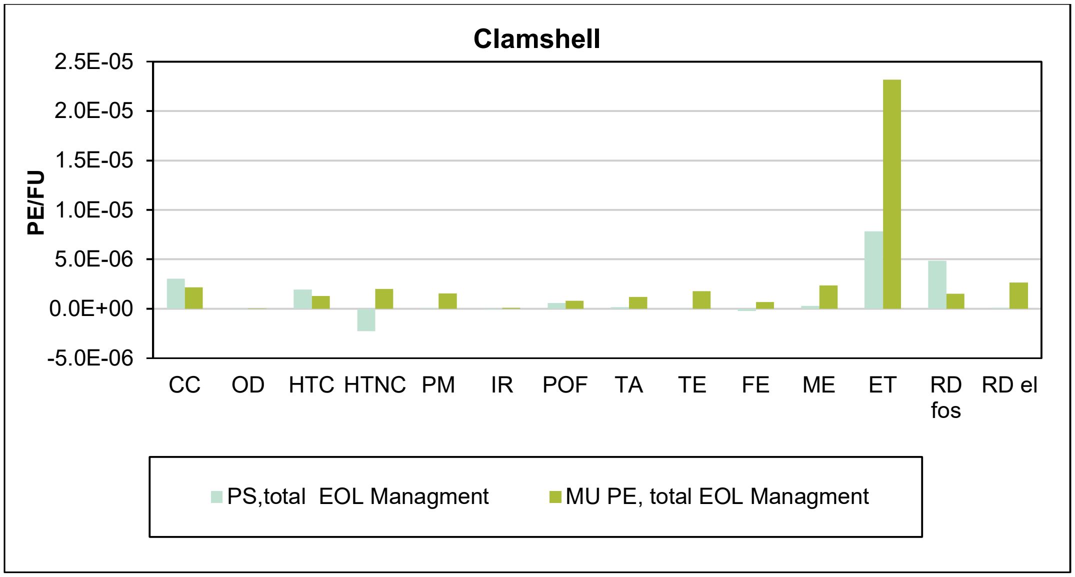


Figure 38: Normalized results for one SUP clamshell and one MU clamshell used one time, best case scenario. See

Table 4 or abbreviation explanation

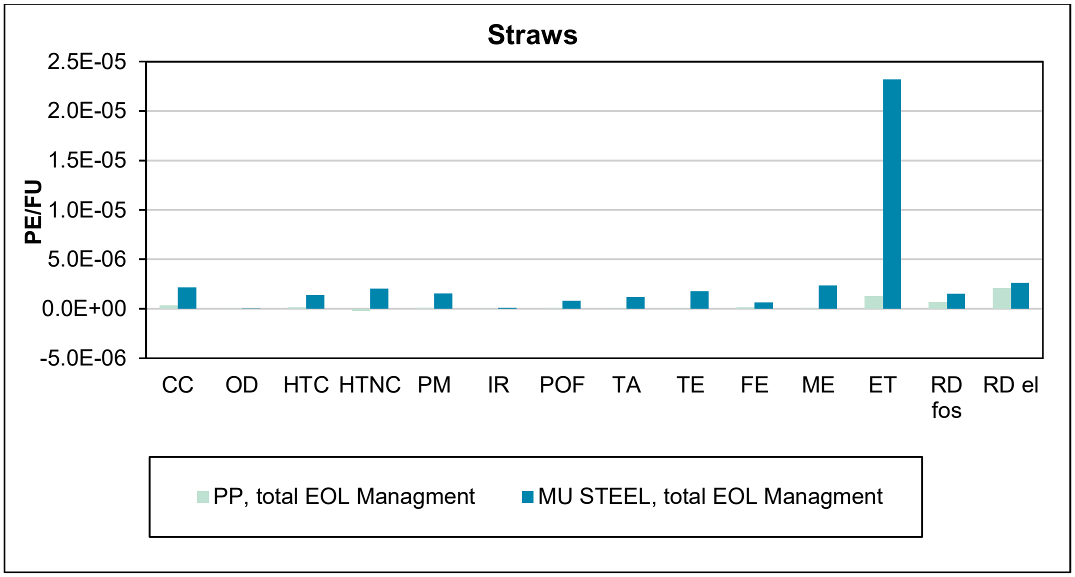


Figure 39: Normalized results for one SUP straw and one MU straw used one time,
best case scenario. See

Table 4 or abbreviation explanation

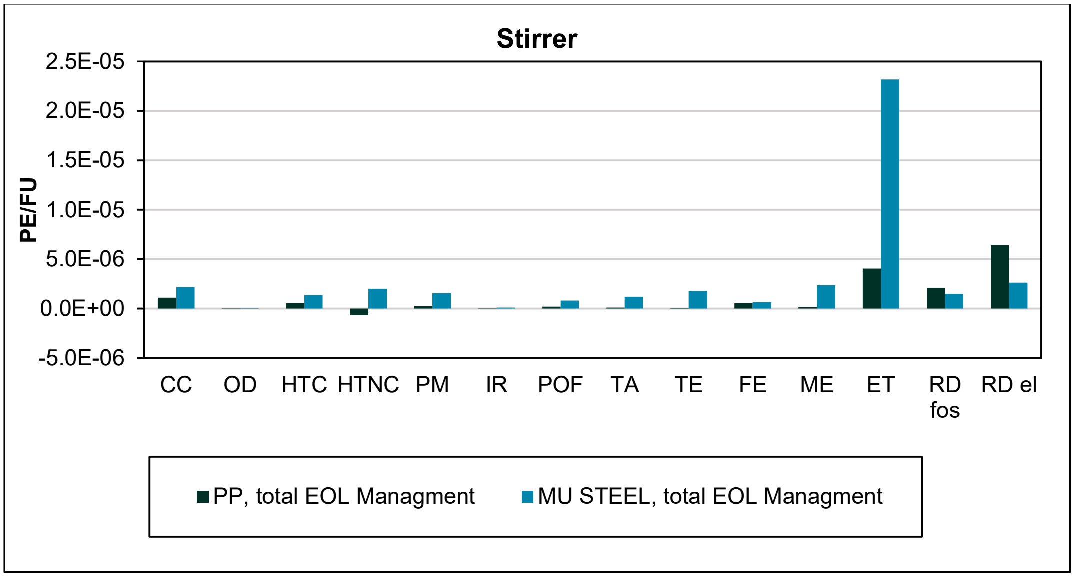


Figure 40: Normalized results for one SUP stirrer and one MU stirrer used one time,
best case scenario. See

Table 4 or abbreviation explanation

Worst Case Scenario'

For the worst case scenario MU performed generally better than SUP only for stirrers for the categories studied. For clamshells and cutlery MU and SUP perform the same, while for cotton buds and straws the MU products are less preferable than SUP (see Figure 40 to Figure 45).

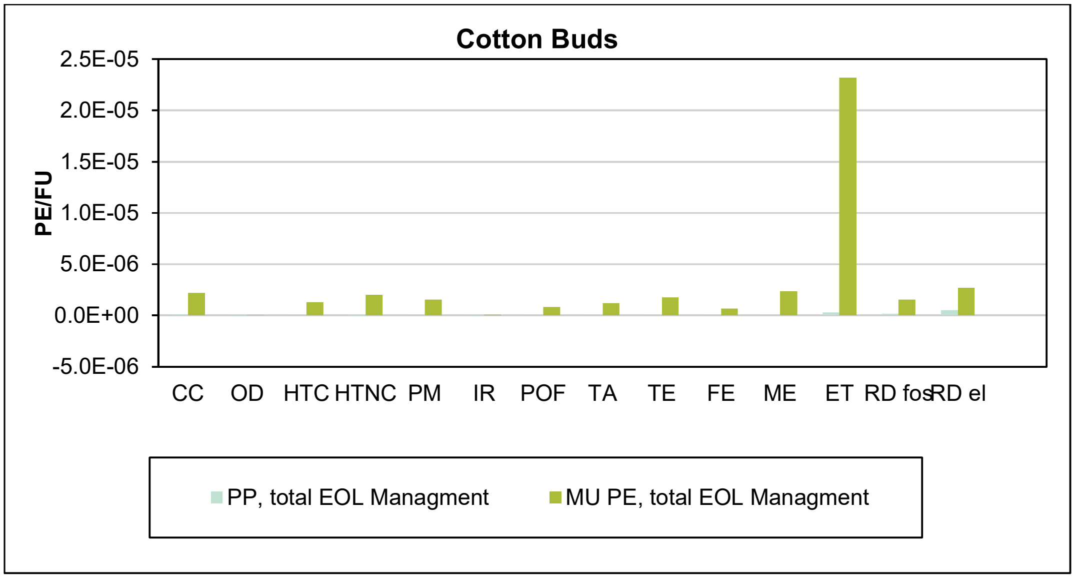


Figure 41: Normalized results for one SUP cotton bud and one MU cotton bud used one time, worst case scenario. See

Table 4 or abbreviation explanation

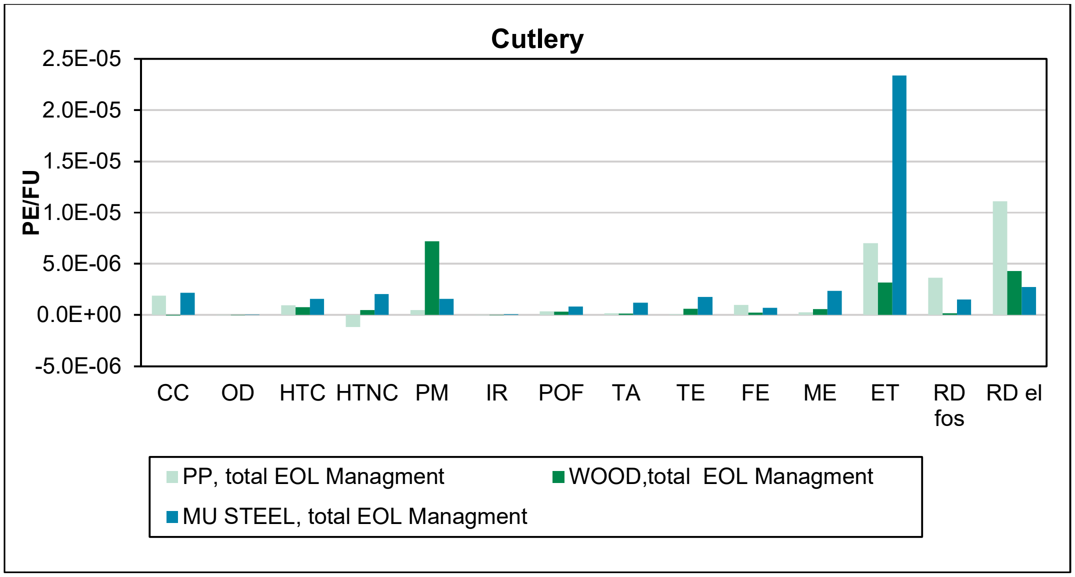


Figure 42: Normalized results for one SUP cutlery and one MU cutlery used one time,
worst case scenario. See

Table 4 or abbreviation explanation

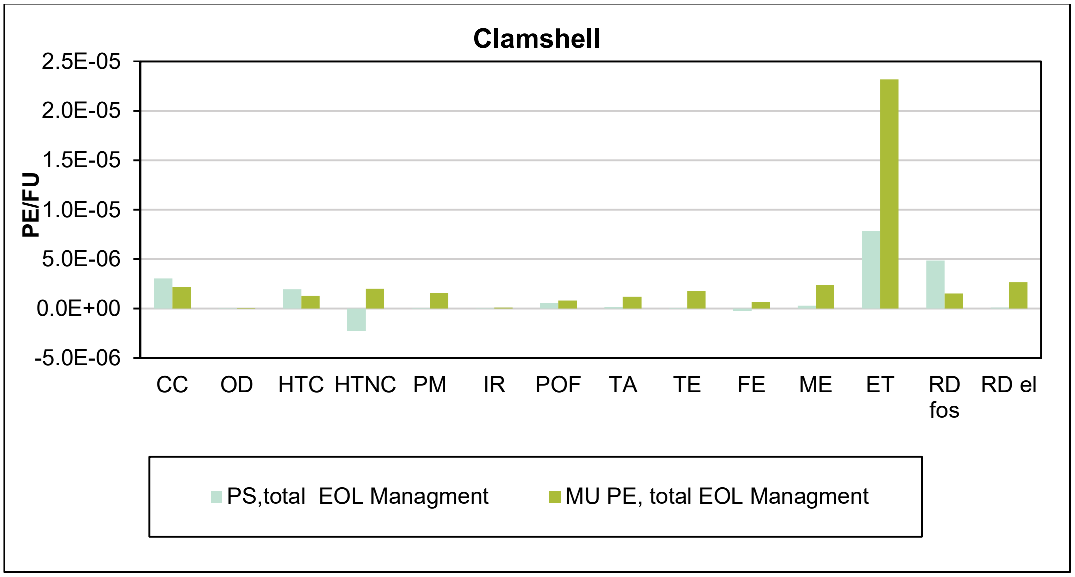


Figure 43: Normalized results for one SUP clamshell and one MU clamshell used one time, worst case scenario. See

Table 4 or abbreviation explanation

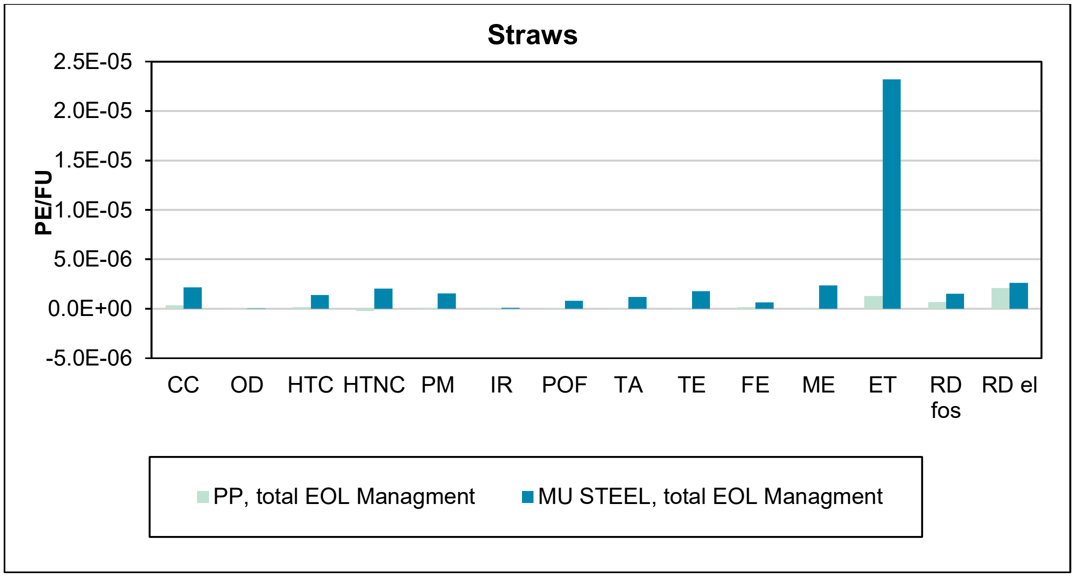


Figure 44: Normalized results for one SUP straw and one MU straw used one time, worst case scenario. See

Table 4 or abbreviation explanation

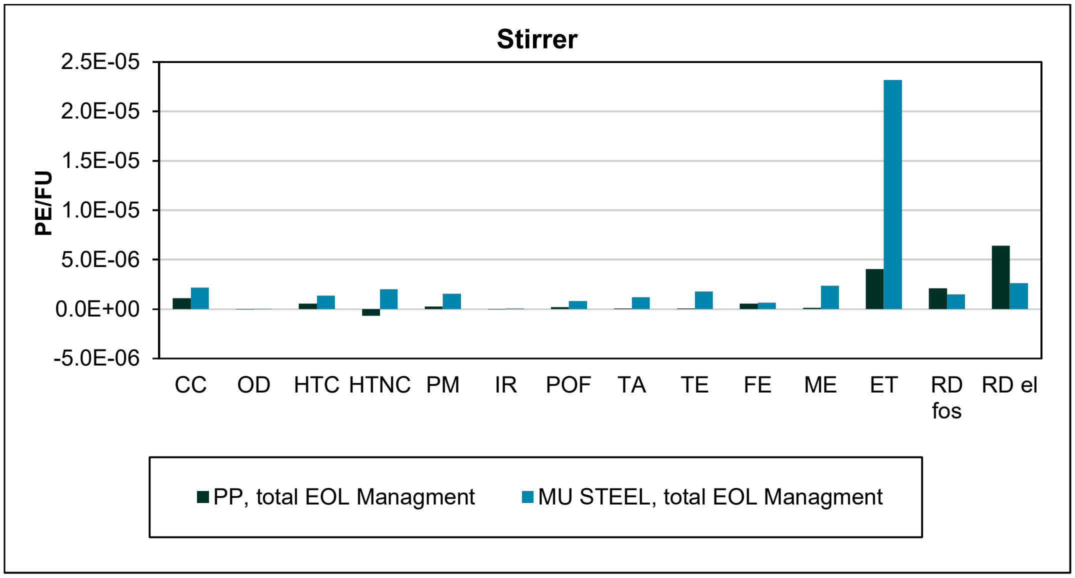


Figure 45: Normalized results for one SUP stirrer and one MU stirrer used one time, best case scenario. See

Table 4 or abbreviation explanation