UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

A Life Cycle Assessment of Plastic vs Cardboard Packaging in the Fast-Moving Consumer Goods Market

Prepared by

Stephanie Anne Rivett

1607396

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School of Chemical and Metallurgical Engineering,
Faculty of Engineering and the Built Environment, University of the Witwatersrand,
Johannesburg, South Africa.

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Supervisor: Professor Kevin Harding

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DECLARATION

I, *Stephanie Anne Rivett* declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

(Signature of candidate)

22nd day of August 2024

EXECUTIVE SUMMARY

Globally there is a movement to mitigate the need for single-use plastics as well as the utilization of plastic materials when alternative options are available. This movement comes in response to the extensive research that has demonstrated the long-term negative environmental impact that plastics pose to our existence when disposed of into landfills. A significant contributing factor to the mass of single-use plastics is the packaging industry. This study focused more specifically on the single use plastic packaging in the fast-moving consumer goods (FMCG) market which are used to shrink-wrap bottles together to be supplied into the trade such as Pick ‘n Pay and Checkers.

South Africa is facing two main challenges pertaining to the FMCG market: namely the constrained supply of energy and the socio-economic pressure to reduce the environmental impact caused by unrecycled packaging waste. This research aimed to investigate the energy requirements and environmental impact of packaging configurations that included shrink-wrap plastic and cardboard cartons versus packaging configurations that utilized only cardboard cartons to ascertain which option provides the lowest possible energy requirements, and environmental impact.

This study aimed to execute a cradle-to-grave life-cycle assessment (LCA) of the two different packaging configurations by utilizing the SimaPro software. The LCA was executed with respect to one reference product that is supplied into the FMCG market year-round known as Prewash Promo. Prewash Promo is a laundry pretreatment that aids in the removal of stains. The first of the two packaging configurations under analysis was the traditional packaging configuration of Prewash Promo that has always been used. This packaging configuration consisted of six bottles that were grouped into two sets of three using rubber bands. The two sets of three were then shrink-wrapped into a group of six. Two shrink-wrapped sixes were then placed into a box that was sealed using plastic packaging tape or sellotape. The second packaging configuration under analysis mitigated the use of shrink wrap plastic and associated materials (elastic bands) thus the second packaging configuration consisted of twelve bottles placed into the box that was then sealed using packaging tape.

The main objective of this LCA was to ascertain the packaging material configuration that was the most energy-efficient and environmentally responsible choice to utilize in the

FMCG market. This LCA was conducted utilizing the data pertaining to the year 2022 and the functional unit of this study was one year's worth of packaging used in the production of Prewash Promo. Prewash Promo was chosen as the reference product as it does not demonstrate seasonal or geographically specific use, and it was a viable option for the change in packaging configuration.

A significant factor that influenced the impact of LCA results was the waste scenarios associated with the use of different materials. In this study, the exact quantities of material that were recycled versus sent to landfills could not be definitively known. It was for this reason that the published industry standard recycling rates for the year 2022 and knowledge of socioeconomic habits were used to formulate assumptions. It was assumed that the minor materials included in the packaging configurations such as packaging tape and elastic bands conformed with social habits and did not exhibit any recycling and went directly to landfill. The recycling rate of corrugated board for the year 2022 was reported to be 61.4% and the recycling rate of plastic for the year 2022 was reported to be 42.8% (Mpact Recycling, 2019a). These recycle rates were utilized to model the packaging configurations to facilitate the comparison between the two. The validity and influence of these assumptions were assessed by means of a sensitivity analysis after the main LCA was executed.

The ecoinvent 3 database library available via the SimaPro software (version 9.4.0.3, 2022) and the ReCiPe Midpoint method were used to execute the impact assessment calculations. This method consisted of eighteen impact categories that assessed the impact of each of the packaging materials with respect to the impact they posed to human health, biodiversity, and resource scarcity. The full eighteen category impact assessment was condensed into five focus categories based on the target audience, the research objectives and geographical location of the study. These five focus categories were: global warming, stratospheric ozone depletion, fine particulate matter formation, freshwater ecotoxicity and water consumption. These five categories were chosen because they provide the best overview of the impact in a summarized form pertaining to factors contributing to environmental decline, changing weather conditions, reduction in air quality and the impact of freshwater resources.

The LCA was first executed for each packaging configuration in isolation to ascertain the impact contributions of each of the individual factors involved in the construction of the packaging set-up. The analysis of each packaging configuration in isolation facilitated highlighting major contributing factors to consider replacing with alternatives or mitigating the use thereof. This assessment highlighted the drastic impact contribution that the use of electricity had on the impact score of the heat shrink-wrap plastic configuration.

The full LCA comparison was then executed to compare the two packaging configurations. In each of the five focus impact categories the corrugated board only packaging configuration achieved an environmental impact score 83% lower than the heat shrink-wrap plastic packaging configuration. This drastic difference was only reduced to 79.6% when excluding long-term emissions.

Upon the conclusion of the LCA comparative assessment the validity of the recycle rate assumptions for corrugated board and shrink-wrap plastic were assessed by executing sensitivity analyses. These analyses determined that the conclusion achieved at the end of the LCA comparison stage remained valid irrespective of the recycling rate of corrugated board or shrink-wrap plastic.

The final objective investigated in this study was the uncertainty analysis to assess the accuracy and reliability of the data utilized in the LCA. The uncertainty analysis was executed in the SimaPro software by utilizing a Monté Carlo analysis with the ReCiPe 2016 midpoint (H) method which consisted of 1 000 fixed runs with a confidence interval of 95%. An uncertainty bar chart was generated that displays the error associated with each of the eighteen impact categories. The uncertainty analyses for both packaging configurations determined that the data for global warming, stratospheric ozone depletion, fine particulate matter formation and freshwater ecotoxicity demonstrated low error. The cardboard only configuration exhibited very low error values of between 8% and 61% as opposed to the plastic packaging configuration which exhibited errors between 16% and 214%. The water consumption data in contrast exhibited significant uncertainty for both configurations due to the difficulty in definitively determining accurate water consumption data for such extensive life cycles. Water was utilized extensively in the developmental stages of each of the materials (forestry, paper/pulp manufacturing and plastic polymer and plastic shrink manufacturing) and exhibited significant variation in volume of consumption due to high degrees of variation in plant technology and process equipment age.

The culmination of the results of each of the assessments executed concluded that the corrugated board only configuration is the packaging configuration that is the most environmentally friendly, and energy-efficient packaging option of the two that were considered.

ACKNOWLEDGEMENTS

I would like to thank the following people and organizations for their contributions to this study:

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ACRONYMS AND ABBREVIATIONS

CFCs	Chlorofluorocarbons
CV	Coefficient of variation
DALY	Disability adjusted life years
ECO	Ecotoxicity
EI	Ecoinvent
EP	Eutrophication
eq	Equivalent
EU	Europe
FU	Functional Unit
FMCG	Fast-Moving Consumer Goods
GHG	Greenhouse gas
GLO	Global
GW	Global warming
GWP	Global warming potential
HFCs	Hydrofluorocarbons
HHC	Human health cancer
HHNC	Human health non-cancer
ISO	International Standards Organization
kg	Kilogram
kg CFC11 eq	Kilogram trichlorofluoromethane equivalent
kg CO_2 eq	Kilogram Carbon Dioxide Equivalent
kg 1,4-DCB eq	Kilogram 1,4-Dichlorobenzene equivalent
kg NO_x eq	Kilogram nitrogen oxide equivalent

kg P eq	Kilogram phosphorus equivalent
kg PM2.5 eq	Kilogram particulate matter 2.5 micrometers or smaller equivalent
kg SO_2 eq	Kilogram sulfur equivalent
kg 1,4-DCB	Kilogram 1,4-Dichlorobenzene
kW	Kilowatt
kWh	Kilowatt-Hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m^3	Cubic Meter
MW	Megawatt
MWh	Megawatt-hour
ODP	Ozone depletion potential
RoW	Rest of the World
SEM	Standard error of mean
US	United States
USD	United States Dollar
WC	Water consumption
ZA	South Africa
ZAR	South African Rand

1. INTRODUCTION

1.1 Background

This research aimed to investigate the environmental impact of different packaging material configurations and their associated manufacturing processes. The primary focus was placed on cardboard cartons and shrink-wrap plastic as selling unit packaging options. The intention was to follow the manufacturing path of shrink plastic and cardboard all the way upstream from Sasol where the plastic pellets were produced as a byproduct of the petroleum industry and Sappi or Mondi where the paper was produced from virgin wood and recycled paper and cardboard. However, the primary focus was placed on the stage that encompasses FMCG product manufacturing as this was where the primary impact of this research was felt.

Globally the use of plastic packaging poses the challenges of consuming a finite fossil fuel, global low recycling rates and high carbon emissions. As opposed to cardboard, that utilizes a renewable raw material, exhibits recycling rates 6 times higher than plastic and offers carbon emissions that are less than a third of that of plastic (Matthew, 2023). These three factors support the global movement away from single-use plastics and unrecyclable packaging.

This research was of specific interest to the South African market as our energy grid is under significant strain; quantifying the environmental impact of the different packaging options will indicate the energy requirement for different materials from virgin conception through to the recycling process. This topic was chosen as it highlighted how traditional choices could evolve to reduce environmental impact and energy consumption to reduce the load on the already overloaded South African energy grid. Unlike existing data that focuses primarily on the economic costs and environmental impact of packaging choices for singular businesses in isolation, this research investigated the impact of different packaging options in its entirety, from conception to the recycling process including a multitude of companies in the chain. The objective of this research was to conduct an environmental life cycle assessment to quantify the environmental impact of each packaging material configuration including transport costs, energy costs, recycling costs and production costs. The aim of this research was to reduce the environmental impact and energy consumption by investigating the packaging material that provided the lowest impact in each sector.

1.2 Problem Statement

South Africa is facing two main challenges pertaining to the fast-moving consumer goods (FMCG) market: namely the constrained supply of energy and the socio-economic pressure to reduce the environmental impact caused by unrecycled packaging waste. This research aimed to investigate the energy requirements and environmental impact of packaging configurations that included shrink-wrap plastic and cardboard cartons versus packaging configurations that utilized only cardboard cartons to ascertain which option provided the lowest possible energy requirements, and environmental impact. This analysis focused on the stage in the lifecycle where cardboard and shrink plastic were utilized to package commodities to be supplied into the FMCG market. The focus was placed on this specific stage as this was where the greatest impact between the two packaging options was realized.

1.3 Research Aims and Objectives

This study aimed to execute an LCA of packaging material configurations used in the packaging of FMCG market product "Prewash Promo." More specifically focused on the LCA of plastic shrink wrap and corrugated board packaging in accordance with the ISO 14044 standard (International Organization for Standardization, 2006)

The goal of this study was to assess and compare the LCA of packaging configurations that include shrink wrap plastic and corrugated board cartons vs packaging configurations that only utilize corrugated board cartons, otherwise known as cardboard boxes. This study specifically aimed to achieve the following:

1. To provide a basis upon which stakeholders can make educated choices with regards to the type of packaging materials used in the production and distribution of commodities in the FMCG market.
    a. To identify the life cycle stages that had the greatest contribution to environmental impact.
    b. To provide viable alternatives for high environmental impact components or processes.

   c. To critically examine processes that contributed to problems uniquely faced by the South African economy.
   d. To provide consolidated information for future comparative studies.
2. To critically compare the results of the LCA of the two above-mentioned packaging configurations to ascertain the most environmentally friendly and economical efficient choice.

The main objective of this research was to ascertain the packaging material configuration that was the most energy-efficient and environmentally responsible choice to utilize in the FMCG market. The main objective was broken down into the following three sub-objectives.

a. To analyze the resource requirements (energy, water, equipment) of the heat-shrink plastic packaging configuration vs the cardboard only packaging configuration for the stages in the lifecycle up until the stage known as the FMCG product manufacturing stage.

b. To discuss if the packaging conditions (selling unit quantity, and packaging tape vs glue) in the FMCG market could be adjusted/changed to reduce the environmental impact (waste, fuel consumption and carbon emissions) of the materials.

c. To analyze the recycling processes of each of the materials to quantify and compare the environmental impact each of these materials poses and the extent to which each of the materials was recycled.

The intended audience of this study was all parties involved in the life cycle of shrink wrap plastic and/or corrugated board. This included all those involved in the production of virgin plastic and paper; the utilization and disposal of packaging materials; and the recycling and end-of-life processes. The target audience of this study was businesses involved in the manufacturing and packaging of FMCG commodities as this research aimed to provide a basis in which stakeholders may make informed decisions about packaging materials.

1.4 Structure of the Dissertation

Chapter 1: *Introduction*

The introduction to this dissertation provides a brief background into the study, the study problem statement and the aims and objectives the study strived to achieve.

Chapter 2: *Literature Review*

The literature review for this dissertation provided an in-depth analysis of the products and materials that were being assessed, the recycling scenarios of the materials mentioned, the local and international market influenced regarding these materials and products as well as an in-depth analysis of what a life-cycle assessment is and what it entails.

Chapter 3: *Goal and Scope of the Study*

The goal of the study defines what the study aimed to achieve and the target audience. The scope of the study provides greater detail into the representativeness of the chosen analysis sample with respect to the population, the chosen functional unit and reference flows as well as defines the system boundaries. The scope also aimed to define the omissions and exclusions, assessment criteria, data quality requirements and clarify the comparisons that will be executed in the study.

Chapter 4: *Life Cycle Inventory*

This chapter aimed to provide a detailed description of the data collection procedures, main data sources and the calculation procedures used in the management of the raw data for this study.

Chapter 5: *Results and Interpretation*

This chapter presented and analyzed all the results of the study: the life-cycle impact assessment results of each of the packaging configurations in isolation, the comparative results between the two packaging configurations, the sensitivity analysis of the waste scenarios of each packaging configuration as well as the uncertainty analysis of the data used in the main comparison.

Chapter 6: *Conclusions*

This chapter contains all conclusions drawn from the results of the LCA and corresponding analyses and the conclusion of the comparative study that was executed.

Chapter 7: *Recommendations*

This chapter aims to suggest recommendations and improvements that could have been made to this study and future studies in this field.

2. LITERATURE REVIEW

2.1. Products Under Study

2.1.1 Corrugated Board

Corrugated board is defined as the structure formed by bonding two or more sheets of fluted corrugating medium to one or more flat facing of linerboard. Corrugated board can be structured in multiple different formats that consist of a variety of combinations of liner board and fluted sheets (Cary, 2017). As described in Figure 1, corrugated board can consist of a multitude of combinations of fluted and flat sheets depending on the desired strength and thickness.

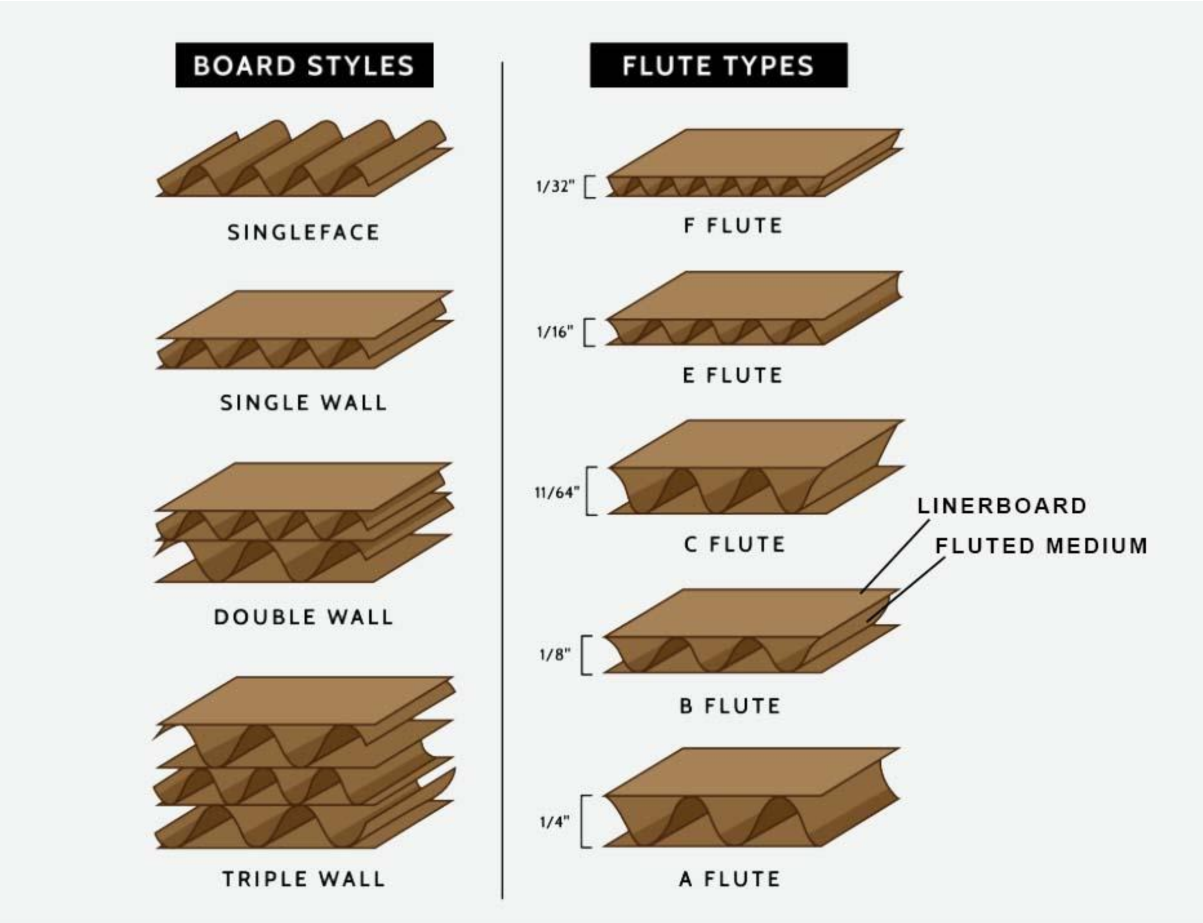

Figure 1: Different types of corrugated board (Southern Champion Tray, 2023)

For this study only double-faced or single wall corrugated board was considered which consists of two liner boards that enclose one sheet of fluted board as described in Figure 2.

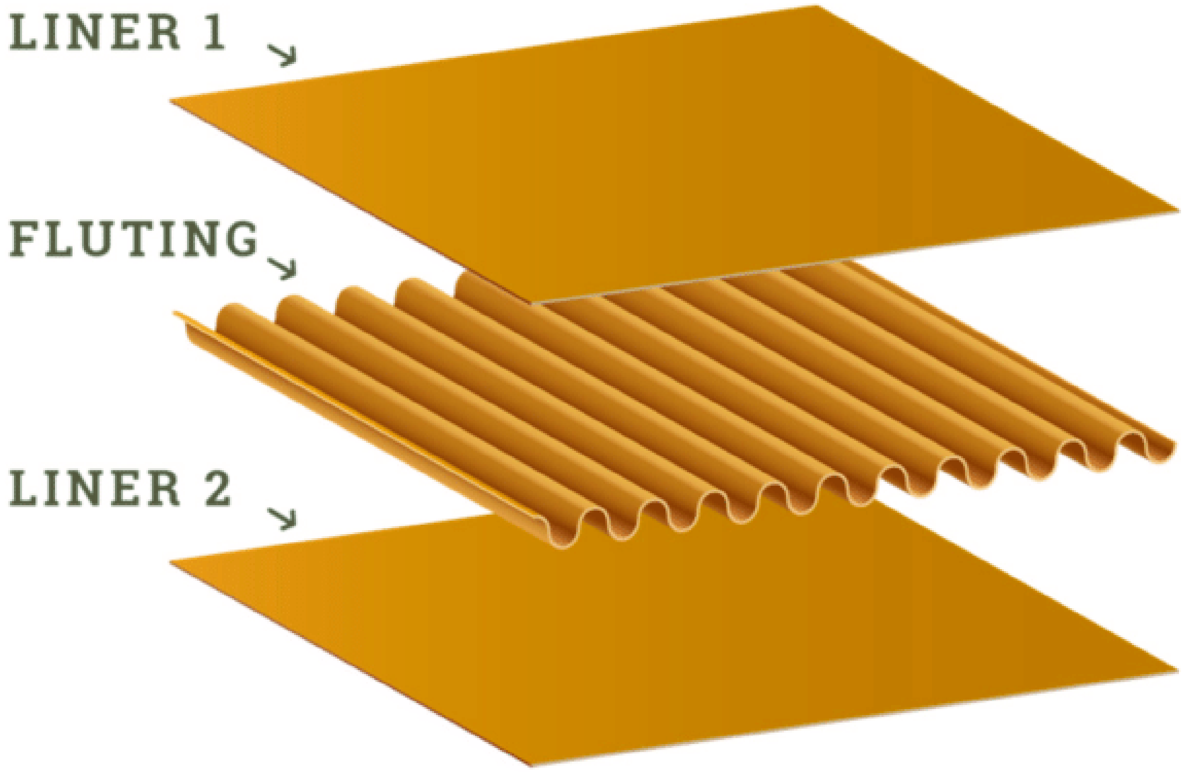

Figure 2: The structure of corrugated board (Böröcz et al., 2022)

2.1.2 Heat Shrink-Wrap Plastic

The second product investigated was shrink plastic film. Heat shrink wrap is any material that shrinks when exposed to heat. Shrink wrap is typically made of one of three different materials: polyvinyl chloride (PVC), polyolefin and polyethylene (Roake, 2016). The choice of material is primarily based on the required function it needs to perform and the force it needs to withstand.

PVC was the shrink wrap material of choice for many years with primary use in the retail sector. Prior to heating PVC shrink wrap is crinkly in appearance resembling cellophane but when heated it becomes rigid and hard. An advantage of PVC shrink wrap is it has very low shrink temperature requirements to be effective however when heated it emits chlorine gas which creates a hazardous work environment that requires additional ventilation previsions in place to mitigate the poisonous chlorine gas (Roake, 2016).

Polyolefin is a term used to describe polyethylene or polypropylene plastic. As opposed to the conventional choice of PVC, polyolefin does not pose the toxicity risk that PVC does because of the presence of chlorine. As such, it is suitable for use in the direct-contact packaging of food. Polyolefin also does not pose the same challenges for ventilation that PVC packaging does thus making it more user friendly. Polyolefin also provides better shelf stability than the conventional PVC shrink wrap packaging (Roake, 2016).

In contrast to the first two heat shrink wrap material options; polypropylene is primarily used in the packaging of heavier commodities such as water bottles and tinned food. Being the most common type of plastic in the world, it is available in a variety of thicknesses, strengths, shrink ratios and clarities depending on the requirements it needs to fulfil (Design Packaging and Tapes, 2018). Polypropylene plastic is the plastic of choice in shrink wrapping of products in the FMCG market owing to the high stretch rate and puncture resistance (Roake, 2016). Polypropylene also offers the option of additional branding on the shrink of products making the overall appearance of the product appealing and eye catching to the target market of the product. It is for these reasons that this study focused on the use of polypropylene heat shrink wrap.

2.1.3 FMCG Reference Product

This study analyzed two main packaging materials: corrugated board and shrink-wrap plastic. This investigation was executed by the in-depth analysis of the packaging materials and alternatives used in the packaging of an FMCG market product known as Prewash Promo, (Figure 3).

Figure 3: Prewash Promo product image

Prewash Promo is a multipurpose stain remover used across all ages and sectors from work clothes, school uniforms, formal attire, and casual wear. Prewash Promo does not demonstrate seasonal use nor is it influenced by climate or weather conditions (Concord Group, 2023).

Prewash promo sold 88 224 bottles in the year of 2022 which equated to 7 352 cases. The product is currently shrink wrapped into packs of six (Figure 4) and 2 shrinks are then packaged into a box (Figure 5). In terms of Prewash Promo, a case refers to a single box that contains two 6-pack shrinks (Concord Group, 2023).

Figure 4: Shrink wrapped Prewash Promo

Figure 5: Prewash Promo cardboard carton/shipper

The boxes, otherwise known as cardboard cartons or shippers are then packed onto a pallet containing forty individual cases of Prewash Promo which was pallet wrapped and shipped out to central distribution facilities that supply into the trade (Figure 6).

Figure 6: Prewash Promo pallet

This research aimed to investigate the impact of current packaging choices compared to alternatives. In the year of 2022, the 7 352 cases of Prewash Promo equated to 1 845 kg of cardboard, 191 kg of shrink wrap polypropylene plastic, 26 kg of packaging tape (Polyvinyl chloride), 19 kg of elastic bands (synthetic rubber) and approximately 27 MWh of electricity to run the shrink wrap tunnel.

This study analysed and compared the current packaging configuration that includes shrink wrapped plastic and a packaging configuration which does not utilize heat-shrink wrap plastic. The below sections clearly define the two primary materials under study: corrugated board and heat shrink wrap plastic.

2.2. Recycling

2.2.1 The Prevalence of Recycling

Cardboard

According to The Paper Recycling Association of South Africa, approximately 68.4% of paper and cardboard was recycled as of 2017 (Joseph and Jhetam, 2017). The percentage of paper recycling increased to 73% in 2020 with the credit given to the increase in recycling facilities and separate bins implemented in offices. Recycling offers a multitude of benefits that include reducing waste in landfills which in turn reduces the production of greenhouse gases; reducing the requirement for energy, water, and trees, and creating a multitude of job opportunities as recycling is a very labour-intensive activity with many stages (SL Recycling, 2023). Recycling one tonne of paper can save 26 498 litres of water, 1 438 litres of oil and approximately 3 m^3 of landfill space (Mpact Recycling, 2019b). The advantage of recycling paper and cardboard is that most types of cardboard and plastic can be recycled together in the same process apart from wax-coated cardboard which requires additional processing to break down this wax coating. Cardboard and paper also provide an indefinite opportunity to recycle the material. As demonstrated by the Mpact graphic (Figure 7), the chain of cardboard use is a cycle or circular economy that can continue indefinitely (Mpact Recycling, 2019b). It is however important to emphasize that although cardboard affords the opportunity for indefinite circular economy, in reality the life cycle of cardboard also includes disposal into landfills which do not facilitate the circular economy concept.

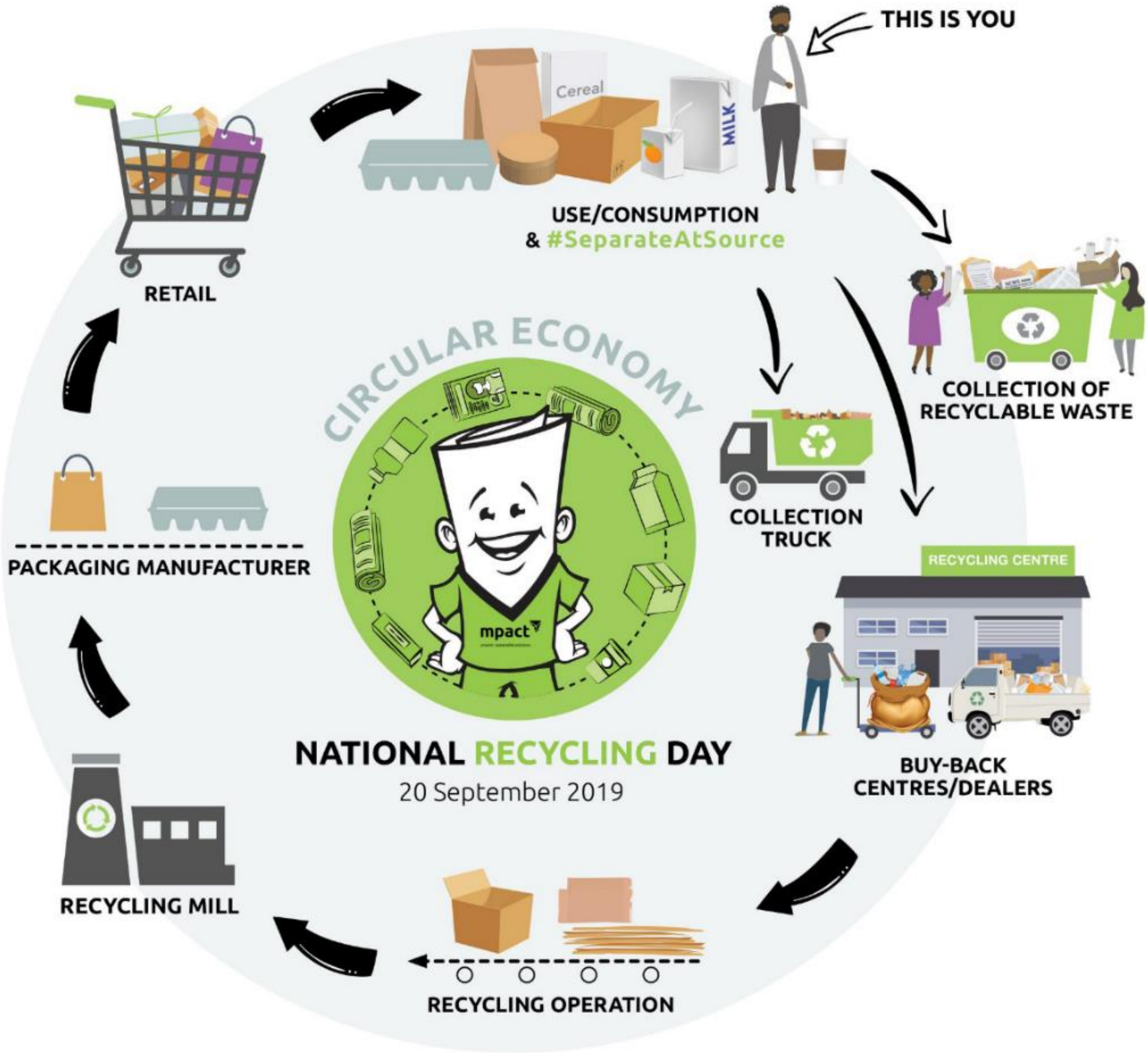

Figure 7: Mpact lifecycle of cardboard and paper (Mpact Recycling, 2019c)

The South African plastic recycling rate was approximately 45.7% as of 2019 of which more than half was the packaging. Aside from the environmental benefits of recycling, the plastic recycling industry contributes 2.3% to the South African GDP and 18.5% to the manufacturing GDP through job creation (SAPRO, 2021). It is estimated that between 60 000-90 000 waste pickers gain income opportunity by the recycling industry (Mpact Recycling, 2019b). For every tonne of plastic recycled, 5.7m^3 of landfill space is saved (SAPRO, 2021). In terms of recycling shrink plastic or plastic film, it presents challenges in mass recycling facilities as it can jam machines. As a result of the high risk of jamming machines the amount of plastic film that is recycled is drastically reduced as it poses additional challenges for recycling facilities to process the material. It is for this reason that many facilities do not recycle plastic film (American Chemistry Council Inc, 2021).

Another factor is the distinct types of plastic that need to be recycled separately. There are approximately fifty diverse types of plastic classified into seven identification classes. Each of these classes determines what resin the plastic is made from and how many times the material can be recycled (Hardin, 2021). Figure 8 clarifies what each of the seven classes includes.

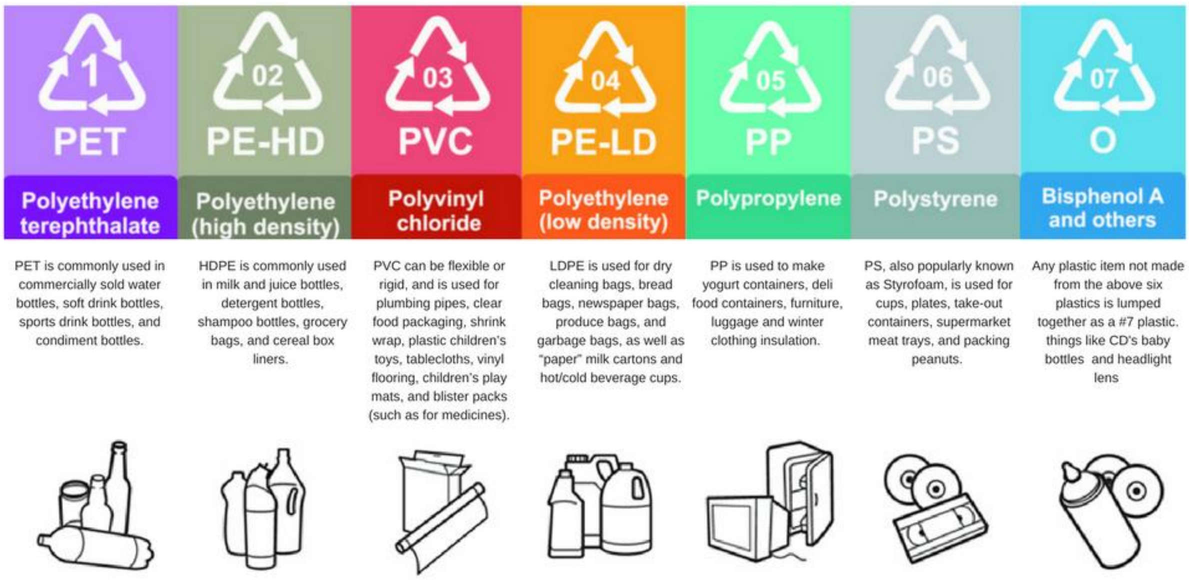

Figure 8: The seven different classes of plastics (GreenPeace, 2021)

Of these seven classes, only code one, PET, and code five, Polypropylene, plastics can potentially be recycled (Mitte, 2021). Code two and four have recently progressed towards becoming more recyclable but are heavily dependent on their previous use and what the containers were commissioned to hold. This is owing to the high possibility of certain chemicals impregnating the material making it unsuitable for recycling. Owing to the low rate of recycling of plastic many will argue to reduce the amount of plastic that is being manufactured owing to the low recycling rate which ultimately results in a greater volume of plastic accumulating in landfills. There is also a significant drive towards the increased use of reusable contains rather than single-use to eliminate the excessive influx of single-use plastics into the recycle chain and into landfills (Mitte, 2021).

2.2.2 Water Requirements

<u>Cardboard</u>

The production of cardboard from recycled paper uses approximately 24 m^3 of water to produce one tonne of paper compared to the 40 m^3 to produce one tonne of virgin paper.

The recycled paper production process uses approximately 47% less water than processes that produce virgin paper (Roger, 2021).

Shrink Plastic

The main difference between the water usage in cardboard recycling and plastic recycling is the requirement for water in cleaning of plastics before the recycling process may begin. Although soiled cardboard or paper presents challenges in the recycling process, the challenges are mitigated as all recycled paper and cardboard is converted back into pulp that is cleaned. Whereas with plastic, the material needs to be cleaned prior to beginning the recycling process as contaminants will interfere with the melting-down of the plastic to be reconstituted. The volumes of water are significant, and the recycling of this water is minimal as it requires extensive decontamination prior to reuse.

2.2.3 Energy Requirements

Cardboard

The main energy requirement in the paper and cardboard making processes are founded in the drying and curing processes. In paper production, the wet pulp needs to be dried to form paper and in the cardboard production process, heat is used to cure the starch glue that seals the layers together. Recycling cardboard reduced energy consumption by 25% compared to the production of virgin cardboard (Kukreja, 2021). The implementation of remuneration for collecting recyclable materials and the increase in facilities available to drop off recyclable compounds increases the volume of recyclables collected in an environmentally and economically friendly manner. This reduces pollution caused by excessive recyclable materials ending up in landfills and littering our streets.

Shrink plastic

According to a study undertaken by Franklin Associates for the Association of Plastic Recyclers (Franklin Associates, 2011), using recycled plastics rather than virgin plastic material reduces the total energy consumption by 88% for high-density polyethylene (HDPE) plastics, 79% for Polyethylene terephthalate (PET) plastics and 8% for Polypropylene (PP) plastics. As a result, the total emissions were limited by 71% for HDPE plastics, 67% for PET plastics and 71% for PP plastics (Franklin Associates, 2011). It must however be considered that although the energy and emissions savings for HDPE plastics are high, the prevalence of recycling of HDPE plastics is relatively low compared to other classes of plastics.

2.3. International Market

The impact of the international market on local South African use of plastic and cardboard is influenced by two main factors: costing and availability.

Cardboard

The South African paper and pulp industry is extensive and well established in both the local and international markets as the fifteenth largest pulp producers and the 24th largest paper producers in the world. Although the local production of paper is significant, the growth in demand for paper as of 2013 showed an increase in paper imports. This statistic has however shifted in recent years owing to the global shortage of cotton used in the production of paper. Sappi invested $380 million into a chemical cellulose project in Mpumalanga to meet the global demand for a cotton alternative. This migration from cotton to chemical cellulose has benefitted the local paper and pulp industry as the exports of paper and chemical cellulose has increased to meet the global demand for a cotton alternative (Fibre Processing and Manufacturing Sector Education and Training Authority and IQ Business, 2014).

Plastic shrink

Plastic is derived from a polymer produced as a by-product of the oil and fuel production industry. As such the availability of polymer is dependent on the volume of production of fuel. Similarly, the cost of the polymer fluctuates in the same way oil prices fluctuate (Mitte, 2021). From a South African perspective this can negatively impact the local requirement for polymer as the fuel price is determined by the international fuel market as such the pricing of fuel and polymer is in line with the international pricing. This negatively impacts the local market owing to the weak South African Rand exchange rate to the US Dollar. An additional factor to consider is that as polymer prices fluctuate towards lower prices it is cheaper to produce virgin plastic than to recycle. Although it may be economically positive as it poses lower economic costs, it increases the rate of pollution as plastics will not be recycled as readily (Mitte, 2021).

2.4. Local Market

The local market for plastic and cardboard is primarily influenced by the scarcity of water and constraints on energy supply. The local South African market is also influenced by the international market through imports and exports that determine local prices and available supply.

Cardboard

The growth of the paper and pulp manufacturing industry in South Africa has exceeded that of the international market growth. Rooted in local resources, human resources and innovation, the forest-to-paper economy equates to 0.6% of the South African gross domestic product (GDP), worth approximately R18.2 billion (Fibre Processing and Manufacturing Sector Education and Training Authority and IQ Business, 2014). There are five major producers of paper and pulp in the country: Mondi South Africa, Sappi, Mpact, Nampak and Kimberly-Clark. These plants are typically located in Gauteng, KwaZulu Natal, Mpumalanga and the Western Cape.

The Paper Manufacturers Association of South Africa (PAMSA) has highlighted the key role that the paper and pulp industry has in the renewable biomass-based energy market. The industry has successfully mitigated the annual 1.4 million tonnes of fossil fuel usage, drastically reducing the carbon emissions associated with pulp and paper production. Mondi and Sappi have placed a specific focus on sustainable manufacturing processes and have, as a result, mitigated the production of 3.66 million tonnes of fossil fuel carbon dioxide emissions. In addition to the reduced carbon emissions, the biomass-based energy production can potentially yield 15-20% more value from the forest resources located in Mpumalanga and KwaZulu Natal (PAMSA, 2021). This alternative source of energy is vital owing to the highly constrained energy grid in South Africa. Alternative means of generating power facilitates the process operating independently of the national grid (PAMSA, 2016).

Similarly, to the constrained energy grid, water is a scarce resource. It is thus vital that water is conserved as far as possible by reducing consumption and maximizing reuse and recycling of water. Although the production of pulp and paper is water intensive, producing paper from recycled material uses 47% less water than virgin material (Roger, 2021).

Shrink plastic

The local plastic market is dominated primarily by the packaging industry (52%) but also features the construction (13%) and agriculture (8%) sectors, among other smaller sectors. The sector divisions within the plastic market are demonstrated in Figure 9 (Plastics SA, 2021).

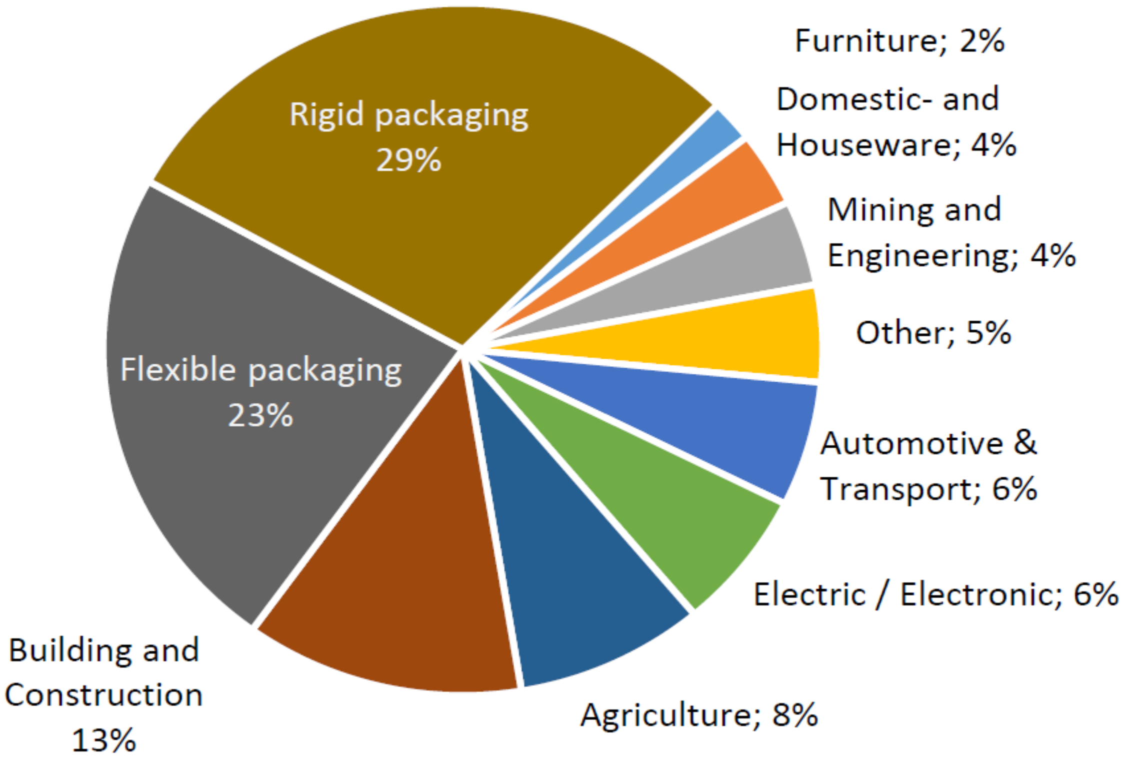

Figure 9: The sector divisions within the South African plastic market (Plastics SA, 2021)

In 2018, the plastic industry contributed more than 2.1% to the South African GDP and 21.8% to the manufacturing GDP. With approximately 1 800 companies nationally, the industry employs approximately 60 000 workers (Republic of South Africa | The Department of Trade Industry and Competition, 2018b). The local plastic production industry does not meet the requirements of the local demand for PE-LD, PE-LLD and PE-HD, however it exceeds the local demand for PP. As a result, excess PP is exported while PE is imported to meet the industry requirements. In 2018, the plastics imports exceeded the exports creating a trade deficit of R18.3 billion while the local domestic market was worth an estimated R84.4 billion – a deficit of 21.6% (Republic of South Africa | The

Department of Trade Industry and Competition, 2018b). The trade deficit between the years of 2009 and 2018 are visually depicted in Figure 10 (Republic of South Africa | The Department of Trade Industry and Competition, 2018b).

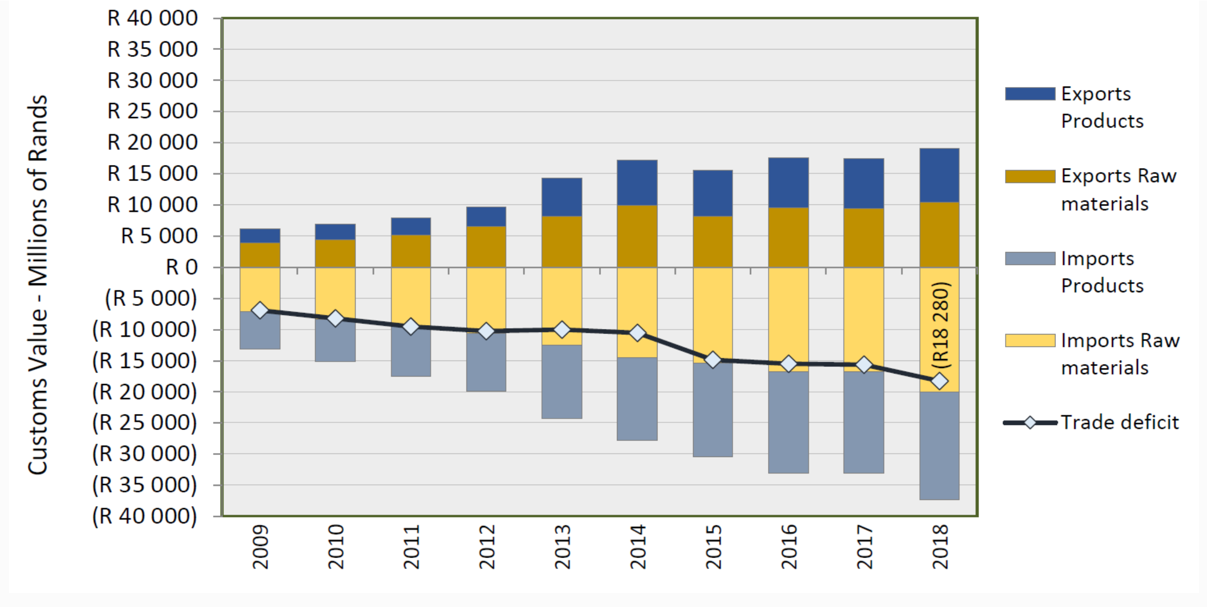

Figure 10: The South African plastic industry trade deficit between years 2009 and 2018 (Republic of South Africa | The Department of Trade Industry and Competition, 2018a)

Aside from the trade deficit, the local plastic market faces other challenges including the high cost of primary plastics, shortage of required skills, small local market, and high electricity costs (Conradie, 2018).

2.5. Life cycle assessment (LCA)

2.5.1. Stages of the LCA

A life cycle assessment is defined as the systematic analysis of potential environmental impacts of products or services for the duration of the life cycle. The LCA is a cradle to grave approach that includes all the upstream and downstream processes. This includes all the associated inputs such as land and resources as well as the outputs or impacts on the air, water, and soil (Sphera's Editorial Team, 2020). The International Organization for Standardization (ISO) offers requirements and guidelines for executing the Life Cycle Assessment as per ISO 14040 and ISO 14044. (International Organization for Standardization, 2006)

The LCA consists of four main stages:

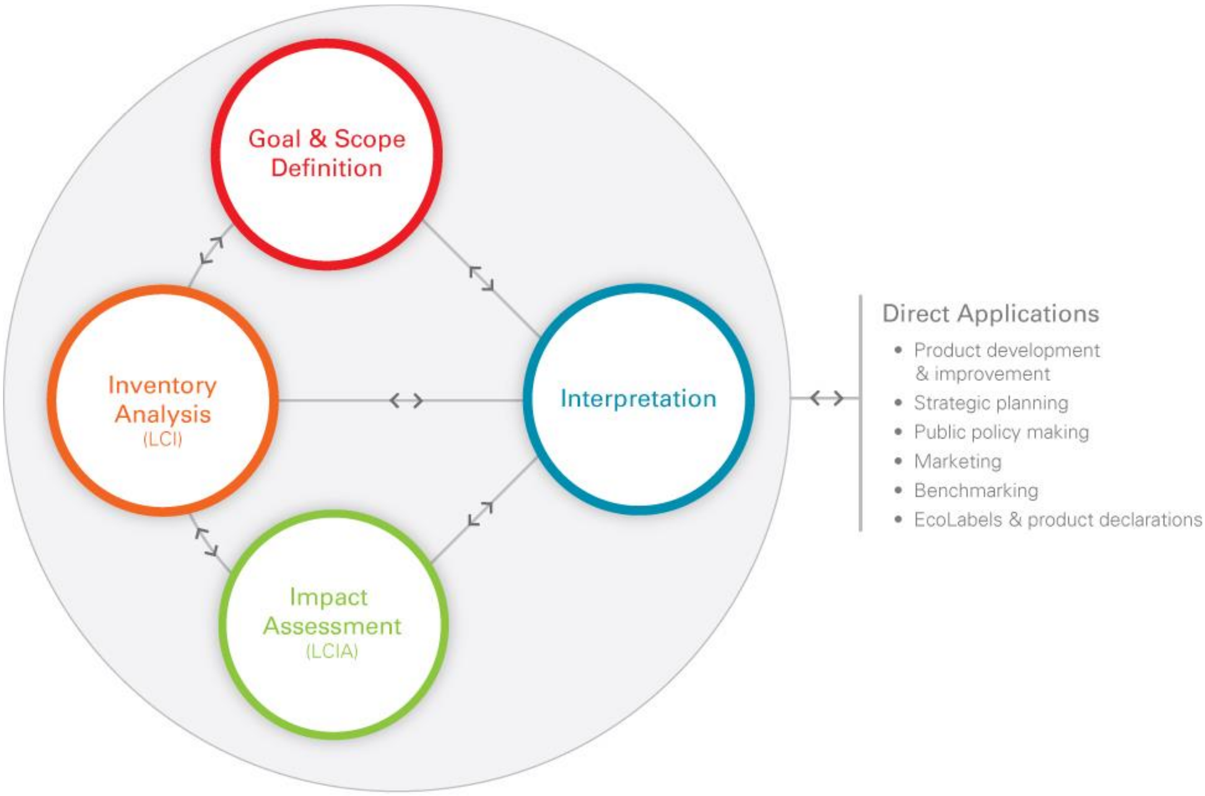

Figure 11: LCA stages graphic (Life Cycle Association of New Zealand, 2023)

Goal & Scope Definition

This stage aims to define the product or service that is to be assessed, the functional basis of comparison and the level of detail of the analysis. By defining a goal, the scope is defined that includes the objective/s, application, and the target audience. Defining the goal determines whether the study aims to conduct a product comparison, product improvement, or a strength and weakness analysis. Defining the functional unit or basis determined the level detail of the investigation (Harding, 2011). The goal and scope definition determines the time frame in which the assessment is executed and the extend of the life cycle that is to be analyzed.

Inventory Analysis

The primary objective of this stage is to compile data and define the system boundaries. The inputs and outputs are analyzed to ascertain the resources sourced from the environment and the emissions into the environment. The final inventory provides a full assessment of the mass and energy flows into and out of each of the defined systems

(Sphera's Editorial Team, 2020). The goal of the inventory analysis is to construct an inventory table that summarizes the mass and energy balances of the life cycle and all the defined systems (Harding, 2011).

Impact Assessment

The impact assessment utilizes all the mass information collated in the inventory analysis to convert it into a manageable number of representative values (Harding, 2011). The large database of information collated in the inventory analysis is converted to a manageable number of representative values relative to the defined functional unit. This concentration of information is executed in three steps: classification, characterization/normalization, and valuation. Classification defines the multitude of entries in the inventory table to an environmental problem. Characterization or normalization gives each category a weighting based on the relative impact to the defined category. The weighting factors are typically given in terms of a specific chemical and are multiplied by the amount of the relevant component. This value is then used as the contributing factor to the LCA score of that category. The valuation is the accumulation of the LCA scores calculated in the normalization step to achieve the final LCA score by the addition of category scores with respect to defined weightings in terms of the relative impacts of each category. By executing this concentration, the resource use and emissions generated quantified in inventory analysis are classified according to their potential impacts and quantify them with respect to a limited number of impact categories (Harding, 2011). These values are then assessed based on their relative importance to the defined LCA goal. The objective of the LCA is to translate emissions and resource extractions into a condensed number of environmental impact scores according to the established characterization factors (Environment, 2018).

Interpretation

The results obtained in stage three are discussed and analyzed with respect to data quality, relevance, contributions, robustness, and limitations. Each category will be systematically evaluated for possibilities to reduce negative environmental impacts. Primary focus is placed on avoiding burden shifting when reducing impacts (Sphera's Editorial Team, 2020). Interpretation of results would also determine data sensitivity and address the presentation of the results.

2.5.2. Assessment Libraries and Methods

SimaPro provides access to five main data libraries:

- Agri-footprint (economic allocation)
- Ecoinvent (allocation, cut-off by classification)
- EU and Danish Input Output
- Industry data 2.0 (includes data from Plastics Europe, ERASM, World Steel, International Molybdenum Association and the Alliance for Beverage Cartons and the Environment)
- US Life Cycle Inventory database

There are several additional data libraries available that may be used in SimaPro but are externally sourced for downloads on the SimaPro format.

This LCA utilizes one main data library stored on the SimaPro software. This data library is known as the Ecoinvent 3 library. The Ecoinvent Association is a non-profit organization based in Zurich, Switzerland. The association's main objective is to provide high-quality data for sustainability and LCA assessments worldwide (The Ecoinvent Association, 2023). With over 20 years of experience, the ecoinvent database currently contains over 20 000 life-cycle inventory data sets which are updated annually to ensure the most accurate and reliable data is available (The Ecoinvent Association, 2023).

The Ecoinvent 3 data library was chosen for this study based on the current, reliable data which it offers with the objective of achieving the most accurate and current impact assessment of the packaging configurations being studied.

After selecting the database library, the method of calculation and assessment in the LCA needs to be selected. SimaPro includes six categories of methods:

- European (methods that are European data focused)
- Global (methods developed with a global scope)
- Northern American (methods for the North American region)
- Single Issue (methods that focus on a single metric or environmental impact area)
- Water footprint (methods to assess only water related impacts)
- Superseded (outdated or no longer supported methods)

Based on the scope and geographical location of this study, the global methods category was selected as this group of methods provided the closest possible representation of the conditions in South Africa. There are three methods within the global category: IMPACT World+, LC-Impact and ReCiPe 2016.

The IMPACT World+ method exhibits results on both the midpoint and endpoint levels however it examines only with respect to the quality of ecosystems and human health and does not consider the impact to areas of concern such as water resources and carbon emissions. Due to the importance of carbon emissions in the impact they pose on this study, this method was not selected to execute the LCA (Bulle *et al.*, 2019).

The LC-Impact method utilizes only the endpoint level and offers no weighting or normalization. These characteristics place limitations on the data results and for these reasons this method was not selected (Verones *et al.*, 2020).

For this study, the ReCiPe Midpoint method was utilized. The ReCiPe method was collaboratively developed between Radboud University Nijmegen, Dutch National Institute for Public Health and the Environment, Leiden University and PRé Sustainability in 2008. The main objective of this method was to condense the vast list of life cycle inventory results into a limited number of impact categories relative to the varying environmental impact severity (PRé Sustainability, 2023).

The ReCiPe method was established on two indicator levels which consisted of 18 midpoint indicators or 3 endpoint indicators (Huijbregts *et al.*, 2017). For both indicator levels the factors can be divided into three main cultural perspectives which represent a series of decisions regarding time, proper management or future technology that may mitigate future environmental damage (PRé Sustainability, 2023). These three cultural perspectives as per the description provided by PRé Sustainability are:

- **Individualist**: short term model which relies on the development and progression of technology to mitigate future problems.
- **Hierarchism**: considered to be the default model, it is common in scientific models and is otherwise known as the consensus model.
- **Egalitarian**: long term model which is based on precautionary principle thinking.

The ReCiPe midpoint method was utilized as opposed to other impact calculation methods because it provided the widest range of impact categories which utilized impact mechanisms that are relevant on a global scale and unlike other methods it does not include potential impacts from future extractions but rather models such impacts as being included in the inventory analysis (PRé Sustainability, 2023).

Since the ReCiPe method was first developed in 2008, it has been reviewed and updated annually, most recently under the supervision of Radboud University (PRé Sustainability, 2023). The most recent update is ReCiPe 2016 which was collaboratively developed by the Dutch National Institute for Public Health and Environment (RIVM), Norwegian University of Science and Technology, PRé Sustainability, and Radboud University Nijmegen (PRé Sustainability, 2023).

2.5.3. Monté Carlo Analysis

The Monté Carlo method is a method of assessing the uncertainty of a dataset or measurements. This method takes samples from input distributions, transforms the selected sample to obtain the derived results and summarizes the resulting distributions to demonstrate the uncertainty associated with the dataset (Jamroz and D.F., 2021). This method of uncertainty analysis is particularly useful as it is accurate for both linear and nonlinear data transformations and is highly effective for systems with complex data outputs such as LCA results (Papadopoulos and Yeung, 2001). The utilization of this method is however limited to studies that have access to extensive computing resources as the analysis is highly computationally intensive. The Monté Carlo uncertainty analysis method is specifically useful in the assessment of LCA results as it facilitates the assessment of large and small uncertainties and is equipped to analyze complex datasets such as those which are generated when executing an LCA.

The use of the SimaPro software facilitated the use of the Monté Carlo uncertainty analysis tool that is built into the software. The uncertainty analysis results vary based on the study but for this study the uncertainty analysis results generated consisted of normally distributed graphs which gave an indication of the mean, median, standard deviation, coefficient of variation (CV) and the standard error of mean (SEM). The mean being the average of the data and the median the middle value of the data set. The mean and median in relation to one another gives an indication of the degree of distribution of the data as well as the degree of accuracy. Standard deviation is a measure of the degree of dispersion of the dataset relative to the mean. The higher the standard deviation value the greater the dispersion of data about the mean (Hargrave, 2023). The coefficient of variation is a measure of the dispersion of data about the mean. It is a ratio of the standard deviation to the mean and is a useful tool is comparing dispersion of one dataset to another (Hayes, 2023). The standard error of mean is an indication of the amount of discrepancy expected by the dataset compared to the true value of the population outside of the testing sample. Thus it is preferable to have a SEM as low as possible which would demonstrate that the data is as close to that of the true population value as possible (Kenton, 2023).

2.5.4. LCAs within the Packaging and FMCG Sectors

No prior life-cycle impact assessment comparisons between heat shrink-wrap plastic and corrugated board in the FMCG market could be sourced. However, studies into alternatives for heat shrink-wrap plastic have been executed in accordance with the worldwide movement away from single use plastics (Jannes, R. et al., 2023). The study considered four alternatives for bundling of products such as the bottles used in the FMCG market. The four materials under analysis were:

- Low-density polyethylene shrink film.
- Recycled low-density polyethylene shrink film.
- Ecogrip (existing paper-based bundle packaging)
- Ecobundle (new corrugated board-based bundle packaging)

The three-bundle packaging are shown in the Figure 12:

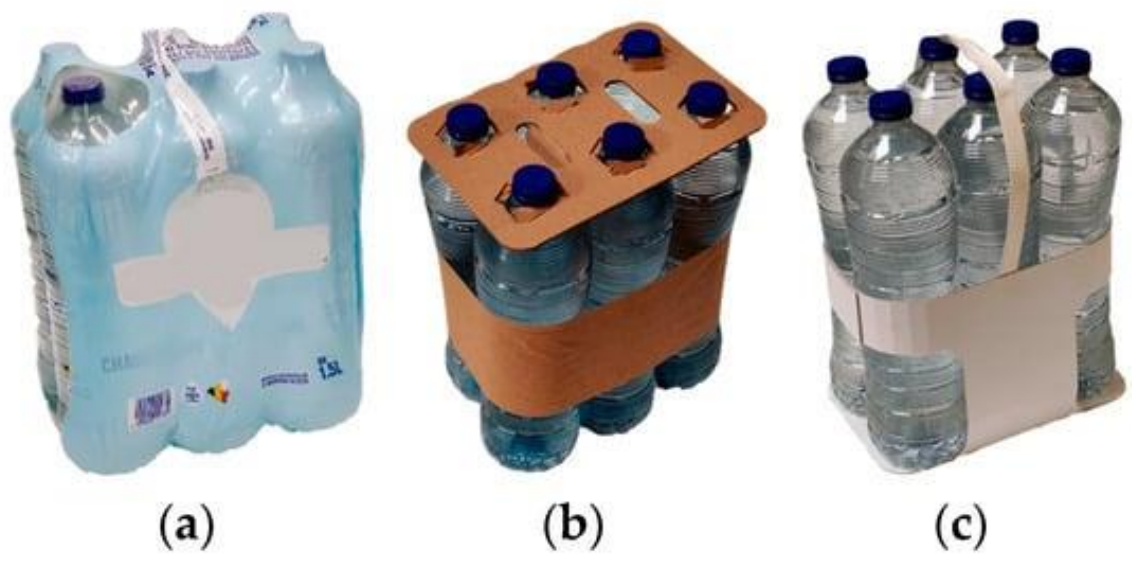

Figure 12: Graphic of the shrink-wrap plastic case study alternatives considered: (a) Recycled low-density polyethylene shrink film; (b) The Ecogrip paper wrap: and (c) The Ecobundle corrugated board bundle (Jannes, R. et al., 2023)

Figure 12 (a) depicts the recycled low-density polyethylene shrink film. Figure 12 (b) depicts the Ecogrip which is existing paper alternative to the use of plastic and Figure 12 (c) depicts the Ecobundle which is the new corrugated board-based bundle packaging (Jannes, R. et al., 2023).

The study concluded that the new Ecobundle paper-based packaging offered the lowest LCA impact score (Jannes; Vanhauwermeiren; Slaets; Juwet, 2023).

3. GOAL AND SCOPE OF THE STUDY

3.1. GOAL OF THE STUDY

The goal of this LCA was to study the impact of two different packaging configurations used in the FMCG market. This study was conducted with respect to the product known as Prewash Promo which is supplied into the trade year-round. The data from the year 2022 was used to assess the annual packaging requirements of an FMCG product.

The assessment was executed from the conception of virgin plastic and corrugated board to the disposal of said materials at the end of the FMCG commodity packaging stage. This LCA did not assess the impacts associated with the process downstream of the FMCG packaging/manufacturing stage. Beyond this stage only the disposal of the packaging was relevant, which was accounted for and analyzed by conducting sensitivity analyses on the impact that the extend of recycling vs end of life disposal as on the LCA of each configuration.

The target audience of this study was all stakeholders involved in the packaging of commodities that are supplied into the FMCG market. However, the audience could also extend to all parties involved in processes upstream and downstream of FMCG packaging stage. The choice of packaging material at this stage will influence the volume of material required from upstream process and the extent of disposal required by downstream processes. The information and conclusions realized from this study could be used to reevaluate packaging choices to minimize environmental impact by identifying high impact materials and their associated processes.

3.2. SCOPE OF THE STUDY

This section aimed to describe the general scope of the study to achieve the above stated goal. This scope outlined the identification of the products under study, defined the boundaries of the systems and established the functional units and data quality requirements for the analysis.

3.2.1 *Representativeness*

Representativeness is an assessment that aims to determine the degree to which the data under analysis reflects the true population of interest (Cary, 2017). In this study, the population of interest was all companies and stakeholders involved in the manufacturing and packaging of commodities that are supplied into the FMCG market.

The laundry pretreatment product, Prewash Promo, was chosen to represent an average FMCG market commodity for several reasons:

a. The product is used year-round and does not demonstrate seasonal use. This ensures that the data used is not skewed by data at certain times of the year.
b. The 750ml bottle size is a good representation of the market of products that are packaged using heat shrink wrap and cardboard cartons that primarily varies between 500*ml* and 1*l* bottles.
c. The product is not geographically specific and is used countrywide across different climates and weather conditions.
d. Prewash Promo is a viable option to change from the current packaging configuration that includes heat shrink wrapping and cardboard cartons to a configuration of only cardboard cartons.

Assessing the validity of selecting Prewash Promo in terms of the top thirteen products produced and sold into the trade by Concord Group, Table 1 details how Prewash Promo performs relative to the other twelve top performing products.

Table 1: Product choice rationalisation analysis table

Product	Number of units sold	% of total units sold	% of turnover
Product A	196 357	23.28	18.02
Product B	171 269	20.31	18.95
Product C	126 858	15.04	13.95
Prewash Promo	98 216	11.65	12.10
Product D	69 002	8.18	6.37
Product E	64 429	7.64	11.37
Product F	28 857	3.42	5.64
Product G	21 059	2.50	4.11
Product H	20 477	2.43	2.37
Product I	13 754	1.63	2.42
Product J	13 374	1.59	1.45
Product K	11 344	1.35	1.91
Product L	8 407	1.00	1.35

The details in Table 1 demonstrate that Prewash Promo is a good representation of an FMCG commodity in terms of the top thirteen products produced by Concord Group. Prewash Promo accounts for 12.1% of the turnover generated by the top thirteen products and 11.65% of the total units sold. Prewash Promo is a viable choice to represent an average FMCG market product as it is within the upper frame of turnover and total units sold but is not the biggest volume of product either. The data analyzed above demonstrates a good average in terms of the product population data accessible to execute this study.

The percentage distribution of total units sold in the year 2022 is displayed in the pie chart (Figure 13) which supports the claim that Prewash Promo demonstrates an average portion of the total units sold.

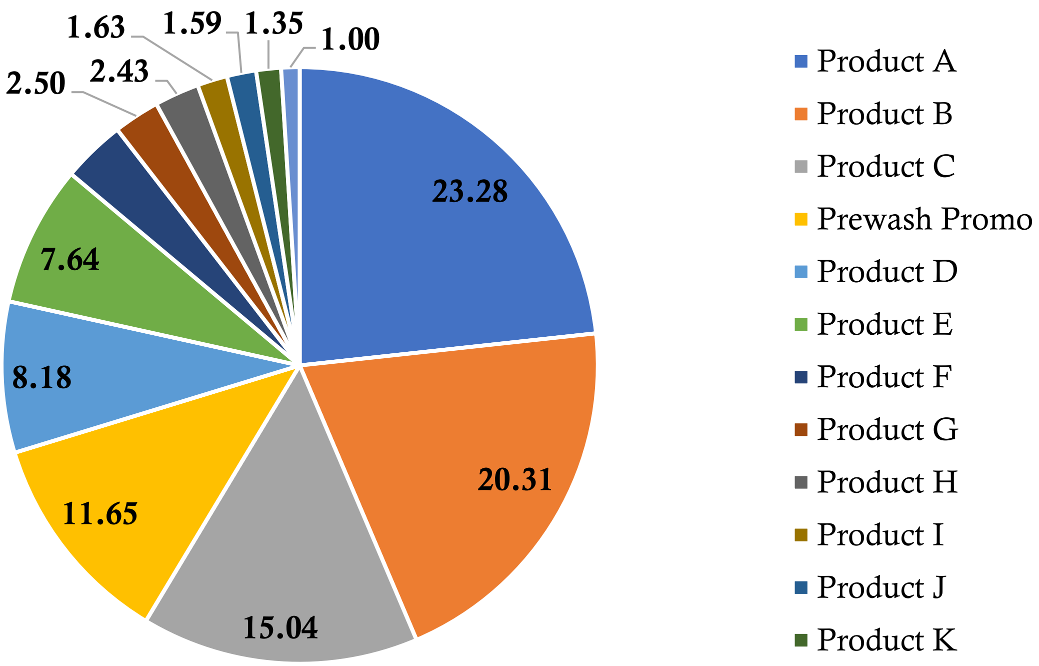

Figure 13: Pie chart of percentage distribution of total unit sales of the top thirteen products in 2022

Similarly, Figure 14 shows the relationship between the total units sold and the percentage of turnover each of the products represents. This data is important as it demonstrates the economic impact relative to the volume of sales.

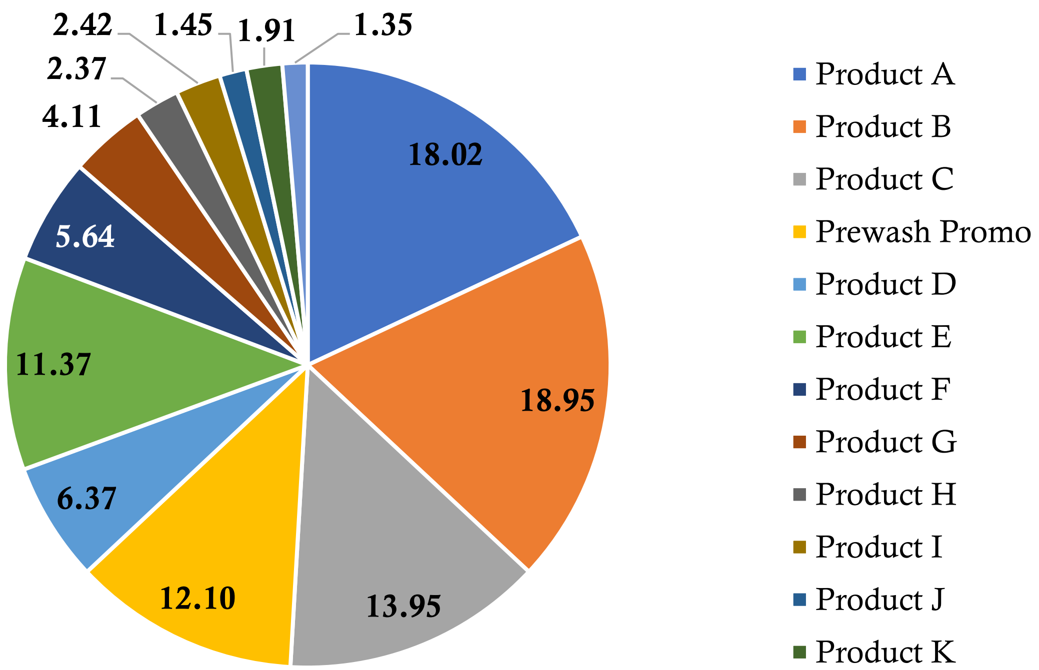

Figure 14: A pie chart showing, the percentage distribution of turnover by the top thirteen products in 2022

3.2.2 Function, Functional Unit and Reference Flows

The function of the product system was to produce fully packaged FMCG market products that are either packaged in shrink-wrapping and a cardboard box or only in a cardboard box. The functional unit of this study was "one year's production of Prewash Promo," with reference flows being all inputs and outputs relative to the functional unit.

The goal of this study was to determine which packaging configuration offered the lowest environmental impact and energy consumption. The metric of one year's worth of packaging was the most appropriate measure as it facilitated an annual assessment of costs and benefits. Companies primarily do growth and loss assessments on a monthly or annual basis. The annual assessment metric was chosen because it provided an assessment of greater depth rather than one month in isolation.

3.2.3 System Boundaries

i. Overview of the Product Systems

The packaging of FMCG products system has many processes upstream of the packaging stage that involve the manufacturing of the virgin packaging materials and processing into the final packaging configurations. The system boundary for this LCA study was modelled to demonstrate a cradle-to-grave process. It must be noted that in all stages downstream of FMCG Product Packaging stage the packaging materials only experience end-of-life processes thus the model of a cradle-to-grave approach was the best representation of the life cycle of the process.

The system boundaries are described in two graphics in Figures 15 and 16. The first graphic depicts the system and corresponding boundaries associated with corrugated board and the second graphic represents the system and corresponding boundaries associated with heat shrink-wrap plastic. These systems are depicted separately to differentiate between the two configurations under analysis: cardboard only and cardboard with shrink-wrap plastic.

The corrugated board process was divided into seven life cycle stages: 1) forestry 2) paper/board manufacturer 3) corrugated board manufacturer 4) box/shipper manufacturer 5) FMCG product manufacturing/packaging 6) central distribution and 7) retail outlet.

1. Forestry

   This stage involved the primary acquisition of wood to produce paper and board. This stage contributed towards the use of all chemicals, fuels, water, and transport costs.

2. Paper/board manufacturer

   The paper manufacturing stage described the processes that occur to convert the wood from the forestry process into the pulp and paper products that are then processed into board. This process contributed towards the overall consumption of electricity, fuel, chemicals, water, and transport costs.

3. Corrugated board manufacturer

   The corrugated board manufacturer was responsible for converting board supplied by the likes of Sappi or Mondi (paper and board manufacturers) into corrugated board. These facilities receive paper and board in large rolls weighing between 1 and 2 tonnes which are then combined in unique combinations to achieve the desired product. For this study, this conversion entailed the development of a double sheeted board with a single fluted layer in the middle. This stage contributed significantly to the life-cycle's overall use of electricity to generate heat as well as chemical uses in the form of glue to laminate the sheets together. This stage however also contributed to transport costs, fuel, and water usage.

4. Box/shipper converter.

   Similarly, to that of the corrugated board manufacturer, this stage in the life cycle primarily contributed towards the electricity consumption of the system owing to the requirement for large machinery that cuts and shapes the corrugated board into recognizable shapes and sizes to use as boxes and shippers in the FMCG product packaging. This stage also contributed towards the chemical impact of the life cycle as it utilizes glues to construct with and transport costs to move the finished product.

5. FMCG product manufacturing/packaging

   This stage was where the primary difference between the two packaging configurations was realized. In terms of the corrugated board life cycle, this stage contributed very little to the environmental impact as the box does not undergo any process that contributed negatively to the environment. The shipper or cardboard carton arrived as per the transport costs accounted for in stage 4 the box was used to package commodities, and the finished product was complete. It must however be accounted for that packaging tape (polyvinylchloride) was used to close the box which was accounted for in this life-cycle stage as it is essential for the use of this packaging material. This stage was the primary focus of this study as this was the stage where the greatest difference between the two configurations was realized.

6. Central distribution

   Central distribution in terms of Concord Group pertains to one bulk distribution facility in Johannesburg that then distributes around the country to the smaller direct distribution facilities of each of the retail facilities. The primary impact of these facilities in terms of packaging is the disposal there of either due to damage or breaking into smaller selling units.

7. Retail outlet

   Similar to that of stage 6, retail outlets account only for the waste scenarios of the packaging material whereby if it was recycled or disposed of in general waste.

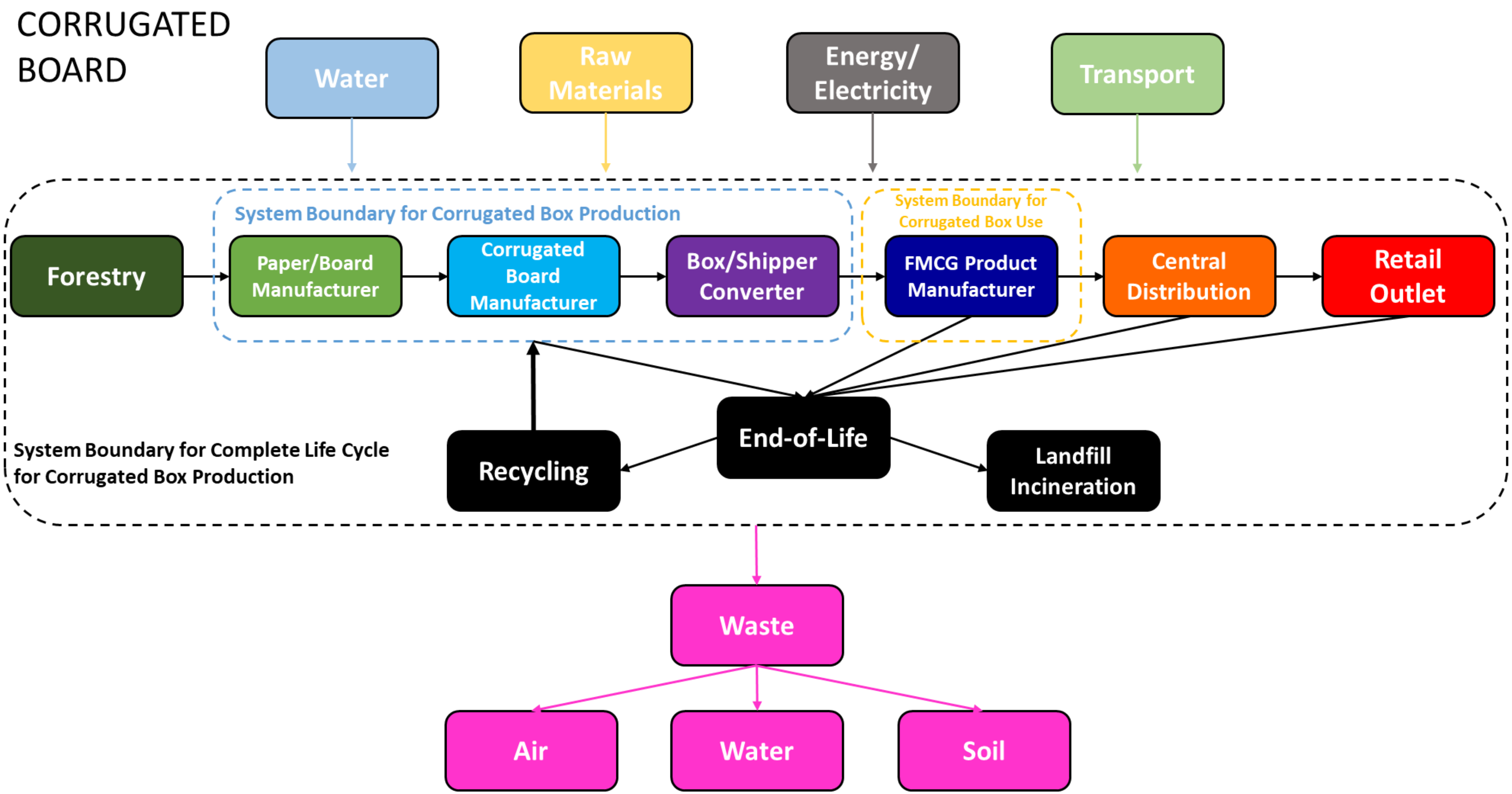

Figure 15: Corrugated board system boundary diagram

The heat shrink-wrap plastic process can be divided into five stages: 1) Plastic polymer manufacturer, 2) Shrink plastic manufacturer 3) FMCG product manufacturer/packager, 4) Central distribution, and 5) Retail outlet.

1. Plastic polymer manufacturer

   This stage involved the primary production of plastic polymer as a by-product of the petroleum industry. This stage contributed towards the use of all chemicals, fuels, water, and transport costs.

2. Shrink plastic manufacturer.

   The shrink plastic manufacturing stage described the processes that occur to convert the plastic polymer by-product into the heat shrink-wrap plastic. This process contributed towards the overall consumption of electricity, fuel, chemicals, water, and transport costs.

3. FMCG product manufacturer/packager

   This stage was where the primary difference between the two packaging configurations was realized. The packaging configuration that included heat shrink-wrap plastic was the packaging setup that consisted of shrink-wrapped products contained within a cardboard carton. For Prewash Promo, the product was grouped into sets of three with two elastic bands per group and then shrink-wrapped into packs of six and two six-packs were sealed into a cardboard carton which was sealed with packaging tape. The primary difference between the two setups was the presence of additional raw materials and the additional requirement for shrink-wrap tunnels needed to package the products. Shrink wrap tunnels are highly energy intensive and highly inefficient. This stage was the primary focus of this study as this was the stage where the greatest difference between the two configurations was realized.

4. Central distribution

   Central distribution in terms of Concord Group pertains to one bulk distribution facility in Johannesburg that then distributes around the country to the smaller direct distribution facilities of each of the retail facilities. The primary impact of these facilities in terms of packaging was the disposal there of either due to damage or breaking into smaller selling units.

5. Retail outlet

Like that of stage 6, retail outlets account only for the waste scenarios of the packaging material whereby if it was recycled or disposed of in general waste.

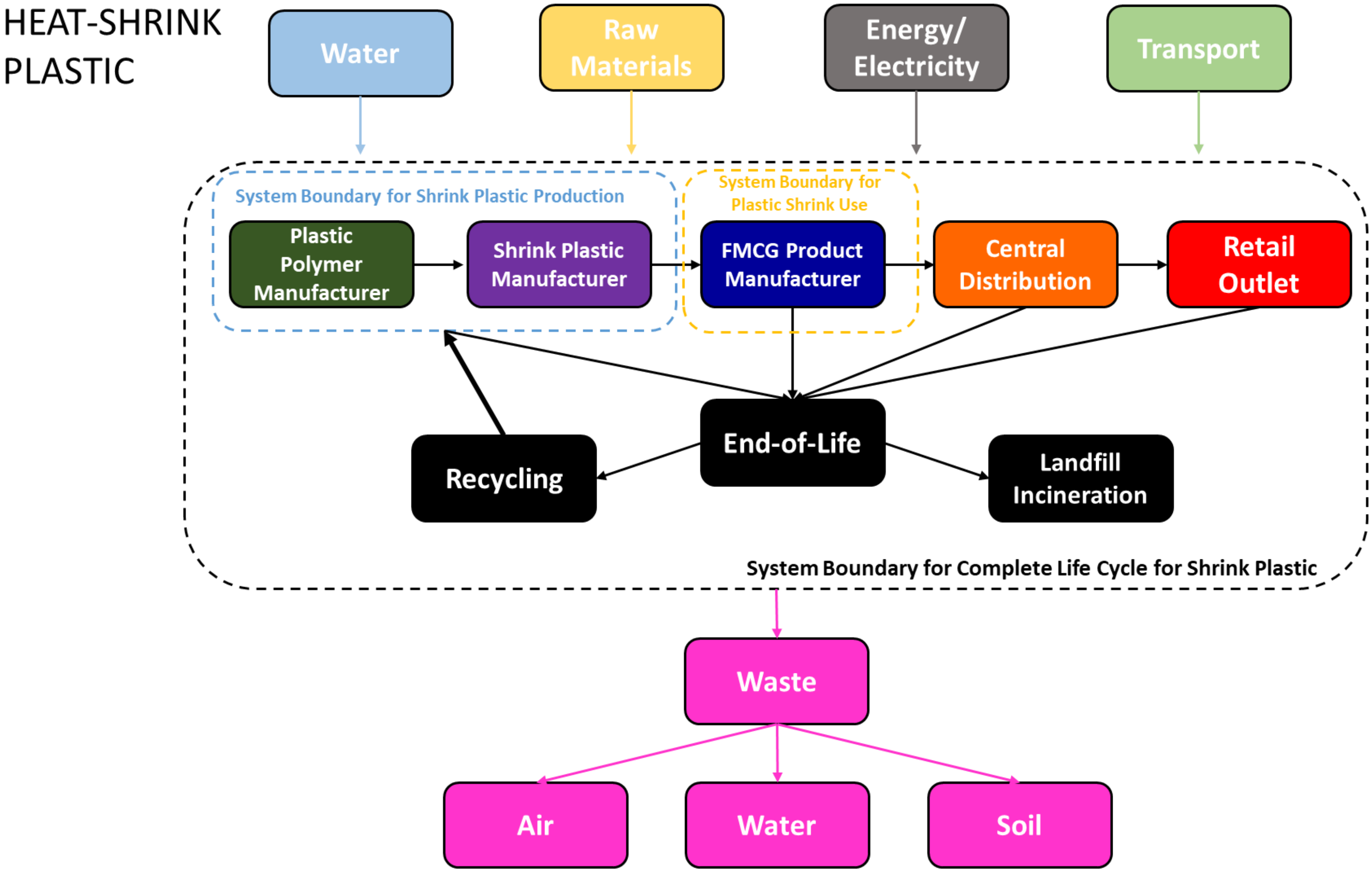

Figure 16: Heat shrink-wrap plastic system boundary diagram

ii. *Omissions and Exclusions from the Product Systems*

- **Human activities**: These inputs were excluded from the study owing to the considerable time frame required to gather data on this aspect of the processes. This time frame exceeded the allotted time for the study. Secondly this forms part of a social LCA which falls outside the scope of this study.
- **Capital equipment and maintenance**: The capital outlay on machinery, land, buildings, and plant equipment was excluded from this study as the life span of most of the capital goods exceeds 5 years that falls outside the single year of analysis for this study. The associated considerations pertaining to machinery maintenance costs and the requirements for plant layout considerations were discussed and considered later in this study but do not form part of the primary analysis or LCA calculations.

The factors excluded or omitted from this study may be considered as possible areas to further and improve the depth of this study in the future.

iii. *Geographic Boundary, Temporal Boundary and Summary of Unit Processes Included*

The geographical boundaries of this LCA study influenced various aspects of the analysis, given that:

- The resources used in producing the packaging materials may come from different areas of the country and in terms of the available data on the Simapro database may be modelled in terms of what was available and the closest alternative to the South African market.
- The infrastructure of basic services was heavily influenced by the country from which the data was modelled. Similarly, to that of resources, the infrastructural data was limited by the available databases on Simapro. The infrastructure under analysis included transport systems, electricity production and waste management; all of which were region specific and vary greatly from one country to the next.
- The region may exhibit varying sensitivities to certain pollutants rather than others. This was primarily considered when looking at inland locations vs. coastline locations.

The temporal boundary of a LCA includes the period associated with the functional unit, considering the periods of production, distribution, use and end-of-life management (Cary, 2017). In this study the period associated with the functional unit was the year 2022. All activities and resources associated with the packaging of Prewash Promo in this calendar year were therefore included in the temporal boundary of this system. The delayed emissions associated with the disposal of certain materials in the process that exceeded 1 year were accounted for in the LCA by including long-term emissions and comparing when they are accounted for and when they are not.

3.3 Assessment Criteria

The Simapro software (version 9.4.0.3, 2022) used to conduct the LCA utilizes different calculation methods to assess the impact of products systems and processes. ReCiPe is a LCA impact assessment method that translates emissions and resource extractions into a limited number of environmental impact categories. The ReCiPe impact assessment method can be defined into two main streams: midpoint level and endpoint level (Environment, 2018). The ReCiPe method calculates:

- 18 midpoint indicators
- 3 endpoint indicators

ReCiPe midpoint indicators focus on individual environmental problems such as ozone depletion and global warming. ReCiPe endpoint indicators show the environmental impact in terms of the three higher impact categories: 1) effect on human health (DALY), 2) biodiversity and 3) resource scarcity (Environment, 2018). Graphically represented the relationship between the 18 categories of the midpoint method and the three categories of the end point method can be seen in Figure 17 (Shaik, 2022).

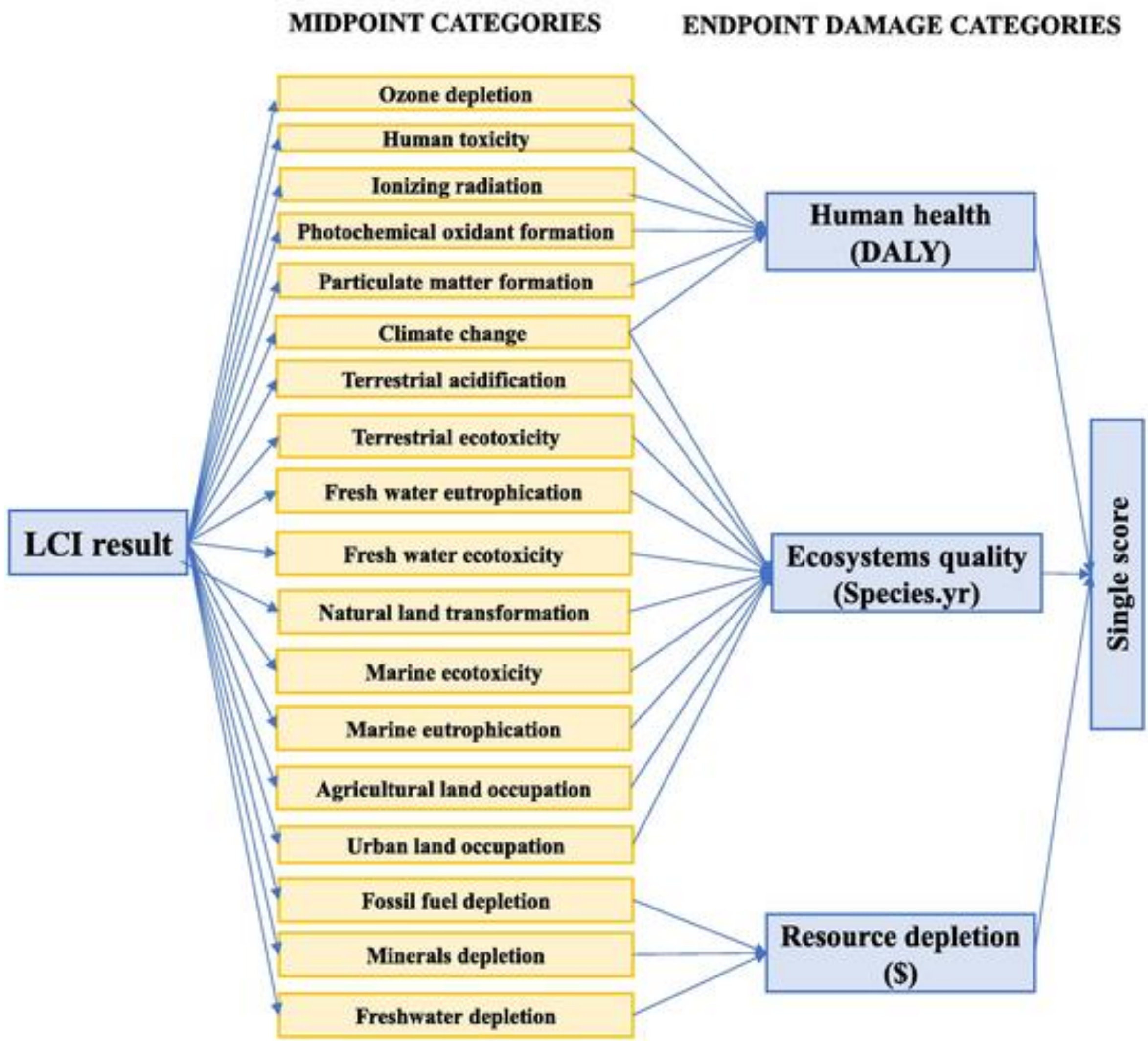

Figure 17: ReCiPe LCA method impact categories (Shaik, 2022)

Both the endpoint and midpoint methods will achieve the same assessment of a process or product however the degree of uncertainty will vary. Owing to the summarized nature of the endpoint method there are greater variations in the results. It is for these reasons that the ReCiPe midpoint 2016 method was used to execute the LCA for this study.

This study focused primarily on five main categories:

1. Global warming
2. Stratospheric ozone depletion
3. Fine particulate matter formation
4. Freshwater ecotoxicity
5. Water consumption

These five categories were chosen because they provide the best overview of the impact in a summarized form compared to the full eighteen category assessment. Global warming, stratospheric ozone depletion and fine particle matter formation were all contributing factors to our environmental decline, change in weather conditions and the drastic reduction in air quality. The final two categories: freshwater ecotoxicity and water consumption demonstrated the impact on our water source. Primarily focusing on freshwater supplies owing to the geographical location of this studying being in the heart of land-locked Johannesburg.

These five focus categories were also chosen specifically with the target audience in mind as these categories are relatable to all parties regardless of level of understanding of LCA. These five categories were also selected as they not only emphasize the impact in areas of interest but also demonstrate a good representation of all the categories involved in the ReCiPe method assessment of each of the packaging configurations that were analyzed. The five focus impact categories considered the typical contributing factors towards environmental impact: water pollution, air pollution and ground pollution. The target audience of this study was stakeholders that make crucial decisions that impacted how much a company negatively contributed towards these three factors. These five categories also adequately summarized the main areas in which the target audience would have the greatest effect owing to the impacts associated with the activities of businesses in the FMCG manufacturing chain. It was important that the condensed set of impact categories focused on these three impacts allowing stakeholders with limited knowledge of LCA to gain knowledge from the results and conclusions.

3.4 Allocation Choices and Data Quality Requirements

3.4.1. Allocation Choices

The use of heat shrink-wrap plastic and corrugated board cartons both occur in isolation and are unaffected by other by-products at the primary stage of analysis, FMCG product manufacturing/packaging. The cartons are custom made for the product under analysis and the shrink-wrap is specifically designed for use on Prewash Promo. It must also be noted that the data relating to these two products, namely weights of the different packaging raw materials remains constant.

Secondly, the electricity requirements of the packaging configuration including the heat shrink-wrap plastic were ascertained from the practical analysis and gathering of data from a shrink-wrap tunnel that is setup for Prewash Promo and is used to package the product in isolation and does not include the packaging of any other products.

3.4.2. Data Quality Requirements

This study utilized data from the year 2022 to analyze and compare the two packaging configurations under investigation. This study utilized primary data from the sales of 2022 and the practical data concerning the weight of different materials involved in the packaging configurations. Where primary data was unavailable the data available via the SimaPro databases was utilized. This was primarily utilized for the data pertaining to stages before the FMCG manufacturing/packaging stage at this data could not be acquired on a primary basis. It must however be noted that where possible primary data and data pertaining to South Africa is used to best model the system. The use of primary data specifically for the FMCG manufacturing/packaging stage ensures more accurate results. It is also vital that primary data is used for the above-mentioned stage as this will be the life-cycle stage that will demonstrate the biggest differential between the two packaging configurations.

3.5 Comparison between Systems

In this study, one main comparison between two systems was conducted. The impact of the packaging configuration that includes heat shrink-wrap plastic and corrugated board carton, and the packaging configuration that utilizes only a corrugated board carton.

It must also be noted that multiple comparisons were also conducted to ascertain the impact that varying levels of recycling has on the system comparison.

It is important to note that all variables other than the change in packaging material were held constant. The heat-shrink plastic packaging configuration included cardboard and shrink-wrap plastic and all associated materials and processes. The cardboard only packaging configuration was identical but excluded the heat shrink-wrap plastic and the required processes for the use of that material.

4. LIFE CYCLE INVENTORY

4.1 Data Collection Procedures and Main Data Sources

This section covers the procedures executed to collect data pertaining to the primary and secondary processes involved in the life cycles of the two systems under analysis. Primary processes are stages in the life cycle whereby primary data were collected and utilized. Secondary processes are stages in the life cycle whereby secondary data were utilized. In terms of the two systems under analysis, primary data were used for the FMCG manufacturing/packaging stages in both life cycles and secondary data were used for all stages up and down stream of this stage. Secondary data were utilized by means of the databases contained within the SimaPro software.

4.1.1. Data Collection Procedure: Primary Processes

The primary data required from the FMCG product manufacturing/packaging stage were collected as follows:

- The packaging materials involved in the two packaging configurations were practically determined to include the below detailed materials and corresponding weights. The weights of each material were determined on a per case basis. A case of Prewash Promo consists of two six packs of Prewash Promo bottles shrink-wrapped together and sealed into a cardboard shipper or box. In addition to the shrink-wrap plastic material and corrugated board, prior to shrink wrapping the bottles need to be grouped into sets of three with two elastic bands, to facilitate the shrink-wrapping process, and packaging tape is utilized to seal the cardboard box. The heat shrink wrap packaging configuration includes all the materials detailed in Table 2 and the corrugated-board only packaging configuration utilizes only the corrugated board and packaging tape.

Table 2: Summary of the packaging materials used in one case of Prewash Promo

Material	SimaPro material name	Mass (g)
Shrink-wrap plastic	Packaging film, low density polyethylene	26.00
Corrugated board	Folding boxboard carton	251.00
Packaging tape	Polyvinylchloride	3.56
Elastic bands	Synthetic rubber	2.60

- The total number of bottles of Prewash Promo sold in 2022 was obtained from Concord Group sales figures. From these figures the total sales of Prewash Promo were determined to be 88 224 bottles which equates to 7 352 cases of Prewash Promo in 2022. The total packaging used in 2022 is summarized in Table 3.

Table 3: Summary of packaging material used to package total sales of Prewash Promo in 2022

Material	SimaPro material name	Mass (kg)
Shrink-wrap plastic	Packaging film, low density polyethylene	191.15
Corrugated board	Folding boxboard carton	1 845.15
Packaging tape	Polyvinylchloride	26.17
Elastic bands	Synthetic rubber	19.12

- The only remaining primary process input was the electricity requirement of the shrink wrap tunnel utilized to packaging Prewash Promo. This data was obtained by monitoring electrical draw and temperature of the shrink wrap tunnel from start-up until operating temperature. The temperature of the tunnel was measured every five minutes until it reaches the optimum operating temperature of 115°C. The results of this temperature analysis are presented in Table 4.

Table 4: Table of the temperature analysis of the shrink-wrap tunnel start-up

Time (Minutes)	Temperature (◦C)
0	30
5	64
10	86
15	91
20	102
25	104
30	108
35	110
40	112
45	115

Table 4 shows that the tunnel takes approximately 45 minutes to reach operating temperature. This time may vary slightly based on seasonal temperatures.

- The tunnel operates on three-phase power which consists of 220V per phase. The current across the three phases was measured using a clamp meter as the tunnel was started to measure the inrush current, detailed in column two of Table 5. The current was then measured again once the tunnel reaches running temperature with all elements on, detailed in column three of Table 5 and the last column of Table 5 details the steady-state current draw across each phase during normal operation.

Table 5: Summary of the current draw across the three phases of the shrink-wrap tunnel

Phase	**Start-up current (Amps)**	**Minimum draw operation (Elements off) (Amps)**	**Steady-state current (Amps)**
Phase 1 (Red)	25.12	11.42	24.12
Phase 2 (White)	18.84	8.02	17.86
Phase 3 (Blue)	15.35	7.80	14.75

- It was assumed that the steady state running currents demonstrate the majority of the running time of the tunnel thus these currents, column 3, was used in the modelling of the electrical draw of the tunnel.
- The shrink wrap tunnel in question runs for 9 hours per day, 5 days per week, for 48 weeks of the year.
- Adding the three currents exhibited across each of the three phases calculates the instantaneous current draw of the shrink wrap tunnel. The instantaneous current draw of the shrink wrap tunnel is 56.73Amps.
- Accounting for the 9 hours of operation per day,

$$56.73\ A\ \times 9\ hours\ = 510.57\ Amp.hours$$

- Converting to kWh,

$$510.57\ \frac{Amp}{hours} \times 220\ V\ \div 1000\ = 112.33\ kWh\ per\ day$$

- Calculating the annual electricity requirement of the tunnel,

$$112.33\ \times 5\ \frac{days}{week} \times 48\ \frac{weeks}{year}\ = 26\ 959.20\ kWh/year$$

- Converting to MWh/year,

$$Annual\ Electrical\ draw\ = 26.96\ MWh/year$$

4.1.2. Data Collection Procedure: Secondary Processes

The SimaPro software was utilized to model all processes up and downstream of the primary process: FMCG manufacturing/packaging. Publicly available life-cycle inventory databases were used to model the processes and where possible South African specific data was utilized. It must however be noted that the available South African specific data was very limited, thus when unavailable global data was used as the alternative. Global data was utilized as opposed to European or Canadian data to better model the third-world economic and social climate of South Africa.

Lastly, the ecoinvent 3 database was used to fill the remaining gaps and complete the full database required to execute the LCA of the two packaging alternatives under investigation. Ecoinvent 3 was used as this database was the most extensive database to date and was extensively reviewed by external specialists in the LCA field.

The upstream processes included in the two systems are:

For the corrugated board system:

- Forestry.
- Paper/board manufacturer.
- Corrugated board manufacturer.
- Box/shipper manufacturer/converter.

For the heat shrink-wrap plastic system:

- Plastic polymer manufacturer.
- Shrink plastic manufacturer.

The downstream processes include:

- Central distribution
- Retail outlet

The above-mentioned secondary process stages have a variety of different inputs and outputs that need to be accounted for to ensure the LCA is as accurate as possible. The critical inputs that have the biggest influence included transport, electricity/energy, water, and raw materials (specifically fossil fuels). When modelling in SimaPro it was specifically monitored to ensure that the four critically important inputs into the system were adequately included and accounted for at all process stages.

The critical outputs from these stages were the waste scenarios associated with the disposal of packaging material that was no longer needed. The disposal of spent packaging materials occurs primarily in the three stages at the end of each system: FMCG manufacturing/packaging, central distribution, and retail outlets. The need for disposal was either due to damage to the packaging requiring replacement to ensure the safety of the product or the product has reached its destination, and the packaging was no longer required. The end-of-life scenario of the materials involved in the packaging of FMCG products was either recycled or sent to landfills. The percentage distribution between the two end-of-life scenarios cannot be definitively known thus extensive sensitivity analyzes were executed to determine the influence the end-of-life scenario split has on the resulting impact.

4.2 Detailed Description of Product System and Related Processes

This study aimed to compare two packaging configurations: one that included the use of heat shrink-wrap plastic and one that excluded the use thereof. These two configurations included two separate systems: the shrink-wrap plastic system and the corrugated board system. As detailed above the stages included in both systems were divided into primary and secondary processes based on the data used to model that stage of the system. The primary stages used primary data collected on site at Concord Group in Johannesburg, South Africa. The secondary stages that included all stages upstream and downstream of the primary stage were modelled using the SimaPro software and the selected databases. This section aims to elaborate on the components that were included and excluded in the analysis of each configuration in executing the LCA.

4.3 Calculation Procedures

The LCA calculations were executed using the SimaPro software (version 9.4.0.3, 2022).

5. RESULTS AND INTERPRETATION

5.1 Complete LCA Results

In executing the LCA the method by which the calculations were executed was chosen based on the desired results. As discussed in previous sections the ReCiPe midpoint calculations method was used to execute this LCA in SimaPro.

When modelling in SimaPro the inputs and outputs of the system were established either from primary data that was collected or secondary data that was sourced from publicly available databases. The secondary data required for the LCA was obtained from the ecoinvent 3 database library.

Aside from the primary data that was inputted into SimaPro, the waste management scenarios for each of the inputs needed to be modelled as well. Owing to the limited availability of accurate primary data, percentage recycling rates from reliable literature (Mpact recycling review of 2022 recycling figures, (Mpact Recycling, 2019a)) were used to model the waste scenarios. Of the four material inputs: corrugated board, heat shrink plastic, elastic bands, and packaging tape, it was assumed that the recycling rate of corrugated board adhered to the industry average for the year 2022 which was 61.4% (Mpact Recycling, 2019a).

Similarly, it was assumed that the recycling rate of heat shrink-wrap plastic adhered to the industry average of 42.8% (Mpact Recycling, 2019a). The validity and impact of these assumed recycling rates was then analyzed in later sections through a sensitivity analysis. Lastly, it was assumed that based on social habits that the recycling rate of elastic bands and packaging tape was 0%. This assumption was also made based on the limitations of the modelling data available which did not facilitate modelling the recycling of either of these materials.

Table 6: Summary table of recycle rates of two key materials under investigation

Material	Recycle Rate (%)	Recycled Material (kg)	Not Recycled Material (kg)
Corrugated Board	61.4	1 133.05	712.30
Shrink-Wrap Plastic	42.8	81.81	109.34

Executing the LCA in SimaPro, the recycle ratios detailed in Table 6 were used to model each packaging configuration individually first to ascertain the components which contributed the greatest amount to each of the impact categories.

The full set of LCA results has been presented to provide a brief overview of the complete LCA prior to focusing more specifically on the five chosen categories.

5.1.1. Heat Shrink-Wrap Plastic Packaging Configuration

This packaging configuration consisted of:

- Elastic bands, categorized as synthetic rubber when modelling in SimaPro, were used to group the products into sets of three prior to shrink wrapping.
- Heat shrink-wrap plastic then group the twelve bottles of product into two six pack shrinks.
- The corrugated board shipper/box was then used to hold two six pack shrinks.
- The packaging tape, categorized as polyvinylchloride when modelling in SimaPro, was then used to seal the shipper.

The LCA setup accounted for the total mass input of each of the above-mentioned materials as well as the required electricity that was calculated previously. The LCA setup also included the waste treatment scenarios of each of the material inputs. The SimaPro setup is exhibited in greater detail in Appendix A1.

Executing the LCA, the following graph (Figure 18) of results was obtained (full size graph available in Appendix B1):

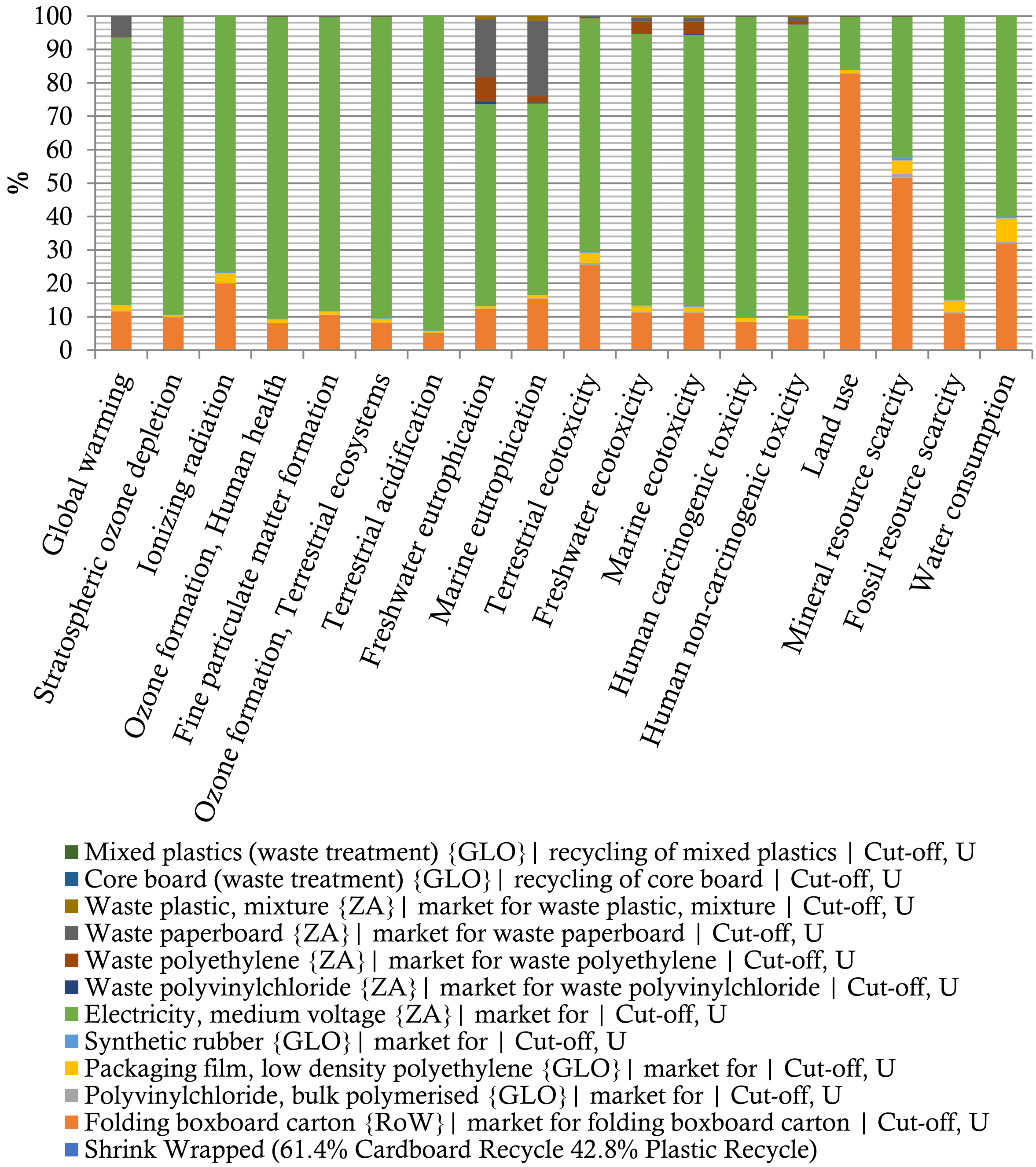

Figure 18: Graph of the complete eighteen category LCA results for the shrink-wrapped packaging configuration

Figure 18 demonstrates that the greatest contributing factor in all eighteen impact categories was the impact resulting from the use of electricity (shown in light green) that demonstrated approximately 80% of most of the categories. The next biggest contributor was the folding corrugated board carton/shipper (shown in orange) which noticibly contributed over 80% to the overall score for the land use category and approximately 50% to the mineral resource scarsity category. There was also a noticible peak from the end-of-life waste scenario of paperboard (shown in dark grey) in three of the eighteen sections: global warming, freshwater eutriphication and marine eutriphication. The impact associated with packaging film and the corresponding end-of-life waste scenario of low-density polyethylene (shown in yellow and dark red respectively) were the only two other materials/material processes that made noticible contributions to the LCA of heat shrink-wrap plastic packaging configuration.

Excluding long-term emissions, the graph depicted in Figure 18 changed to look like the graph depicted in Figure 19 (full size graph available in Appendix B2):

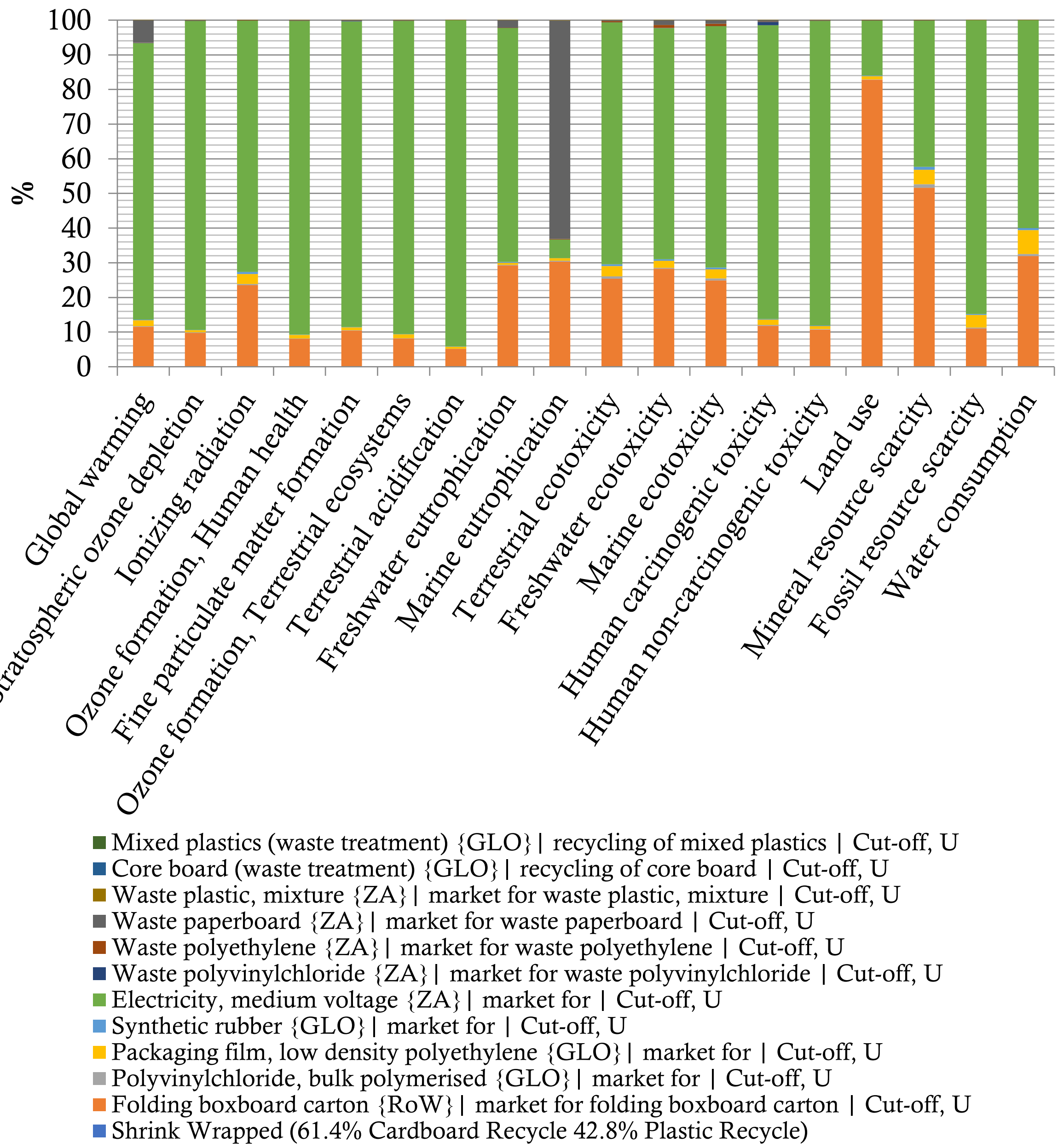

Figure 19: Graph of the complete eighteen category LCA results for the shrink-wrapped configuration excluding long-term emissions

The most noticeable difference in the two graphs was the drastic increase in the contribution of the impact attributed to the waste treatment of corrugated board in the marine eutrophication category. Although this was not a category under focus it important to note the difference when considering long-term emissions vs excluding them.

Another noticeable difference was the significant decrease in the impact realised due to the waste treatment of polyethylene. This demonstrated the long-term impact that the material has on the environment owing to the timeline in which it naturally breaks down in landfills.

5.1.2. *Corrugated Board Packaging Configuration*

This packaging configuration consisted of:

- The corrugated board shipper/box that holds twelve units/bottles.
- The packaging tape, categorized as polyvinylchloride when modelling in SimaPro, seals the shipper.

The LCA setup accounted for the total mass input of each of the above-mentioned materials as well as the required electricity that was calculated previously. The LCA setup also included the waste treatment scenarios of each of the material inputs. The SimaPro setup is exhibited in greater detail in Appendix A2.

Executing the LCA, the following graph (Figure 20) of results was obtained (full size graph available in Appendix B3):

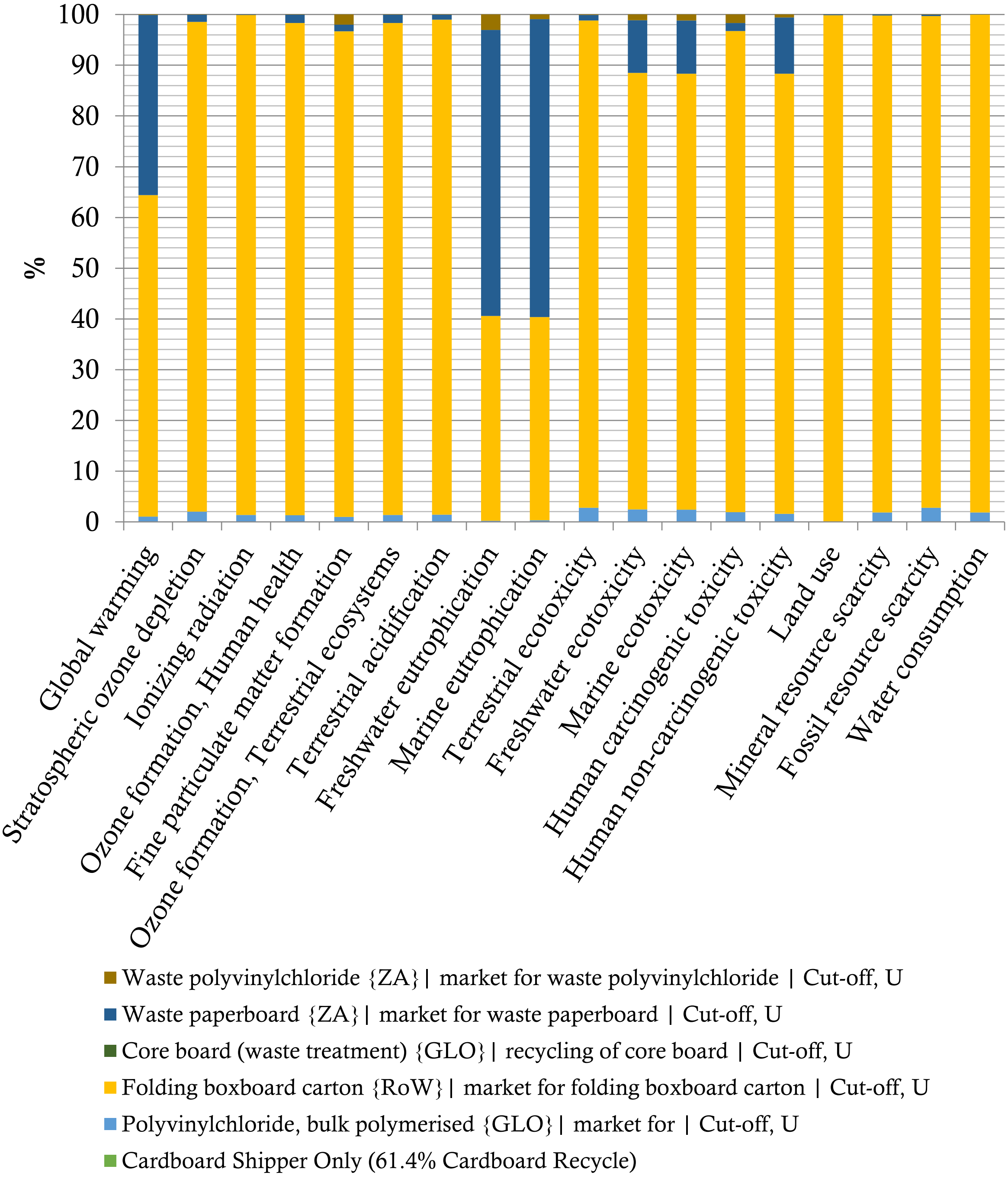

Figure 20: Graph of the complete eighteen category LCA results for the corrugated board only configuration

Figure 20 demonstrates that the greatest contributing factor in all eighteen impact categories was the impact realized as a result of the materials and processes associated with the use and manufacturing of the corrugated board carton (shown in yellow). This folding corrugated board carton contributed between 40% and 95% to the overall impact between all 18 categories. The only other factor that made a noticible impact was the waste treatment scenario of corrugated board cartons; most noticibly contributed almost 60% towards the impact in the freshwater and marine eutrification categories. The impact realised due to the use of packaging tape or polyvinylchloride features in every category except the two eutriphication categories and the land use category; contributed between 1% and 3% to the overall impact in each of the categories.

Excluding long-term emissions, the graph depicted in Figure 20 changed to look like the graph depicted in Figure 21 (full size graph available in Appendix B4):

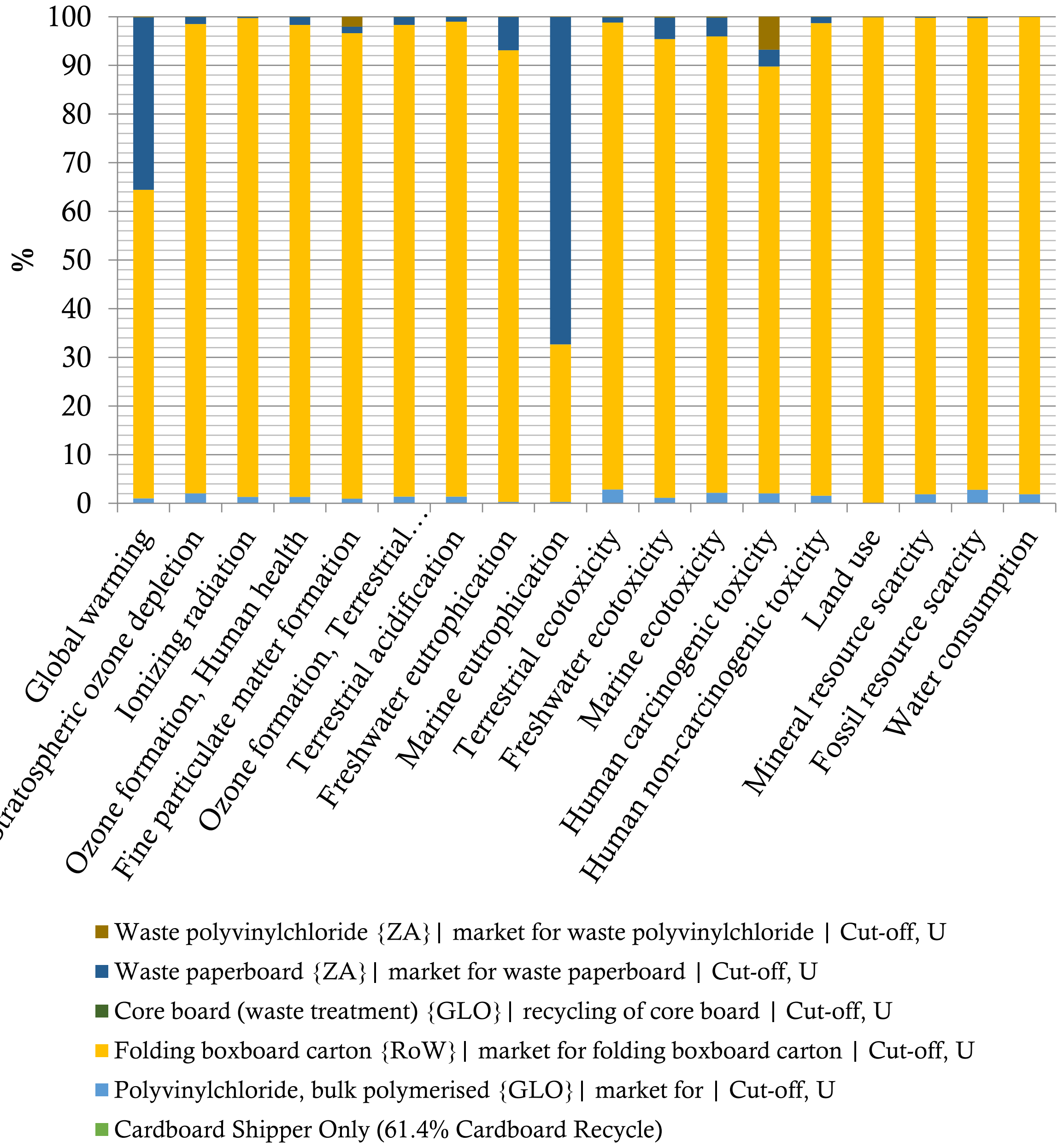

Figure 21: Graph of the complete eighteen category LCA results for the corrugated board only configuration excluding long-term emissions

Unlike the easily noticeable differences in the two graphs of the heat shrink-wrap plastic configuration (Figures 18 and 19), the exclusion of long-term emissions in terms of the corrugated board packaging configuration were less noticeable. This observation demonstrated the significant difference in the long-term effects of the use of plastic packaging vs that of cardboard packaging. Plastic packaging takes much longer to decompose naturally in landfills and thus demonstrates a much longer-term impact than that of cardboard which is susceptible to breakdown when exposed to water.

The only noticeable difference is the significant decrease in the impact realized by the waste treatment of cardboard in the freshwater eutrophication category, which decreased from approximately 56% to 8%.

The above sections have provided a brief overview analysis of the complete eighteen category LCA results. The next sections focus on the condensed set of results which analyzes the results obtained in the five chosen categories discussed previously.

5.2 Condensed Results: 5 Chosen Categories

5.2.1. Heat Shrink-Wrap Plastic Packaging Configuration

When focusing more closely on the five chosen categories specifically for the heat shrink-wrap plastic configuration, the following graph (Figure 22) was obtained (full size graph available in Appendix B5):

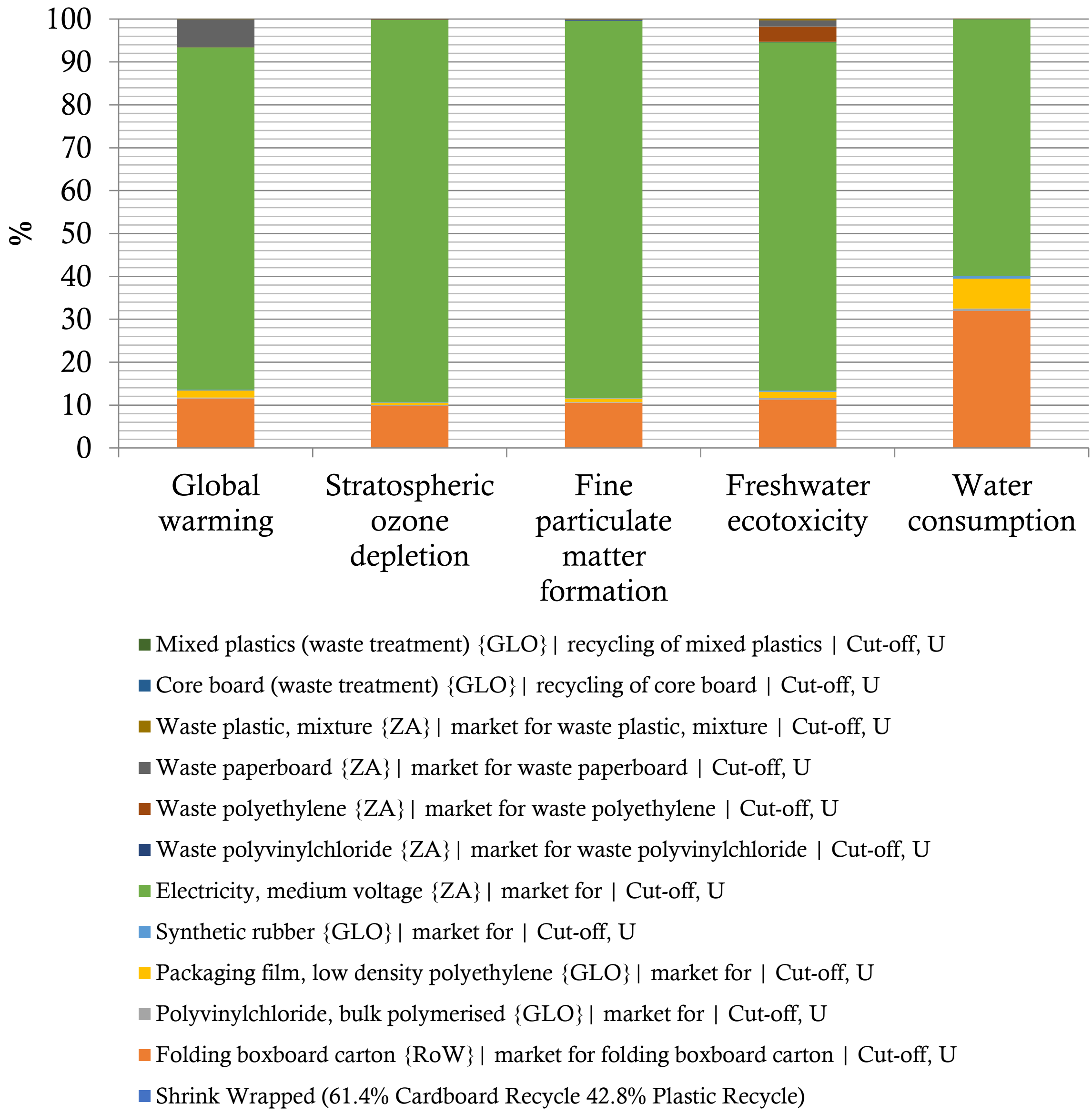

Figure 22: Condensed results graph for the heat shrink-wrap plastic packaging configuration

Across all five of the chosen categories, electricity was the largest factor contributing between 60% and 90% to the overall impact realised. This was critically important to note as in the comparison between the two configurations electricity was not a requirement in the corrugated board only configuration owing to the elimination of the use of shrink-wrap tunnels.

The next largest contributing factor was the impact realised because of the materials and processed used in the manufacturing of folding corrugated board boxes. Contributing between 10% and 30% this factor featured in both packaging configurations.

It was interesting to note that although the defining factor in this packaging configuration was the use of heat shrink-wrap plastic (low-density polyethylene) it demonstrates very small contributions to the impact in each of the categories. However, the use of this packaging material requires the use of a shrink-wrap tunnel which requires electricity. Thus, it may be concluded that the impact of the electricity and the low-density polyethylene were the defining impact factors for this packaging configuration as these are not required by the corrugated board only configuration.

Examining the results obtained when the long-term emissions were excluded, the following graph (Figure 23) was obtained (full size graph available in Appendix B6):

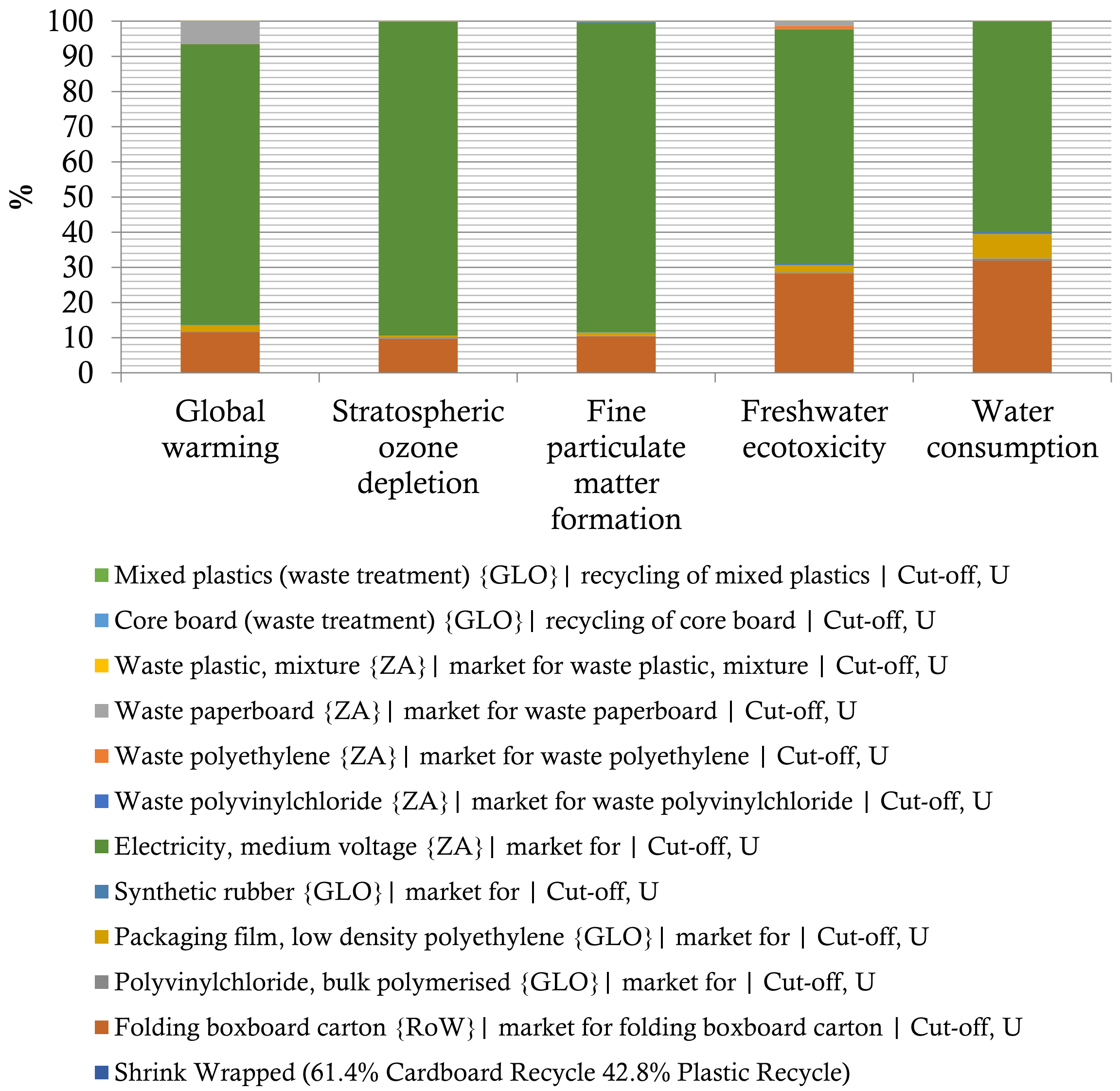

Figure 23: Condensed results graph for the heat shrink-wrap plastic packaging configuration excluding long-term emissions

When excluding long-term emissions, the impact of the folding corrugated board carton on Freshwater ecotoxicity increased from 10% to 30% and the impact of waste low-density polyethylene decreased from 8% to a negligible amount that cannot be easily defined on the graph. Other than the noticeable changes in the Freshwater ecotoxicity category the impact contributions in the remaining five categories remained relatively unchanged which suggests that the impact to our freshwater quality was heavily influenced by the timeline in which it was exposed to the pollutants from this lifecycle. This conclusion also supported the drive towards reducing waste scenarios that result in landfill disposal opposed to recycling. Recycling materials prevents unwanted environmental pollution by the decomposition of the materials in question and reduces the need for mitigation and management of ecotoxicity at a later stage.

5.2.2. Corrugated Board Packaging Configuration

When focusing more closely on the five chosen categories specifically for the corrugated board only configuration, the following graph (Figure 24) was obtained (full size graph available in Appendix B7):

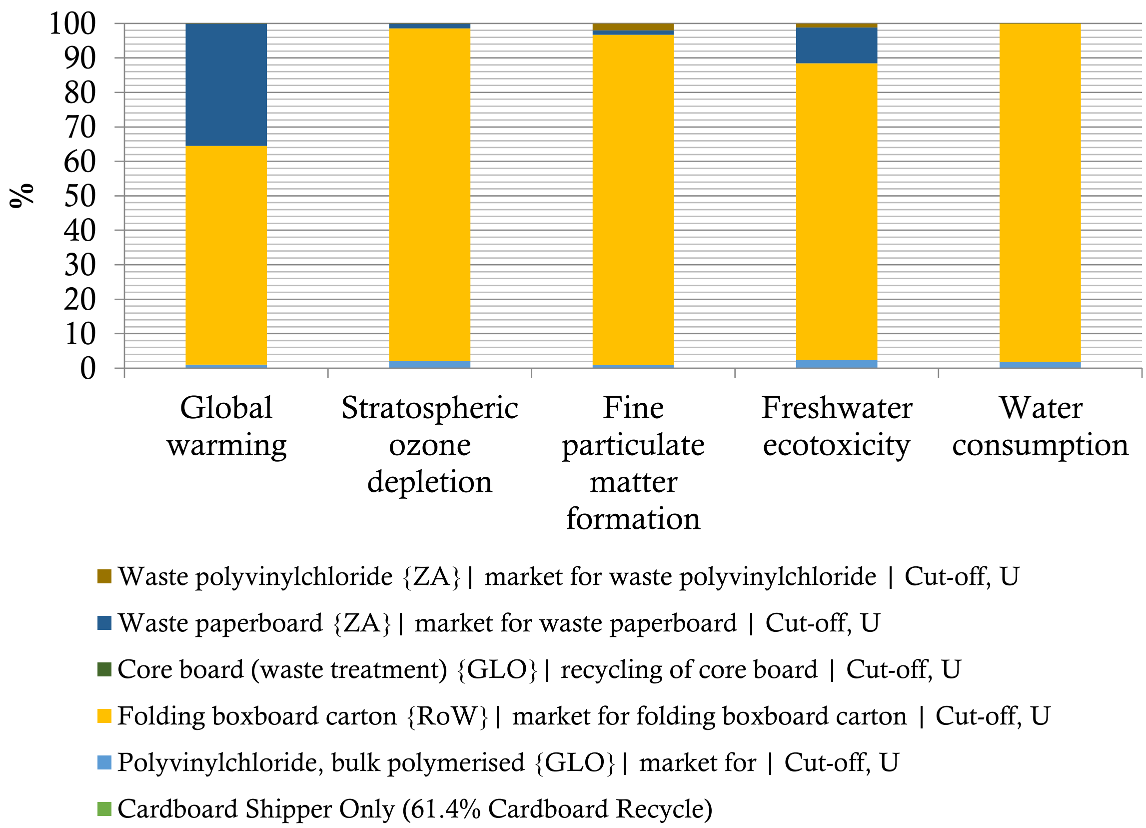

Figure 24: Condensed results graph for the corrugated board only configuration

Analyzing across all five chosen categories, the impact realized because of the folding corrugated board carton contributed the greatest fraction of between 63% for global warming and 98% for water consumption. In contrast to the shrink-wrapped plastic configuration where the folding corrugated board carton was the second largest contributing factor to that of electricity this configuration demonstrated a similar trend in that the folding corrugated board demonstrated a similar dominance as that of electricity in the shrink-wrapped plastic configuration.

Unlike in the shrink-wrapped plastic configuration there was no definitive factor that was the second highest contributor. However, the impact realized because of the end-of-life waste scenario of corrugated board significantly contributed to global warming, accounting for approximately 35% and freshwater ecotoxicity accounted for approximately 10%.

Similarly, the use of packaging tape or polyvinylchloride contributed between 1% and 3% to each of the five categories. The end-of-life waste scenario of polyvinylchloride also contributed the same proportions to the fine particulate matter formation category and the freshwater ecotoxicity category. Although the above-mentioned impact contributions were small the use of packaging tape as the material to seal the cardboard cartons did not negatively impact the overall environmental impact of both packaging configurations under study. Alternative sealing options such as glue, staples or strapping may be investigated as viable options to mitigate the impact realized using packaging tape. The impact was minimal thus it can be concluded that considering alternative sealing methods may positively impact the LCA the effect would be minimal.

Examining the results obtained when the long-term emissions were excluded, the following graph (Figure 25) was obtained (full size graph available in Appendix B8):

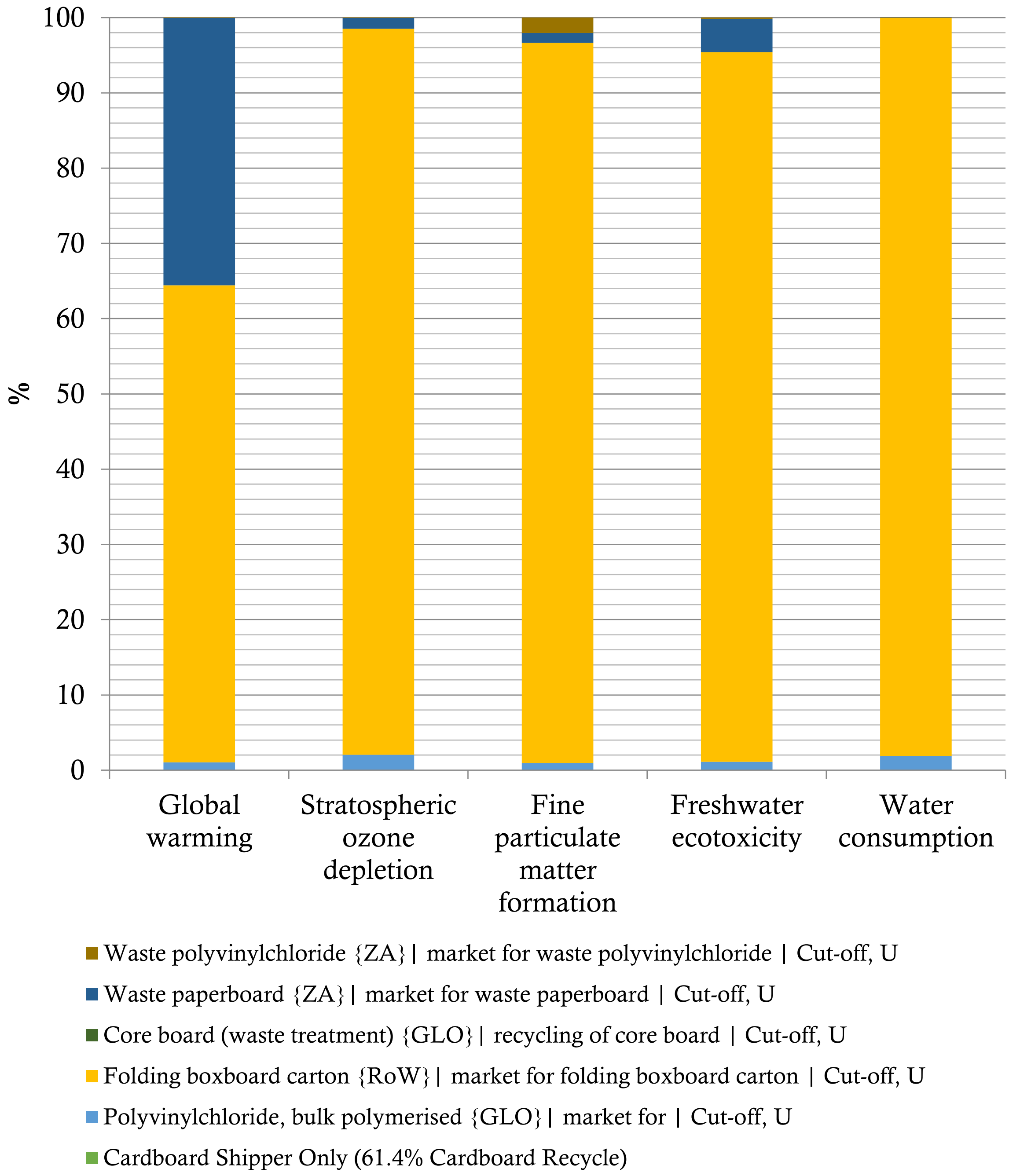

Figure 25: Condensed results graph for the corrugated board only configuration excluding long-term emissions

Excluding long-term emissions demonstrated little to no change in the impact distributions across the five focus categories. From this we concluded that the lifespan of the materials used in the corrugated board only configuration do not exhibit lengthy decomposition scenarios and thus the long-term effects of these materials on the environment were limited.

5.3 Comparison Results

5.3.1. Complete 18 category LCA Comparison Results

After analyzing each of the packaging configurations individually a comparison between the two configurations was executed. Unlike the results from a single configuration whereby each of the materials and resources used was depicted as a fraction of the total impact, the comparison results depict only a total impact score per category without segmenting that score per material. These results are thus discussed relative to the respective packaging configuration rather than a specific material input.

Executing the comparison between the two packaging configurations yields the following graph (Figure 26 and Appendix B9):

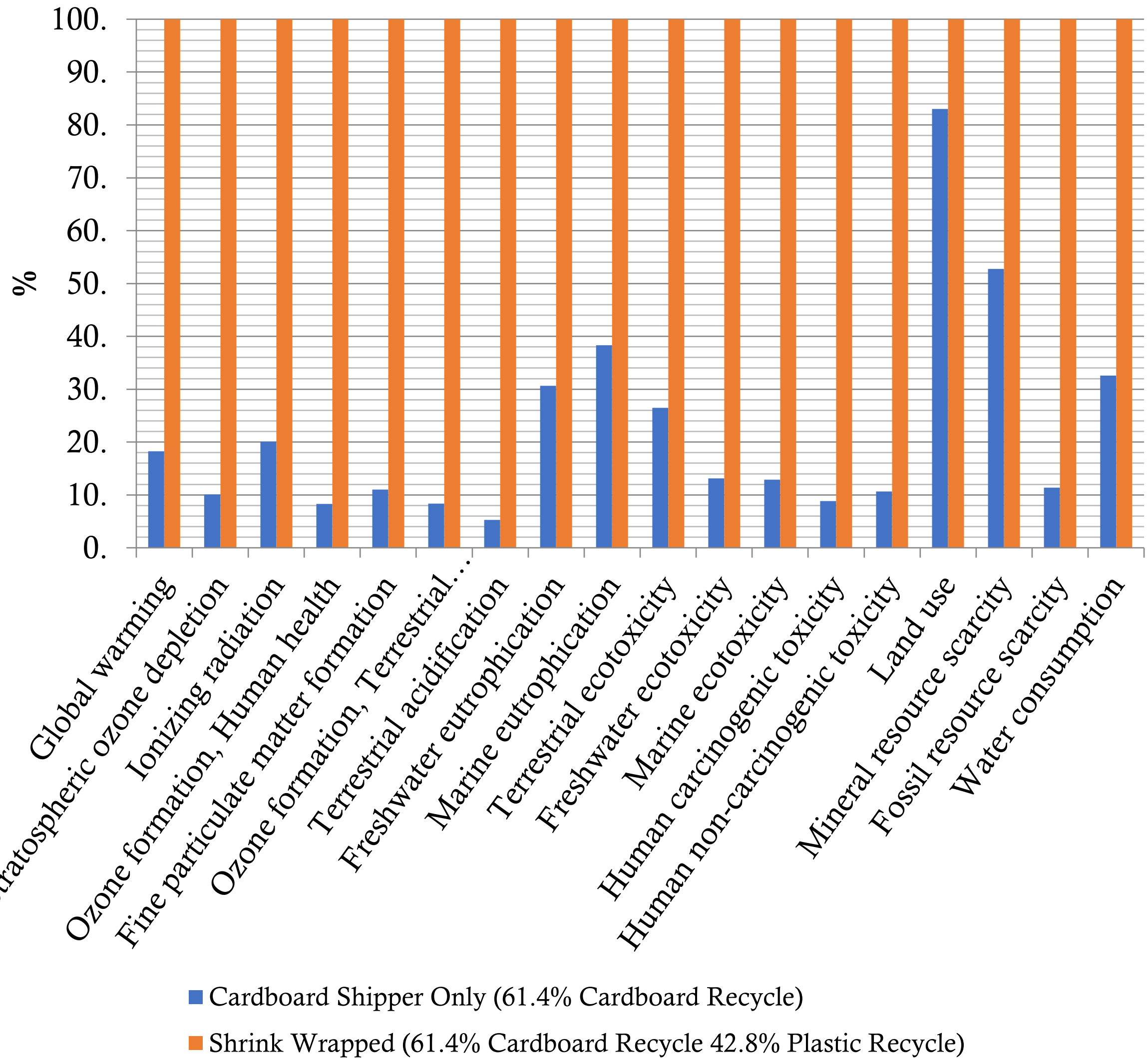

Figure 26: Complete eighteen category comparison results graph

The results graph depicted in Figure 26 clearly demonstrated the drastic difference between the two packaging configurations' LCA results. The corrugated board carton only configuration demonstrated a lower impact across all eighteen of the impact categories. The category that exhibited the closest results was the Land Use category that demonstrated only a 17% difference between the two packaging configurations. The remaining categories demonstrated a difference between 47%, in the Mineral Resource Scarcity category, and 95%, in the Terrestrial Acidification category.

Comparing the two configurations excluding long-term emissions exhibits the following results graph (Figure 27 and Appendix B10):

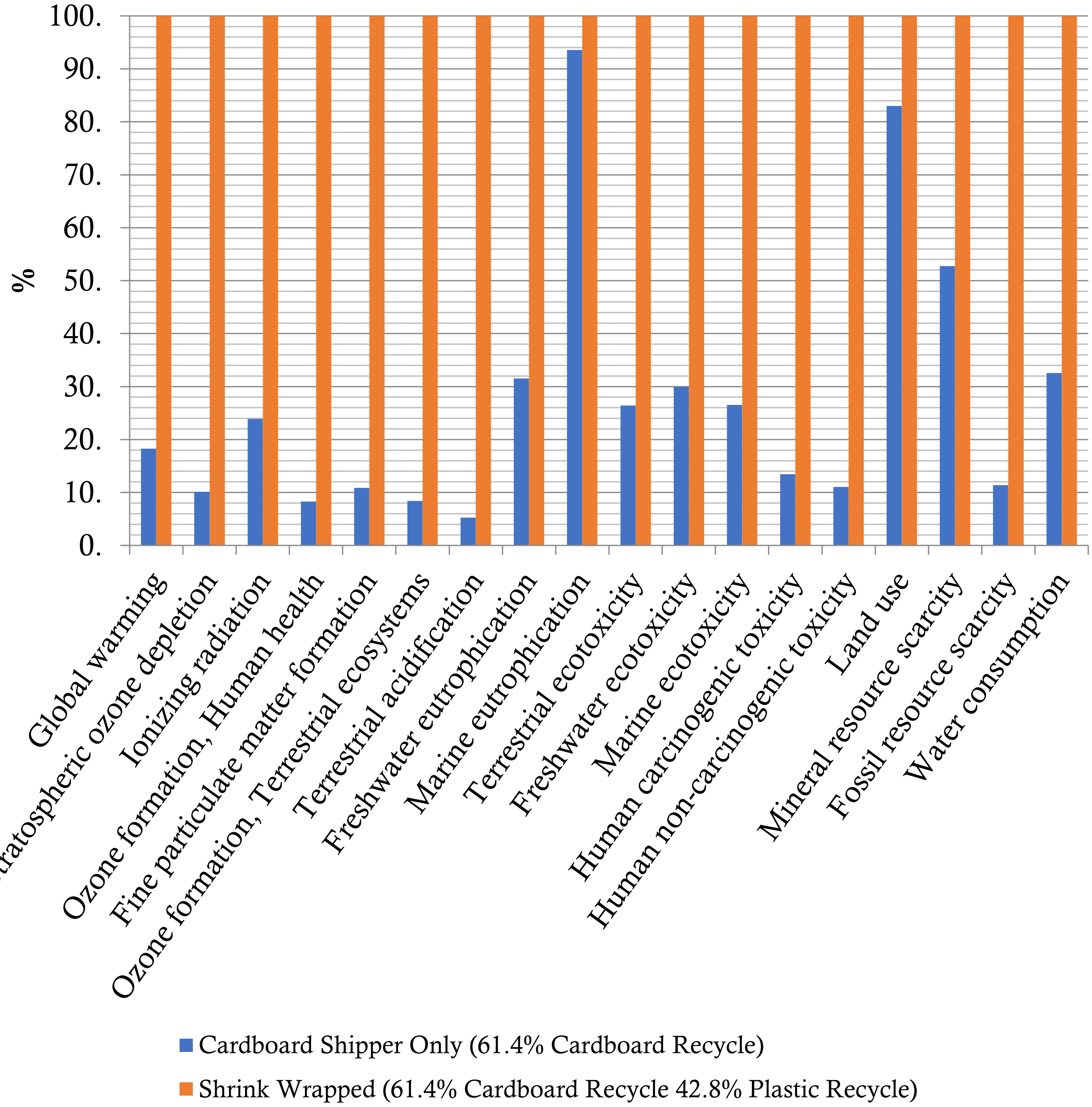

Figure 27: Complete eighteen category comparison results graph excluding long-term emissions

The comparative results remained relatively unchanged when long-term emissions were excluded however a noticeable change occurred in the Marine Eutrophication category where the cardboard only configuration score increased from 38% to 94%. Other than that drastic rise of 56% the remaining seventeen categories exhibited no significant changes which demonstrated that the comparison between the two configurations remains valid irrespective of the timeline of the comparison.

5.3.2. Condensed LCA Comparison Results

Analyzing the five focus categories in more detail it was evident that the impact differential between the two configurations was significant. The results for each of the packaging configurations including and excluding long term emissions are given in Table 7.

Table 7: Condensed comparative results table

Category Name	**Cardboard Only Configuration (%)**		**Shrink Wrapped Plastic Configuration (%)**		**Difference (%)**	
	Standard	Excluding Long-Term Emissions	Standard	Excluding Long-Term Emissions	Standard	Excluding Long-Term Emissions
Global warming	18.3	18.3	100	100	81.7	81.7
Stratospheric Ozone Depletion	10.1	10.1	100	100	89.9	89.9
Fine Particulate Matter Formation	11.0	10.9	100	100	89.0	89.1
Freshwater Ecotoxicity	13.1	30.0	100	100	86.9	70.0
Water Consumption	32.6	32.6	100	100	67.4	67.4
Average					83.0	79.6

Depicting these results in graph form the following two bar graphs were established (Figure 28 and Figure 29) (full size graphs available in Appendix B11 and B12 respectively):

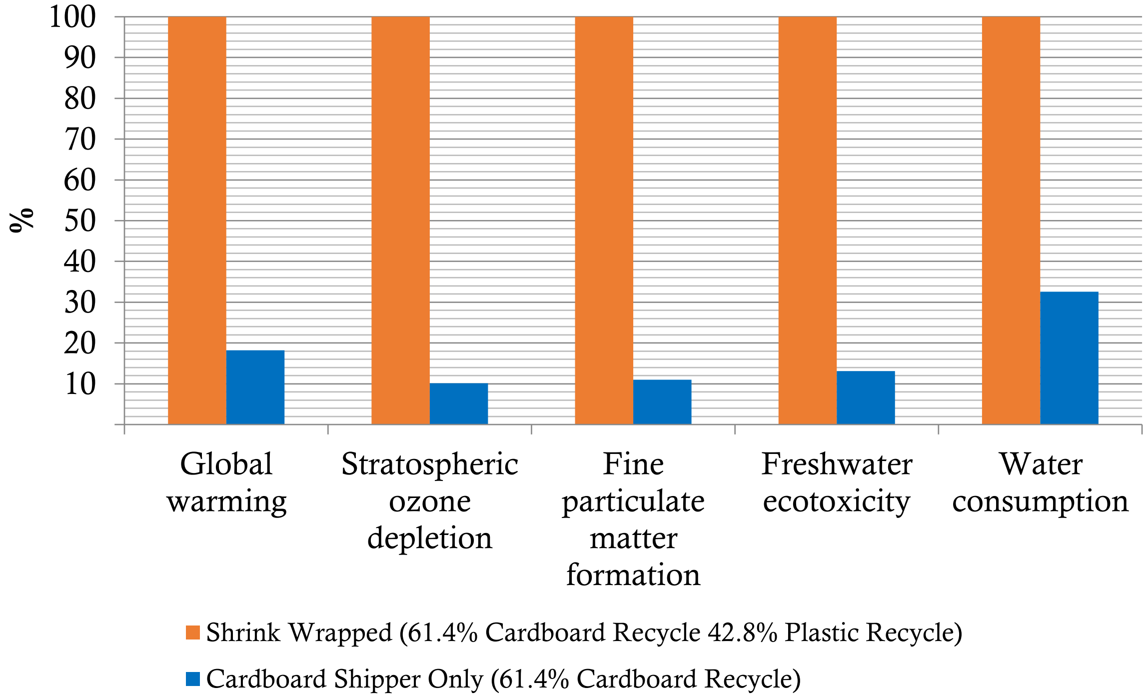

Figure 28: Condensed comparative results graph

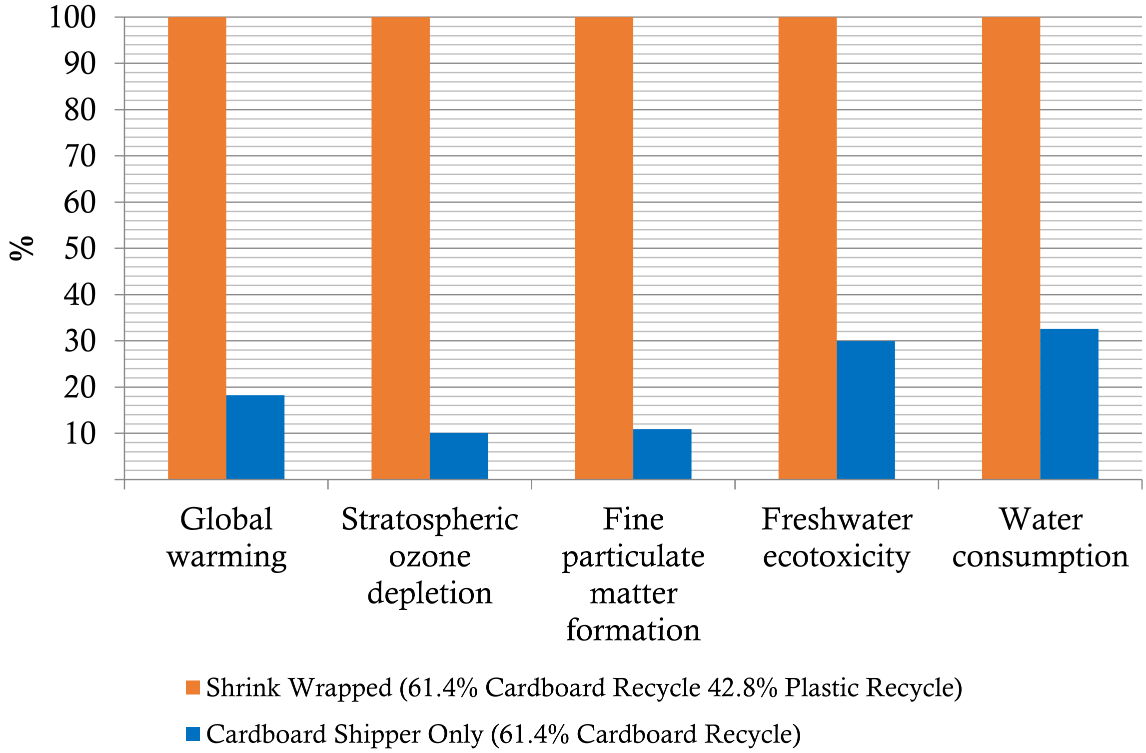

Figure 29: Condensed comparative results graph excluding long-term emissions

Figure 28 and Figure 29 demonstrate the significant difference between the two packaging configurations under analysis. The corrugated board only configuration on average demonstrated an LCA score 83% lower than that of the heat shrink-wrap plastic packaging configuration. These results demonstrate that the impact of the corrugated board only configuration was better than the heat shrink-wrap plastic configuration and will offer lower environmental impact as well as reduced load on the energy system as it excludes the need for electricity beyond the point of manufacturing the packaging materials.

5.4 Sensitivity Analysis: Plastic Recycle Rate

The analysis of the different packaging configurations and the comparative results of these two options were both executed under the assumption that the recycling-to-waste ratio conformed with the industrial average as per the literature studied. These sub-sections aim to assess the validity and impact of these assumptions and ascertain the impact these assumptions had on the conclusions drawn from the results discussed in the previous sections. This section will comparatively examine varying recycling-to-waste ratios of corrugated board and shrink-wrap plastic relative to the industrial average of the opposing material.

5.4.1. Complete LCA Results: Shrink-Wrap Plastic Recycle Rate

The first sensitivity analysis that was executed was to assess the validity and effect of the assumed shrink-wrap plastic recycle ratio of 42.8%. The percentage of recycled plastic was varied in 20% intervals from 0% to 100% and these results were then compared with the industry average of 42.8% as well as to the comparative packaging configuration of corrugated board only at the industry average. The data used to analyze this sensitivity analysis is displayed in Table 8:

Table 8: Data used in the sensitivity analysis of the recycle rate of shrink-wrap plastic

%	Recycled (kg)	%	Non-Recycled (kg)
100.0	191.15	0.0	0.00
80.0	152.92	20.0	38.23
60.0	114.69	40.0	76.46
42.8	81.81	57.2	109.34
40.0	76.46	60.0	114.69
20.0	38.23	80.0	152.92
0.0	0.00	100.0	191.15

This data was used to simulate the sensitivity analysis in SimaPro to analyze the impact at varying recycle rates. Figure 30 displays the varied plastic recycling rate compared to the industry standard for the comparative packaging configuration of corrugated board only (full size graph available in Appendix B13).

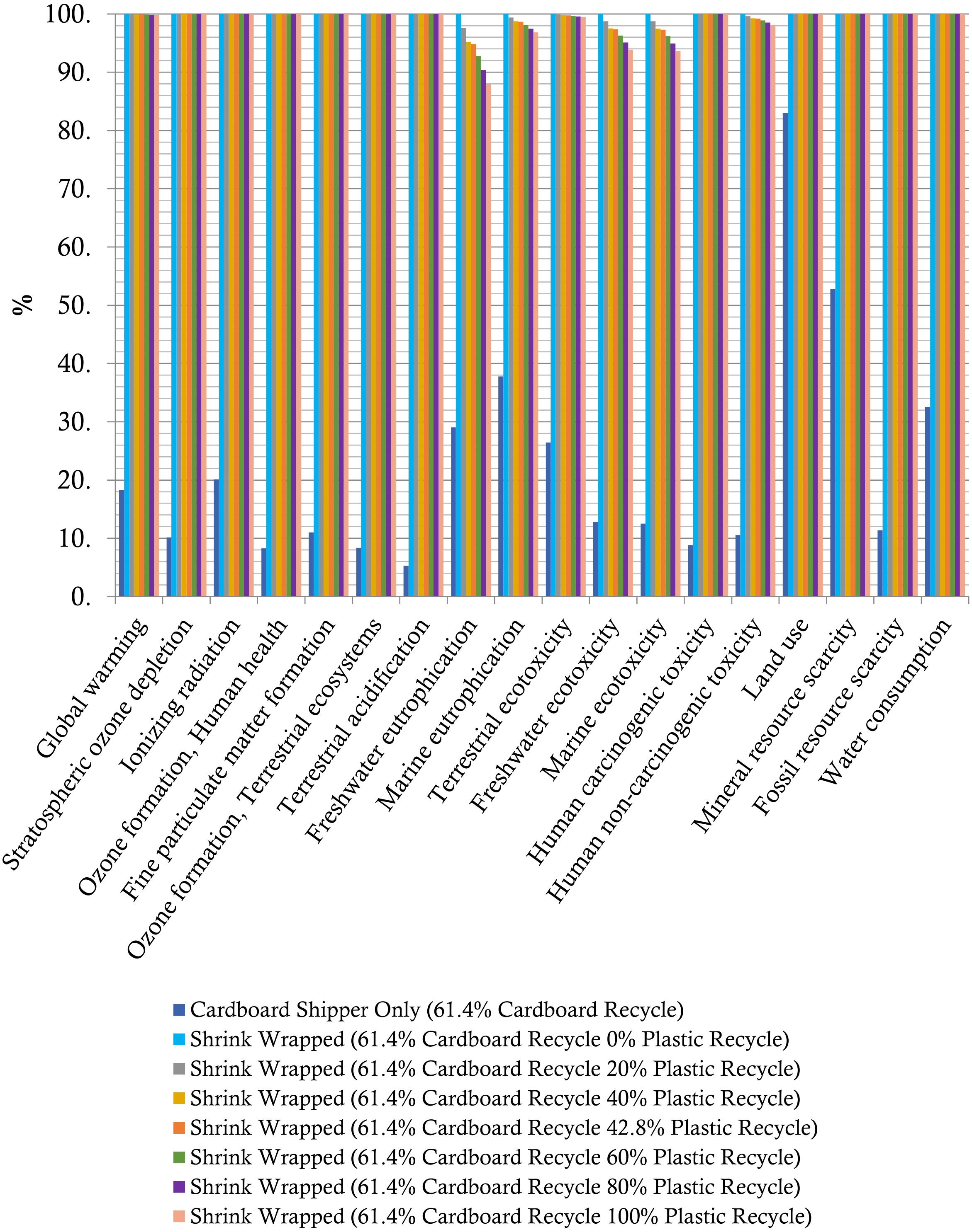

Figure 30: Sensitivity analysis graph of the recycle rate of heat shrink-wrap plastic

Figure 30 demonstrates that the variation in recycle rate of heat shrink plastic demonstrated very little change in the impact score of this packaging configuration. A steady decrease in the impact score was evident in five of the eighteen impact categories. In the Freshwater eutrophication category, which demonstrated the greatest variation, the impact score decreases approximately 3% for every 20% increase in recycle rate of plastic. It must be noted however that even at a recycle rate of 100% the heat-shrink plastic configuration still demonstrated an impact score 58.9% higher than the cardboard only configuration.

The marine eutrophication category demonstrated a decrease of approximately 0.5% in the impact category for every 20% increase in the plastic recycle rate. Similarly, to that of the freshwater eutrophication category, even at 100% plastic recycle rate, the cardboard only configuration demonstrated an impact score 59% lower than that of the lowest scoring shrink-wrap plastic configuration.

In the freshwater and marine ecotoxicity categories a decrease of approximately 1.5% in the impact was evident per every 20% increase in plastic recycle rate. The cardboard only configuration demonstrated a score approximately 81% lower than the best possible score for the heat shrink-wrap plastic configuration.

The only other category that demonstrates a noticeable variation was the human non-carcinogenic toxicity which demonstrated a variation of only approximately 2% between a plastic recycle rate of 100% or 0%. Compared to the impact score of the corrugated board only configuration with a score of 10.5% the best shrink-wrap plastic configuration is 87.6% higher.

Excluding long-term emissions, the below graph (Figure 31) was generated (full size graph available in Appendix B14):

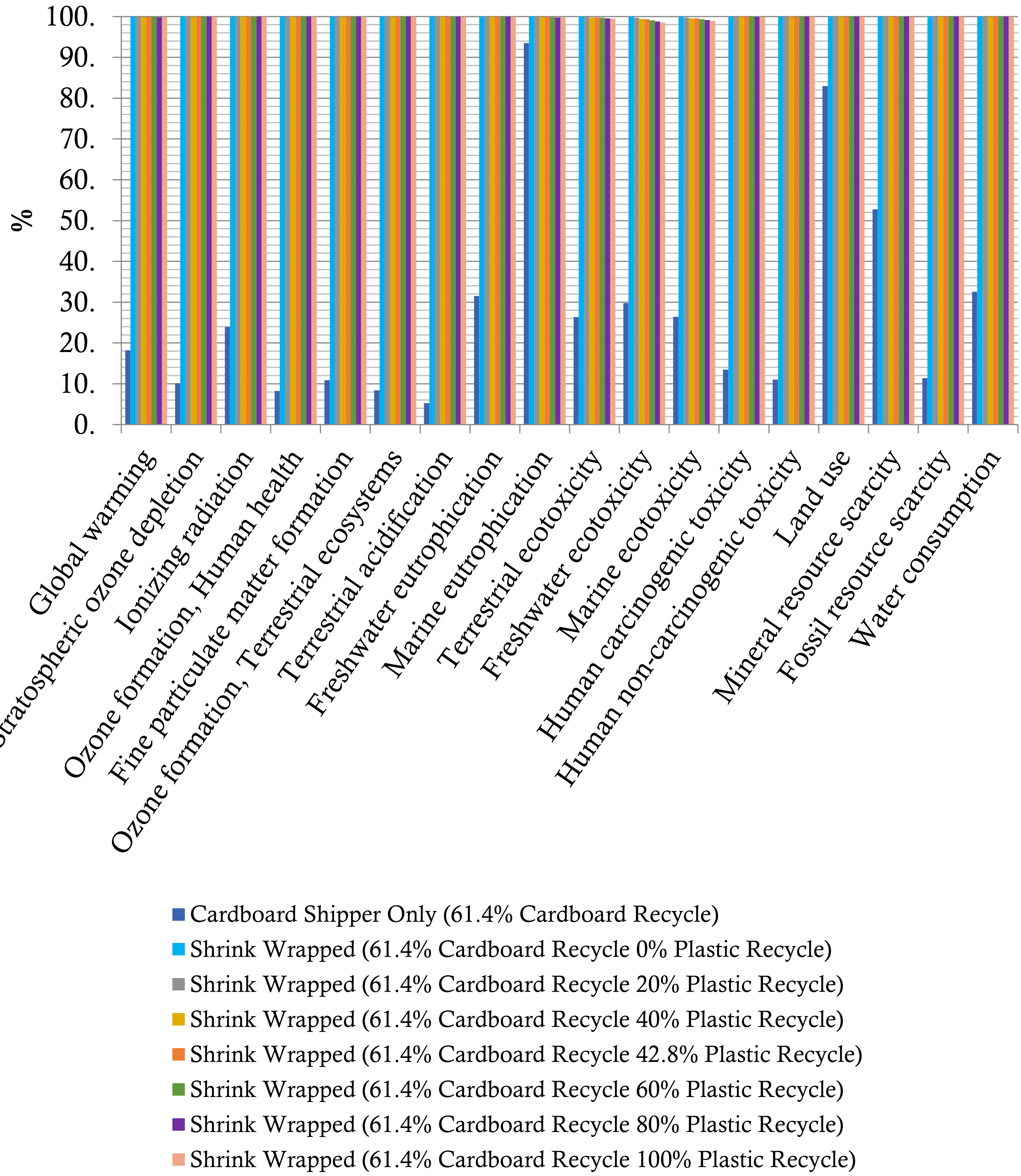

Figure 31: Sensitivity analysis graph of the recycle rate of heat shrink-wrap plastic excluding long-term emissions

When excluding long-term emissions, the variations that were previously evident in the above five mentioned categories became negligible. However, it was interesting to note the drastic increase in the score of the corrugated board only configuration in the marine eutrophication category which increased from 37.8% to 93.5%. Although still lower than all the possible recycle rates of the heat shrink-wrap plastic configuration it was interesting to note the short-term impact that the corrugated board configuration has on marine ecosystems.

5.4.2. Condensed LCA Results: Shrink-Wrap Plastic Recycle Rate

Looking more closely at the five chosen impact categories, the cardboard only configuration remains the better of the two configurations irrespective of the recycle rate of shrink-wrap plastic. Figure 32 shows only the results for the five chosen categories (full size graph available in Appendix B15):

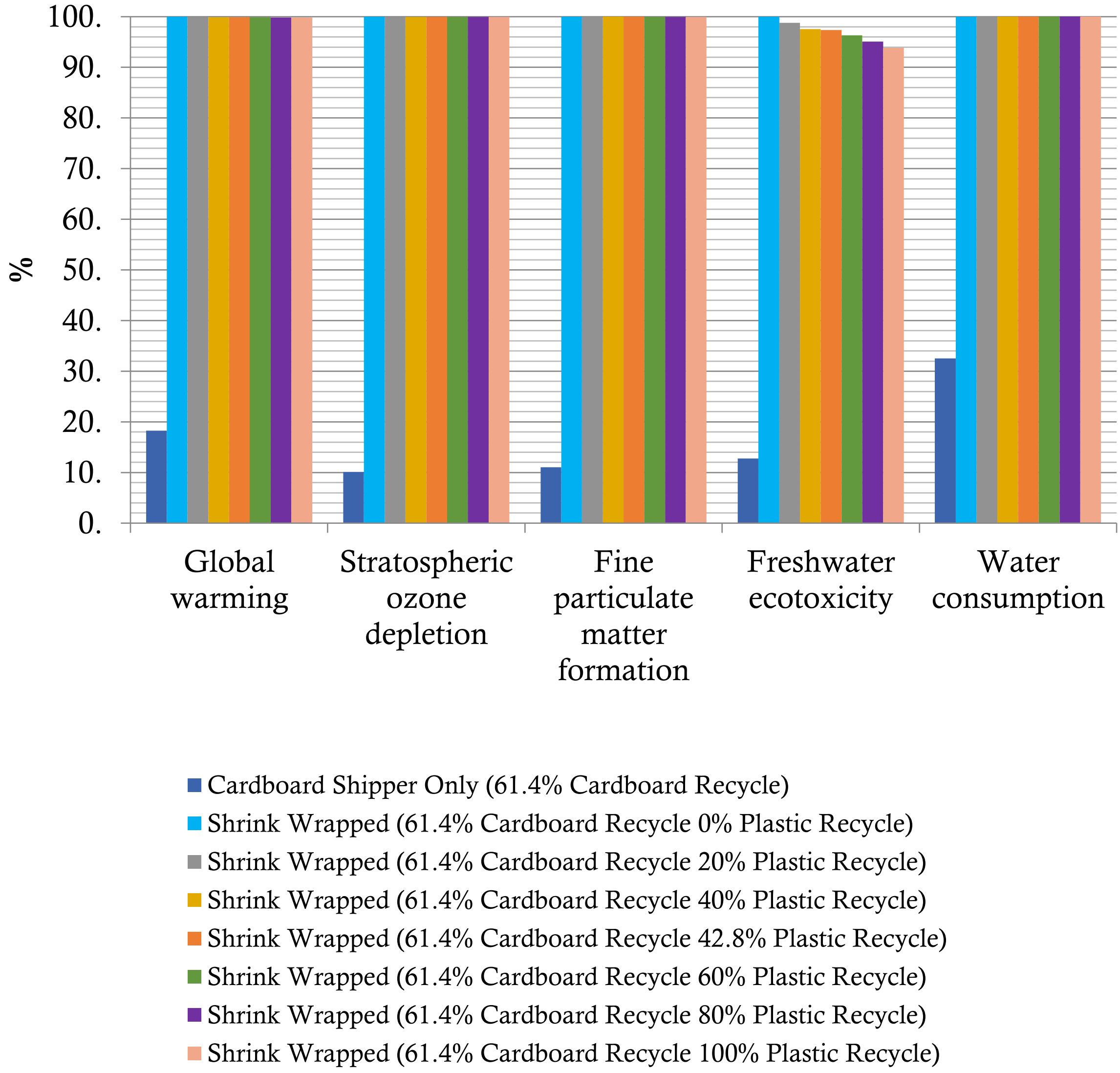

Figure 32: Condensed sensitivity analysis graph of the recycle rate of heat shrink-wrap plastic

The only focus category that demonstrated variation in the impact result with varying recycle rate was the freshwater ecotoxicity category. With a difference of only 6.1% between the impact score of 0% recycle rate vs that for 100% recycle rate. The other four focus categories demonstrated the same impact score respective of whether the plastic was recycled or not. This suggests that the recycling process for heat shrink-wrap plastic is as environmentally detrimental as that of the landfill disposal of the material. This is likely due to the very energy intensive processes required to recycle plastic as well as the chemical requirements to clean and decontaminate the soiled material.

The use of the industry standard of 42.8% recycle rate of heat shrink-wrap plastic when analysing this graph demonstrated a good average of all possible recycle rates that have been considered. It is however evident that in four of the five categories the change in recycle rate had no influence on the impact score of that plastic configuration in those categories.

When comparing the two packaging configurations, the cardboard only configuration demonstrated a score between 10.1% (in the Stratospheric Ozone Depletion category) and 32.6% (in the Water Consumption category) better than the heat-shrink wrap plastic packaging configuration.

Excluding long-term emissions, the graph in Figure 33 was obtained (full size graph available in Appendix B16):

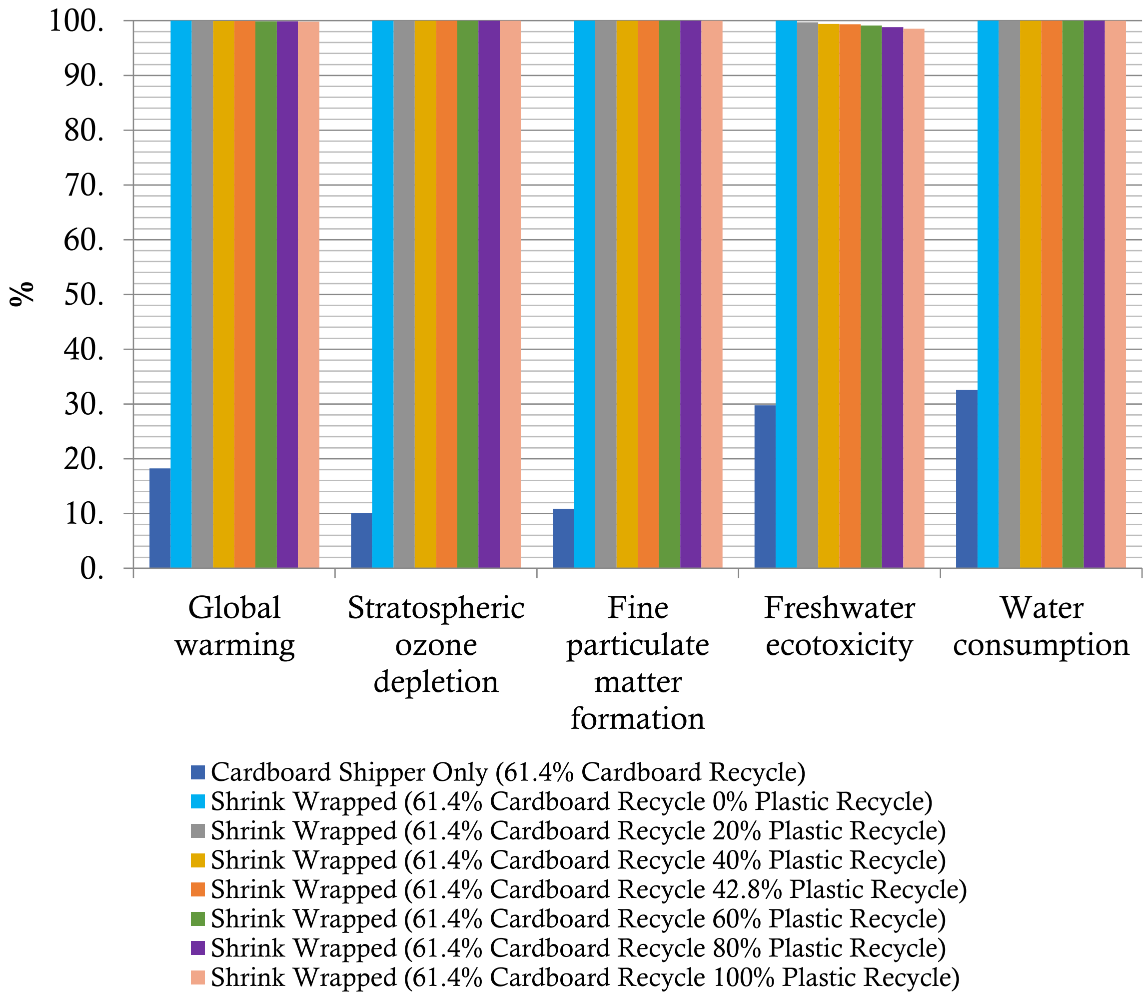

Figure 33: Condensed Sensitivity analysis graph of the recycle rate of heat shrink-wrap plastic excluding long-term emissions

The only difference evident when the long-term emissions were excluded was the decrease in variation of the impact score for the plastic configuration in the freshwater ecotoxicity category. The lack of significant variation in impact scores whether long-term emissions were included or excludes demonstrates that the cardboard only configuration offered lower impact irrespective of the timeline in which the two packaging configurations are compared.

5.5 Sensitivity Analysis: Cardboard Recycling Rate

5.5.1. Complete LCA Results: Cardboard Recycle Rate

The second sensitivity analysis that was executed was to assess the validity and effect of the assumed corrugated board recycle ratio of 61.4%. The percentage of recycled cardboard varied in 20% intervals from 0% to 100% and these results were then compared with the industry average of 61.4% as well as to the comparative packaging configuration of heat shrink-wrap plastic at the industry average. The data used to analyze this sensitivity analysis is displayed in Table 9:

Table 9: Table of data used in the sensitivity analysis of the recycle rate of corrugated board

%	Recycled (kg)	%	Non-Recycled (kg)
100.0	1 845.35	0.0	0.00
80.0	1 476.28	20.0	369.07
61.4	1 133.04	38.6	712.31
60.0	1 107.21	40.0	738.14
40.0	738.14	60.0	1 107.21
20.0	369.07	80.0	1 476.28
0.0	0.00	100.0	1 845.35

This data was used to simulate the sensitivity analysis in SimaPro to analyze the impact at varying recycle rates. The graph in Figure 34 displays the varied corrugated board recycle rate compared to the industry standard for the comparative packaging configuration of heat shrink-wrap plastic (full size graph available in Appendix B17):

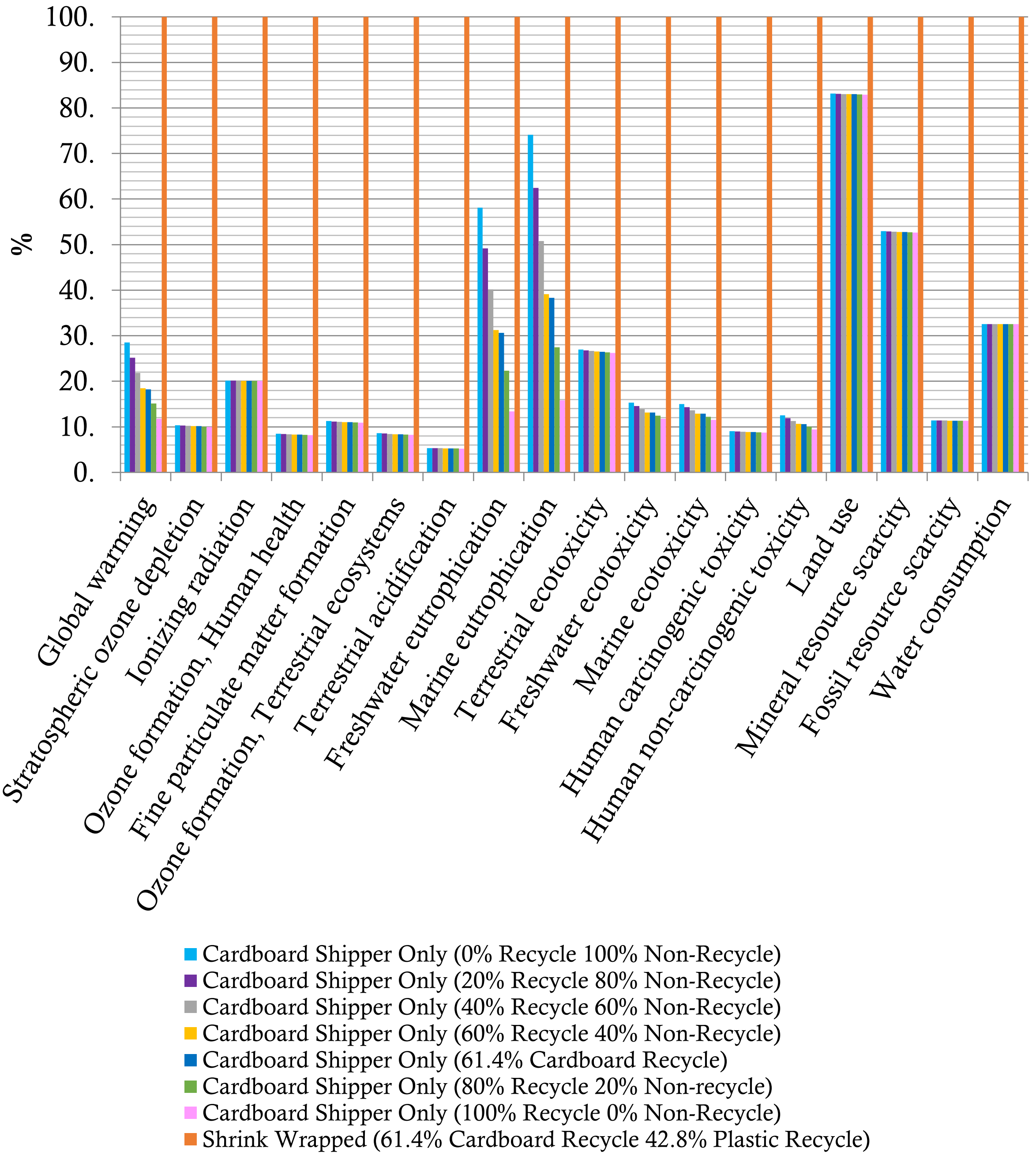

Figure 34: Sensitivity analysis graph of the recycle rate of corrugated board

The variation in cardboard recycle rate exhibited a differential in the impact results in six of the eighteen categories: Global Warming, Freshwater Eutrophication, Marine Eutrophication, Freshwater Ecotoxicity, Marine Ecotoxicity and Human Non-Carcinogenic Toxicity. The most drastic variations were evident in the two Eutrophication categories where the impact score varies by approximately 12% for every 20% change in recycle rate. The trend demonstrated in these categories was that the impact score increased with decreasing rate of recycle.

When comparing the different recycle rates to that of the comparative packaging configuration of heat shrink-wrap plastic, even with the worst possible recycle rate of 0% the cardboard only packaging configuration demonstrated a lower impact score. The Land Use category demonstrated the closest scores with a difference of only 17% with no noticeable impact difference between the different recycle rates. Compared to that of the Terrestrial Acidification which exhibited a difference of 94.7% between the worst cardboard only recycle rate of 0% and the industry standard of the shrink-wrap plastic configuration.

The complete eighteen category results graph provides a good indication as to the validity of the assumption to use the industry standard of 61.4%. The results at this recycle rate fall approximately in the middle which demonstrated a good average of the variable recycle rates which will be evident in reality.

Excluding long-term emissions, the graph in Figure 35 was obtained (full size graph available in Appendix B18):

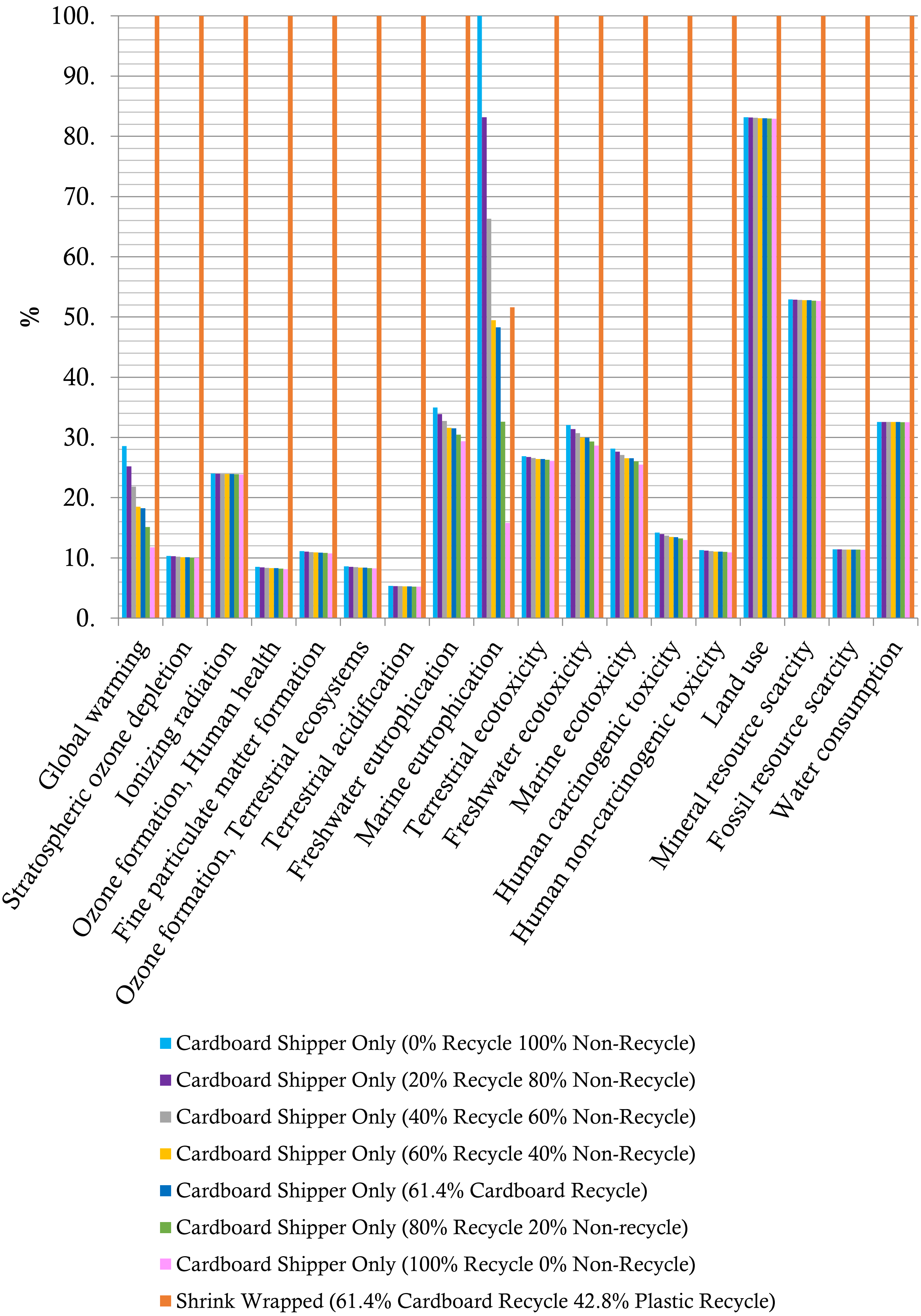

Figure 35: Sensitivity analysis graph of the recycle rate of corrugated board excluding long-term emissions

The only significant changes evident between the two graphs above were the drastic change in the Freshwater and Marine Eutrophication categories. When long-term emissions are excluding the Freshwater Eutrophication impact categories become significantly closer in value for the varying cardboard recycle rates which suggests that the variations are heavily influenced the timeline of exposure.

The focus, however, between these two graphs was the drastic changes that have occurred in the marine eutrophication category. Considering that this category was not a focus due to the geographical location of the studying being in the center of Gauteng and completely isolated from direct contact with marine life it was still important and interesting to note how critical the recycle rate was to the outcome in this category. If the recycle rate of cardboard drops below 60% the impact score of the cardboard only packaging configuration exceeded the score of the heat shrink-wrap plastic configuration by between 14% and 48%. For the industry standard of 61.4% the cardboard only configuration remains the configuration with the lower impact score. However, when the recycling rate drops this conclusion does not hold for this category in isolation. Given that this was only one of the eighteen impact categories that was assessed it was however valid to conclude that the cardboard only configuration demonstrated a lower impact score compared to the heat shrink-wrap plastic packaging configuration irrespective of the recycle rate of cardboard.

5.5.2. Condensed LCA Results: Cardboard Recycle Rate

Looking more closely at the five chosen impact categories, the cardboard only configuration remains the better of the two configurations irrespective of the recycle rate of corrugated board. The graph in Figure 36 shows only the results for the five chosen categories (full size graph available in Appendix B19):

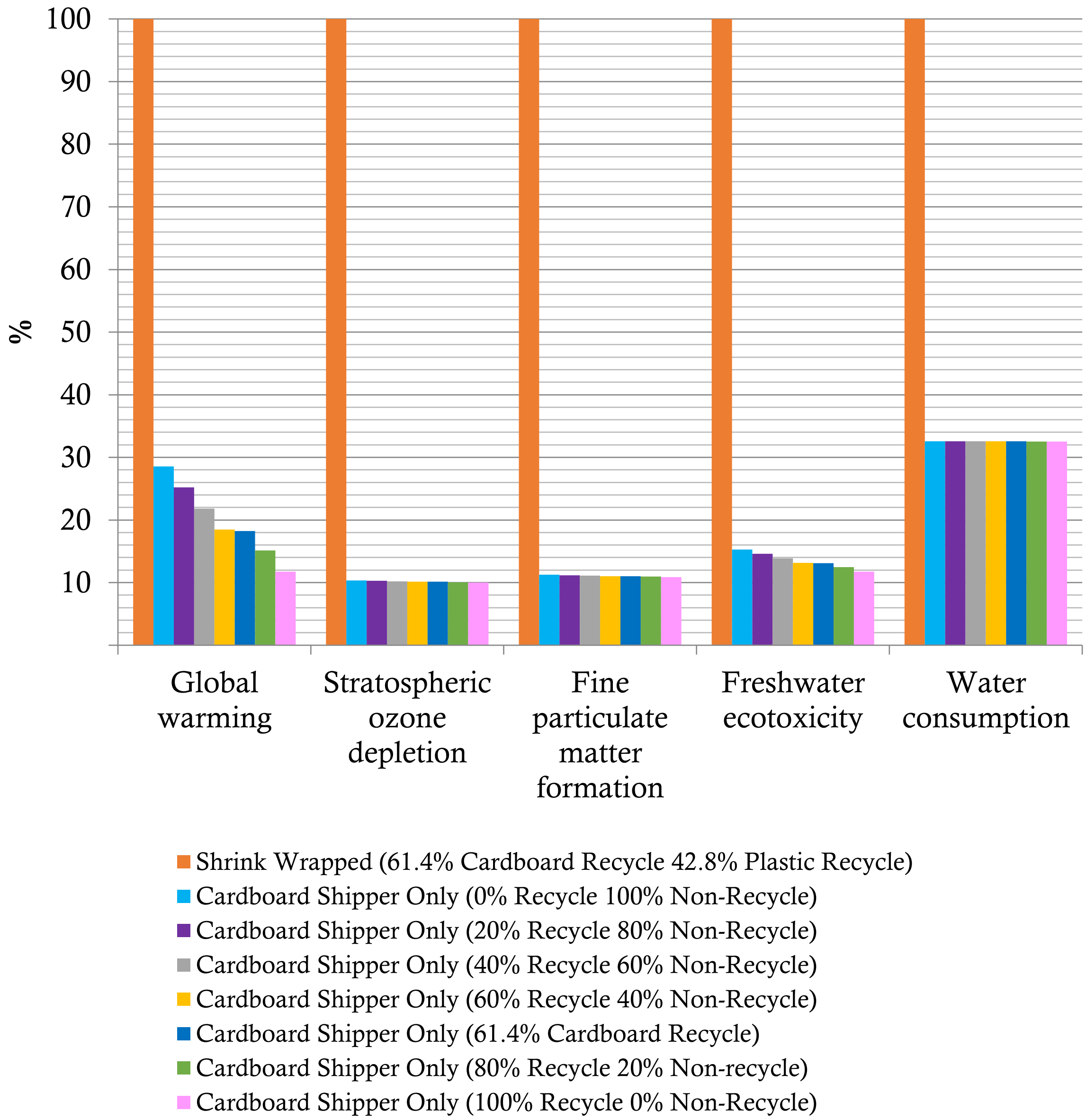

Figure 36: Condensed sensitivity analysis graph of the recycle rate of corrugated board

The Global Warming category was the only focus category that demonstrates noticeable variation between recycling rates. The impact score decreases approximately 4% for every 20% increase in recycle rate of corrugated board. When compared to the contrasting heat shrink-wrap plastic packaging configuration, the cardboard only configuration exhibited an impact score 72% lower even when 0% of the cardboard was recycled. This result emphasizes the importance of recycling cardboard to minimize the impact on global warming.

The remaining four categories exhibited very little variation in the impact score as the cardboard recycling rate was varied. The industry standard recycling rate of 61.4% for

2022 demonstrated a good average for the recycling rates analyses, specifically in the global warming category where variation was evident.

Excluding long-term emissions, the graph in Figure 37 was obtained (full size graph available in Appendix B20):

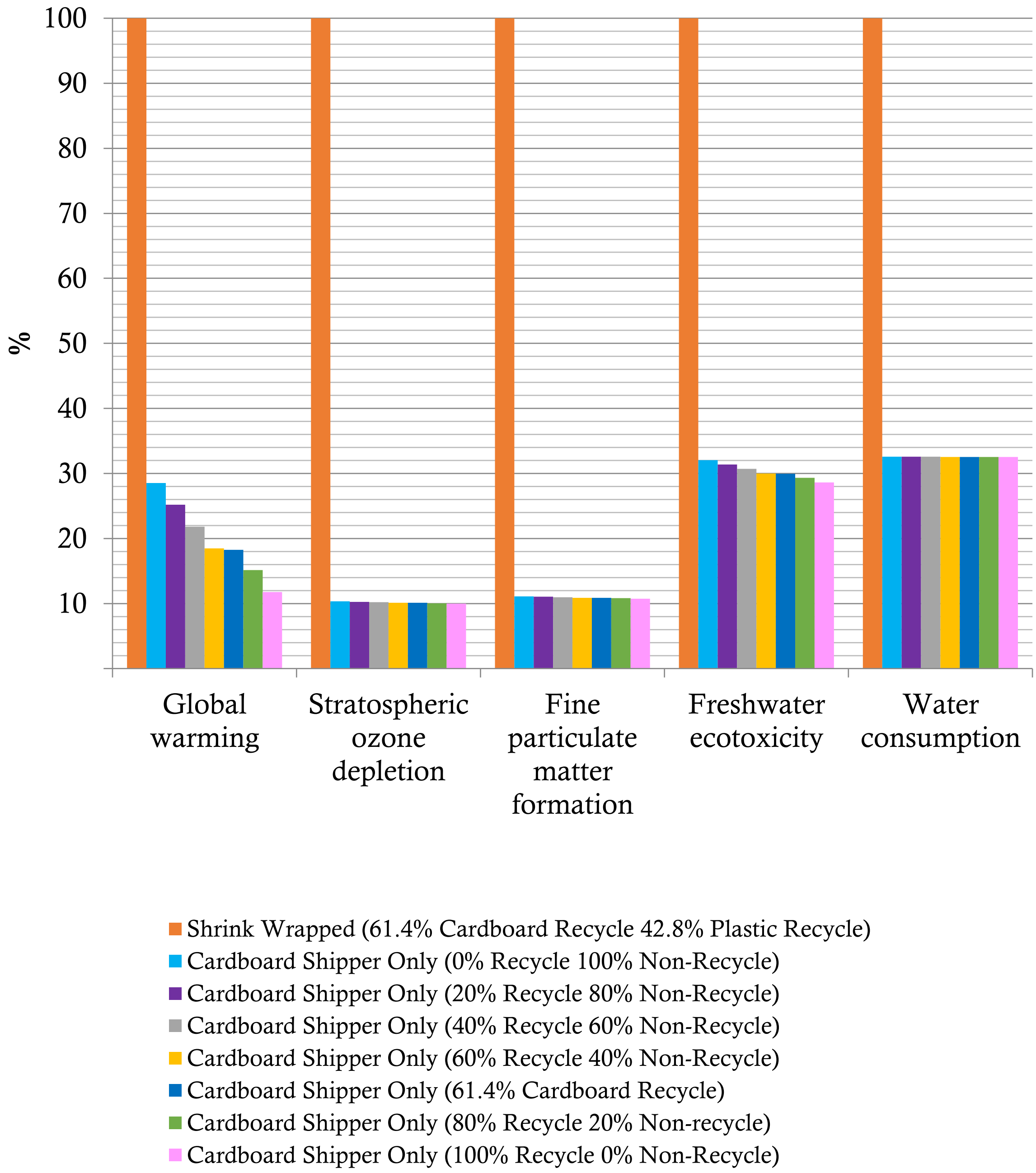

Figure 37: Condensed Sensitivity analysis graph of the recycle rate of corrugated board excluding long-term emissions

The only noticeable difference when long-term emissions are excluded was the overall increase in the impact scores in the Freshwater Ecotoxicity category which exhibited approximately a 12% increase across all analyzed recycling rates. This suggests that the toxicity of the corrugated board to freshwater sources was very time dependent and a greater impact differential was realized in the short term rather than over a lengthy period. This may be due to the shorter decomposition period of cardboard as opposed to plastic.

It was evident that regardless of the extent to which corrugated board was recycled the cardboard only packaging configuration exhibited a lower impact score compared to the heat shrink-wrap plastic packaging configuration.

5.6 Uncertainty Analysis

The uncertainty of the data used in the calculations within SimaPro was accounted for by facilitating a standard deviation of three for each of the manual data inputs. The full uncertainty analysis was executed in the SimaPro software by utilizing a Monté Carlo analysis with the ReCiPe 2016 midpoint (H) method which consisted of 1 000 fixed runs with a confidence interval of 95%. An uncertainty bar chart was generated that displays the error associated with each of the eighteen impact categories. This uncertainty bar chart serves as a summary of the complete uncertainty analysis for the packaging configuration under analysis.

The detailed uncertainty analysis was executed only for the five focus categories. For each of the five categories a normal distribution graph was generated to ascertain the quality of the impact data generated for that category.

5.6.1. Uncertainty Analysis: Heat-Shrink Wrap Plastic

Shrink-Wrap Plastic Configuration Uncertainty Bar Chart

The uncertainty analysis executed in SimaPro yielded the following error bar values (Table 10 and Figure 38).

Table 10: Heat Shrink-wrap plastic configuration uncertainty error bar values

Label	Shrink Wrapped (61.4% Cardboard Recycle 42.8% Plastic Recycle)	Low	High
Global warming	100	23.32	32.23
Stratospheric ozone depletion	100	46.37	138.01
Fine particulate matter formation	100	16.10	19.16
Freshwater ecotoxicity	100	46.24	214.24
Water consumption	100	1439.82	1318.31

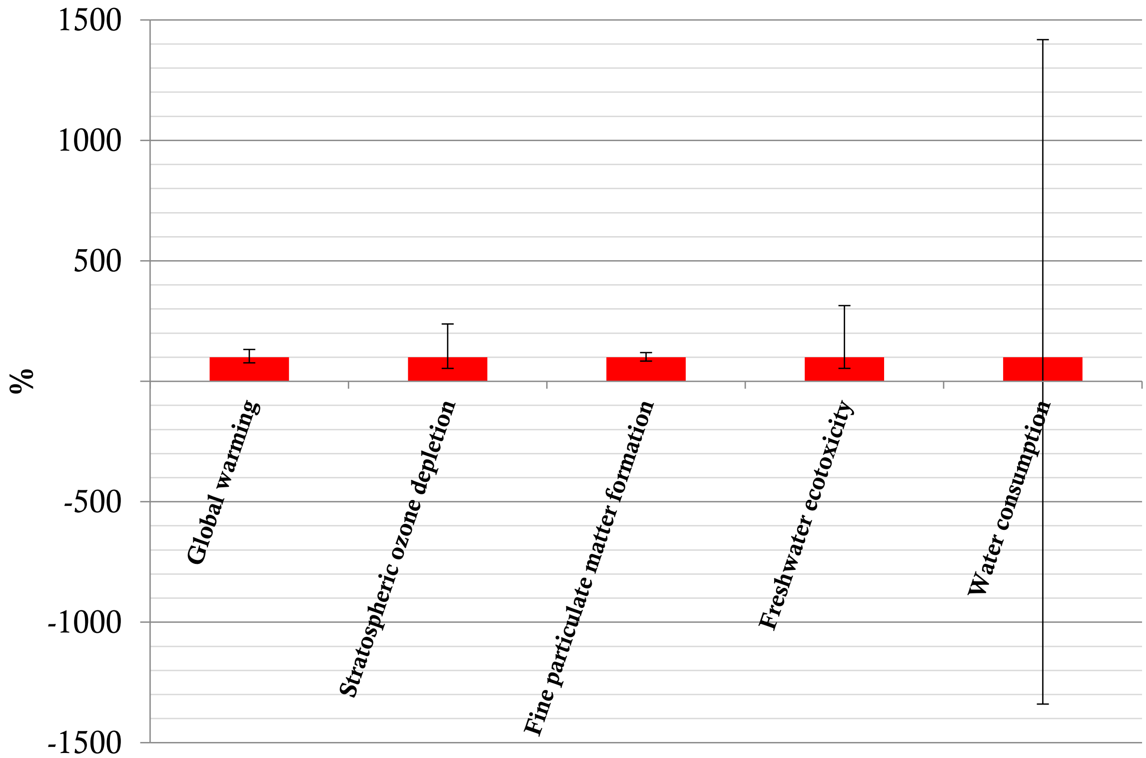

Figure 38: Uncertainty analysis bar chart for the shrink wrap plastic packaging configuration

Focusing specifically on the five chosen categories, the error bars exhibited for four of the five of the categories were relatively small. The low error boundary was between 16% and 46% and the upper error boundary was between 19% and 214%. Unlike the water consumption category which exhibited a very large error bar with the low error boundary of approximately 1 440% and an upper error boundary of 1 318%. (Full size graph available in Appendix B21).

The large error bar values that were evident in the water consumption category were due to the uncertainty of the data on which the impact score was modelled. The high degree of uncertainty was due to a combination of several factors. The life cycle that was analyzed consists of multiple stages in which water consumption was evident in most stages in varying quantities. The generation of electricity and manufacturing of virgin plastic material exhibited the highest water consumption and the highest associated uncertainty. The high degree of uncertainty in these stages can primarily be attributed to the variety in ages of the processes used and as well as that of the plant equipment. Older processes and plant equipment by virtue of length of use and progression of technology exhibit lower efficiencies than newer more advanced equipment. Lower efficiencies result in higher volumes of resources used to achieve the target output. Older plants and processes are also significantly less water conscious owing to the era in which they were developed.

Similarly, the rate of recycling of water back into the process cannot be definitely determined as it will vary from one production facility to the next. The rate of recycle of water back into the process will also be vastly different between older and newer production plants owing to the significantly higher degree of focus that was placed on environmental conservation in more modern facilities opposed to older plants.

Considering all the above factors the high degree of uncertainty exhibited for the water consumption category was due to the vast variation in the available processes to achieve the same product which exhibit high degrees of variation in the consumption of water due to the age of the plant equipment and processes; and the defining features of the process such as recycle rates of water and water conservation considerations.

The uncertainty of each of the five focus categories will be analyzed in greater detail in the sections to follow.

<u>Global Warming</u>

The uncertainty analysis of the global warming impact exhibited a normal distributed graph (Figure 39 and Appendix B22). The mean of the data (dashed red line) was calculated to be 367 000 kg CO_2 eq and the median (solid red line in the middle) was 364 000 kg CO_2 eq. The standard deviation of this data set was 5 040 kg CO_2 eq and the coefficient of variation was 13.7%. The data set exhibited a standard error of the mean of 159 kg CO_2 eq. The upper and lower red lines depict the 95% confidence internal.

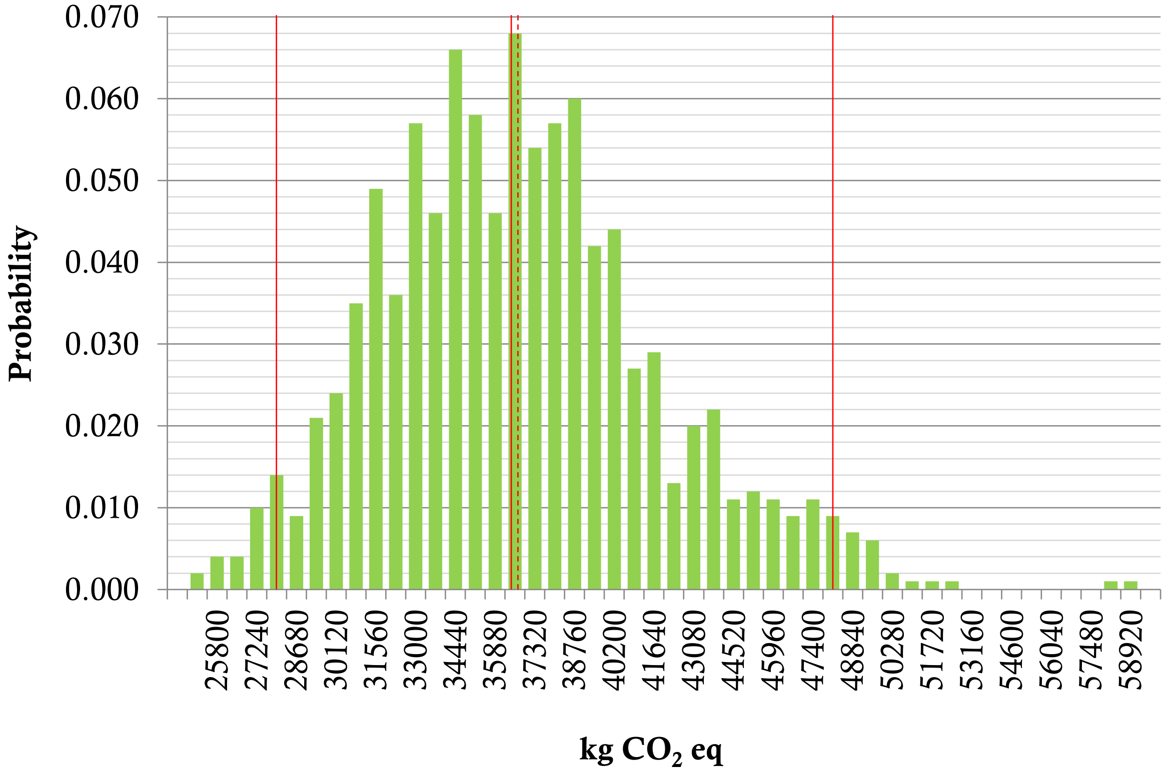

Figure 39: Heat shrink-wrap plastic global warming normal distribution uncertainty analysis graph

The bell-shape of the graph and the similarity of the mean and median demonstrated that the data was evenly distributed. The low coefficient of variation shows that the data was accurate and evenly distributed. The low standard error of the mean also supported the claim that the data was accurate and evenly distributed.

Stratospheric Ozone Depletion

The uncertainty analysis of the stratospheric ozone depletion impact exhibited a normally distributed graph screwed to the left (Figure 40 and Appendix B23). The mean of the data was calculated to be 0.0246 kg CFC11 eq and the median was 0.022 kg CFC11 eq. The standard deviation of this data set was 0.0107 kg CFC11 eq and the coefficient of variation was 43.3%. The data set exhibited a standard error of the mean of 0.000337 kg CFC11 eq.

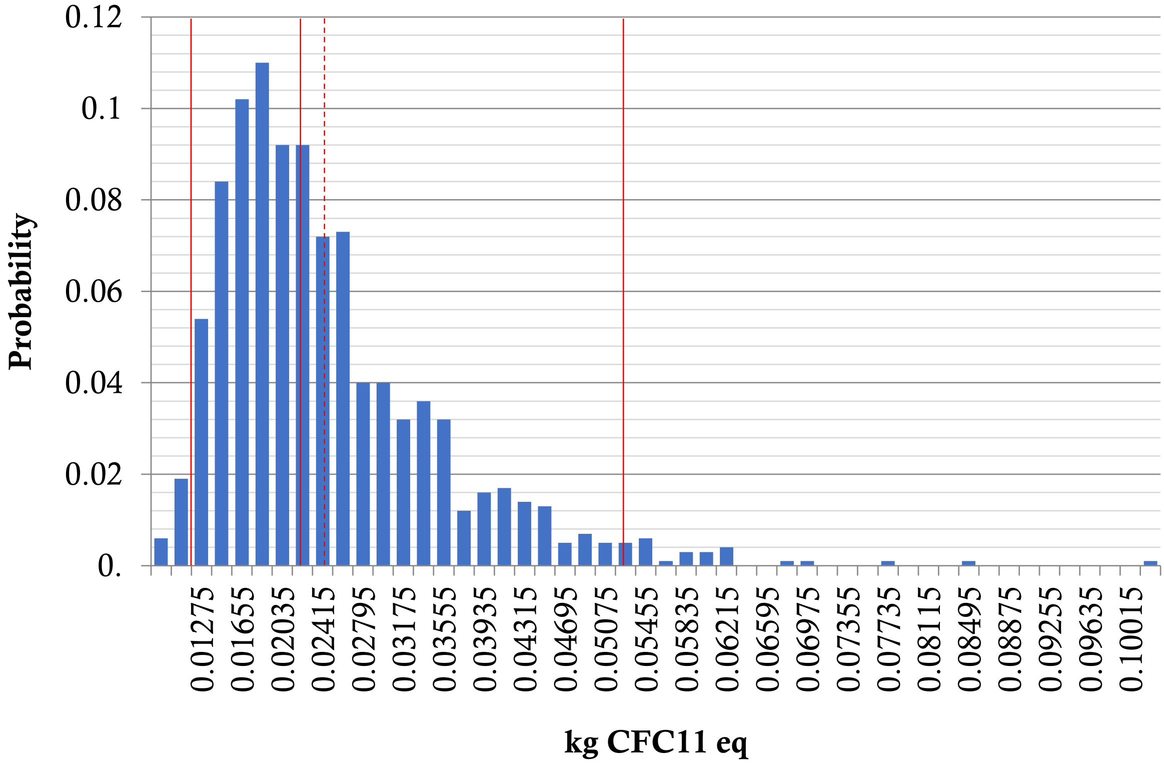

Figure 40: Heat shrink-wrap plastic stratospheric ozone depletion normal distribution uncertainty analysis graph

The bell-shape of the graph, although skewed to the left, and the similarity of the mean and median demonstrated that the data was evenly distributed. The high coefficient of variation shows that the data has a higher level of dispersion around the mean. The very low standard error of the mean supports the claim that the data was accurate and evenly distributed. These differences account for the larger error bar on the stratospheric ozone depletion value on the uncertainty bar chart in Figure 38 as compared to the global warming data that exhibited a smaller error.

Fine Particulate Matter Formation

The uncertainty analysis of the fine particulate matter formation impact exhibited a normally distributed graph (Figure 41 and Appendix B24). The mean of the data was calculated to be 95 kg PM2.5 eq and the median was 94.5 kg PM2.5 eq. The standard deviation of this data set was 8.55 kg PM2.5 eq and the coefficient of variation was 9%. The data set exhibited a standard error of the mean of 0.27 kg PM2.5 eq.

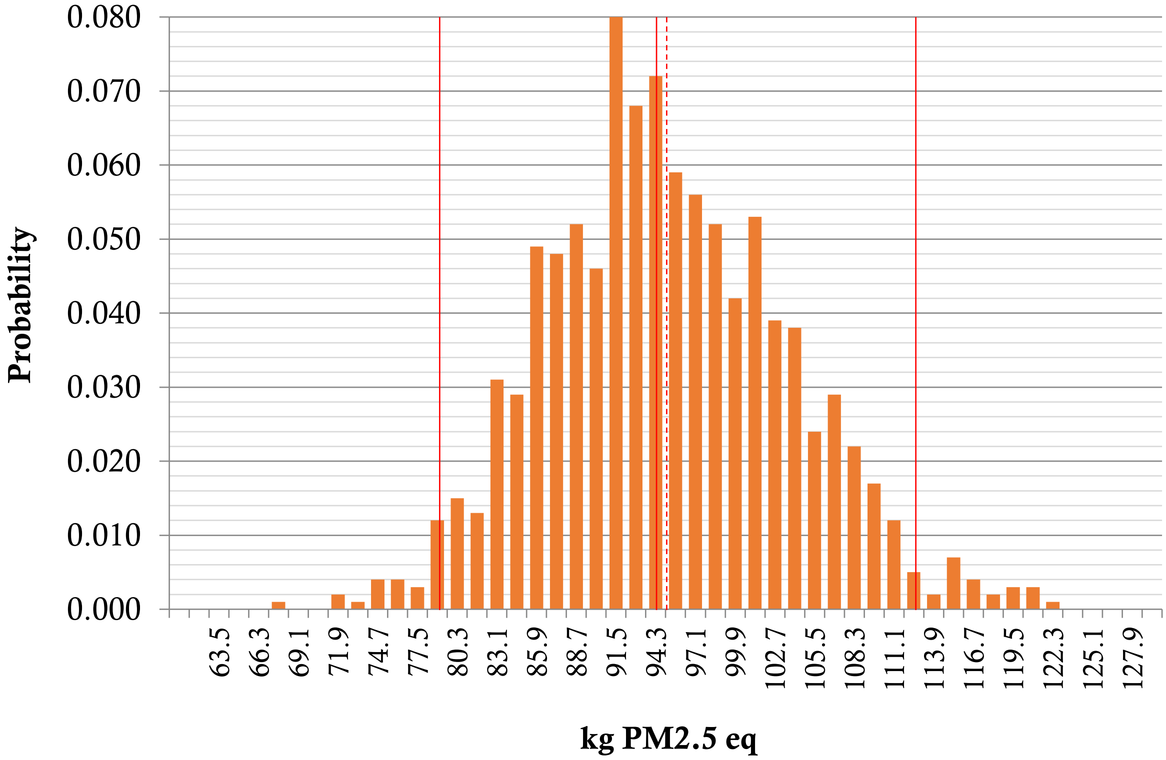

Figure 41: Heat shrink-wrap plastic fine particulate matter formation normal distribution uncertainty analysis graph

The bell-shape of the graph and the similarity of the mean and median demonstrated that the data was evenly distributed. The low coefficient of variation shows that the data was accurate and evenly distributed. The low standard error of the mean also supports the claim that the data was accurate and evenly distributed.

Freshwater Ecotoxicity

The uncertainty analysis of the freshwater ecotoxicity impact exhibited a normally distributed graph screwed to the left (Figure 42 and Appendix B25). The mean of the data was calculated to be 1 020 kg 1,4-DCB and the median was 860 kg 1,4-DCB. The standard deviation of this data set was 642 kg 1,4-DCB and the coefficient of variation was 62.9%. The data set exhibited a standard error of the mean of 20.3 kg 1,4-DCB.

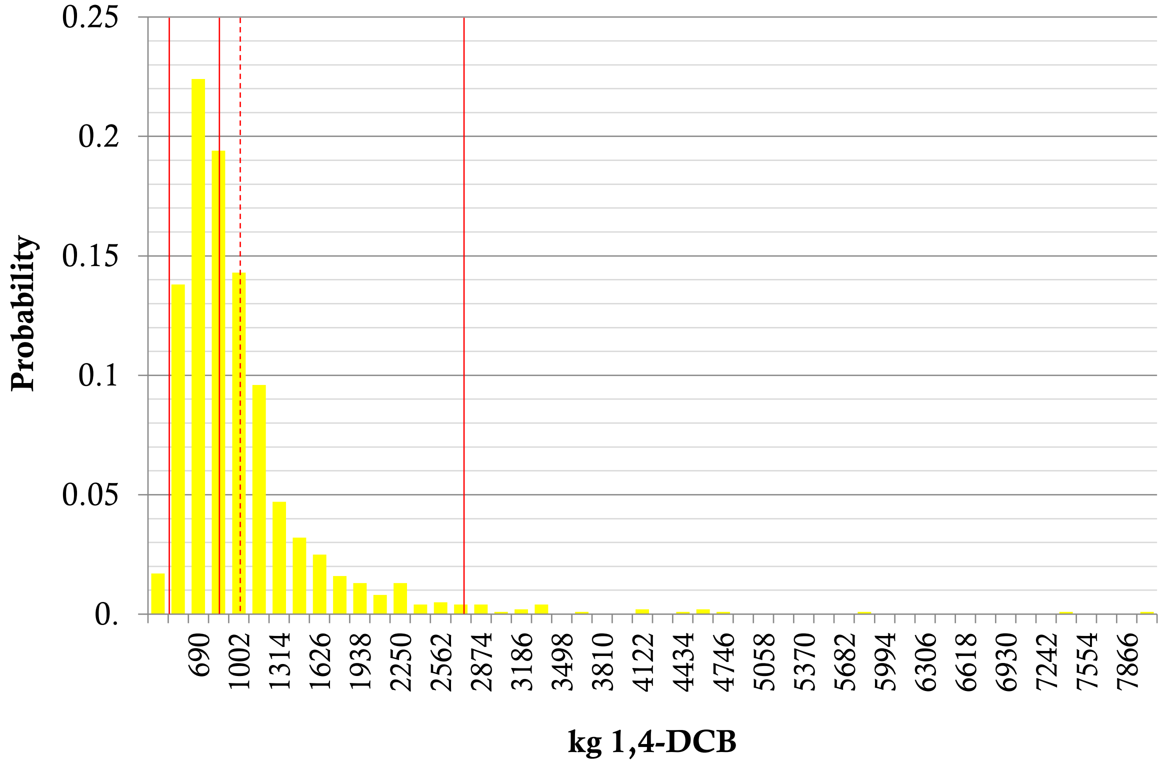

Figure 42: Heat shrink-wrap plastic freshwater ecotoxicity normal distribution uncertainty analysis graph

The bell-shape of the graph, although skewed to the left, and the similarity of the mean and median demonstrated that the data was evenly distributed. The high coefficient of variation shows that the data has a higher level of dispersion around the mean. The low standard error of the mean supports the claim that the data was accurate and evenly distributed. These differences account for the larger error bar on the freshwater ecotoxicity value on the uncertainty bar chart in Figure 38 as compared to the three previous categories data that exhibited smaller errors.

Water Consumption

The uncertainty analysis of the water consumption impact exhibited a normally distributed graph (Figure 43 and Appendix B26). The mean of the data was calculated to be 157 m^3 and the median was 228 m^3. The standard deviation of this data set was 1 580 $m^3$and the coefficient of variation was 1 010%. The data set exhibited a standard error of the mean of 49.8 m^3.

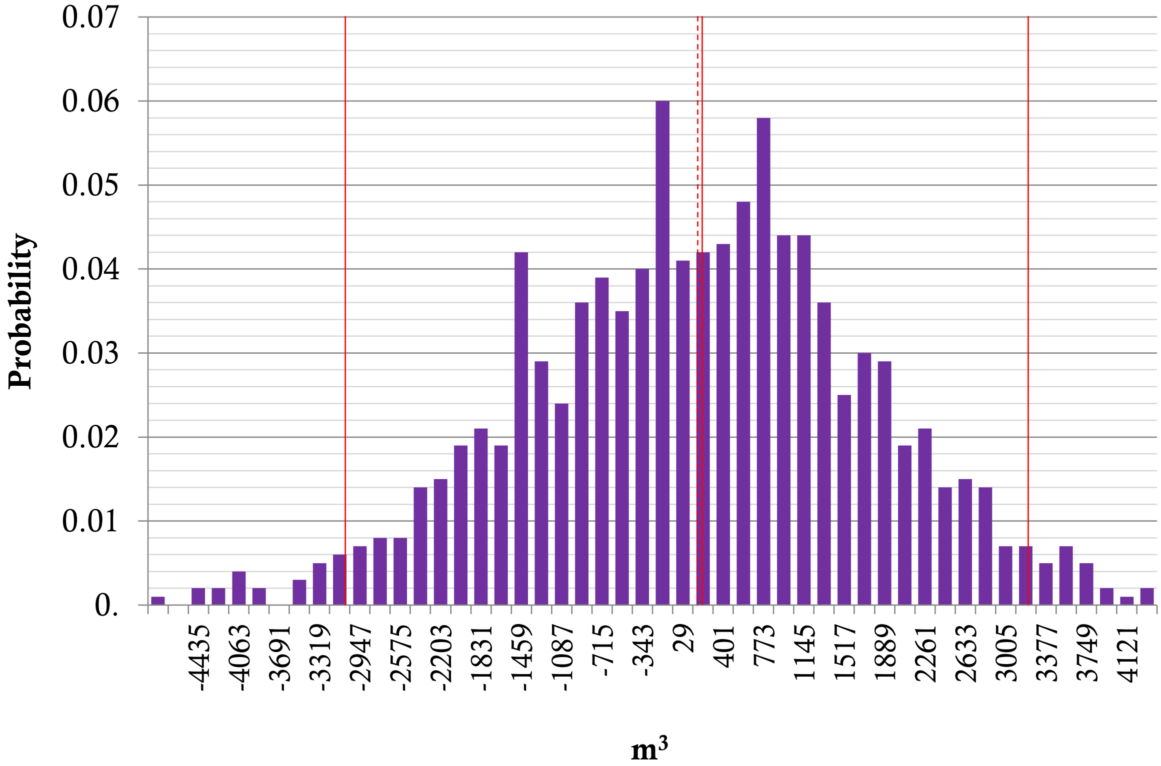

Figure 43: Heat shrink-wrap plastic water consumption normal distribution uncertainty analysis graph

The bell-shape of the graph and the similarity of the mean and median demonstrated that the data was evenly distributed. The very high coefficient of variation shows that the data exhibited a high degree of inaccuracy and was unevenly distributed. The high standard error of the mean also does not fully support the claim that the data was accurate and evenly distributed.

This data supports the very large error bar that was displayed in Figure 38 for the water consumption impact data. This very large error was due to the uncertainty associated with definitively determining the exact water requirements of the processes associated with all the stages in the life cycle of this packaging configuration. It can thus be said that the uncertainty data regarding the water consumption impact data suggests that the data may possible not be as accurate as other impact categories thus may be a factor to consider as it may significantly influence the modelling data for water consumption.

5.6.2. Uncertainty Analysis: Corrugated Board

The uncertainty analysis executed in SimaPro yielded the following error bar values (Table 11 and Figure 44).

Table 11: Corrugated board configuration uncertainty analysis error bar values

Label	Cardboard Shipper Only (61.4% Cardboard Recycle)	Low	High
Global warming	100	10.33	13.36
Stratospheric ozone depletion	100	10.70	13.02
Fine particulate matter formation	100	8.56	12.01
Freshwater ecotoxicity	100	35.88	61.37
Water consumption	100	5321.46	4068.63

<u>Corrugated Board Configuration Uncertainty Bar Chart</u>

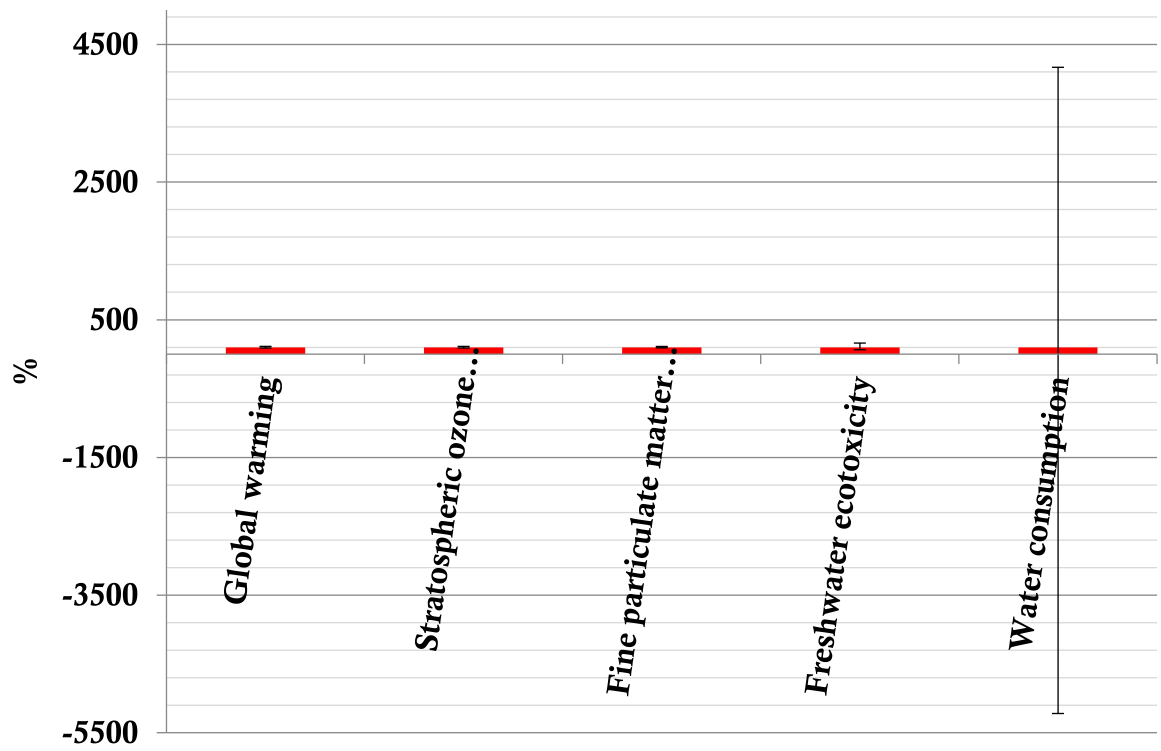

Figure 44: Uncertainty analysis bar chart for the corrugated board only packaging configuration

Focusing specifically on the five chosen categories, similarly to the heat shrink-wrap plastic configuration data, the error bars exhibited for four of the five of the categories are very small. The low error boundary was between 8.6% and 35.9% and the upper error boundary was between 12% and 61.4%. It was interesting to note the lower error boundary values evident for the cardboard only configuration compared to that of the heat shrink-wrap plastic configuration. Unlike the first four impact categories, the water consumption category exhibited a very large error bar with the low error boundary of approximately 5 322% and an upper error boundary of 4 069%. The higher degree of error in the cardboard only configuration was evident owing to the high consumption of water evident in the paper and pulp industry as opposed to the plastic and petroleum industry. (Full size graph available in Appendix B27).

Similarly to that of the heat shrink-wrap plastic configuration, the large error bar values that were evident in the water consumption category were due to the uncertainty of the data on which the impact score was modelled. The high degree of uncertainty was due to a combination of several factors. The life cycle that was analyzed consists of multiple stages in which water consumption was evident in most stages in varying quantities. The forestry and paper and pulp manufacturing stages exhibited the highest water consumption and the highest associated uncertainty. The high degree of uncertainty in these stages can primarily be attributed to the variety in ages of the processes used and as well as that of the plant equipment. Older processes and plant equipment by virtue of length of use and progression of technology exhibit lower efficiencies than newer more advanced equipment. Lower efficiencies result in higher volumes of resources used to achieve the target output. Older plants and processes are also significantly less water conscious owing to the era in which they were developed.

Similarly, the rate of recycling of water back into the process cannot be definitely determined as it will vary from one production facility to the next. The rate of recycle of water back into the process will also be vastly different between older and newer production plants owing to the significantly higher degree of focus that was placed on environmental conservation in more modern facilities opposed to older plants.

In addition to the contribution that plant age has on the consumption of water the geographical location of the various stages in the life cycle also contributes to the variable water consumption. Specifically for the forestry stage the climate and associated rainfall will play a significant role in the requirement for water. In an area of greater rainfall, the requirement for supplemental water is drastically reduced as opposed to more arid areas. The geographical location of where resources are sourced also contributes to the uncertainty of the data used. Owing to the availability of more than one supplier of resources the degree of uncertainty of consumption of water increases as there are a greater number of possible suppliers.

Considering all the above factors the high degree of uncertainty exhibited for the water consumption category was due to the vast variation in the available processes to achieve the same product which exhibit high degrees of variation in the consumption of water due to the age of the plant equipment and processes; the defining features of the process such as recycle rates of water and water conservation considerations; and the geographical location of resources which is influenced by climate and weather which significantly influences the requirement for additional water consumption.

The uncertainty of each of the five focus categories will be analyzed in greater detail in the sections to follow.

Global Warming

The uncertainty analysis of the global warming impact for the corrugated board only packaging configuration exhibited a normally distributed graph (Figure 45 and Appendix B28). The mean of the data was calculated to be 6 690 kg CO_2 eq and the median was 6 650 kg CO_2 eq. The standard deviation of this data set was 409 kg CO_2 eq and the coefficient of variation was 6.11%. The data set exhibited a standard error of the mean of 14.5 kg CO_2 eq.

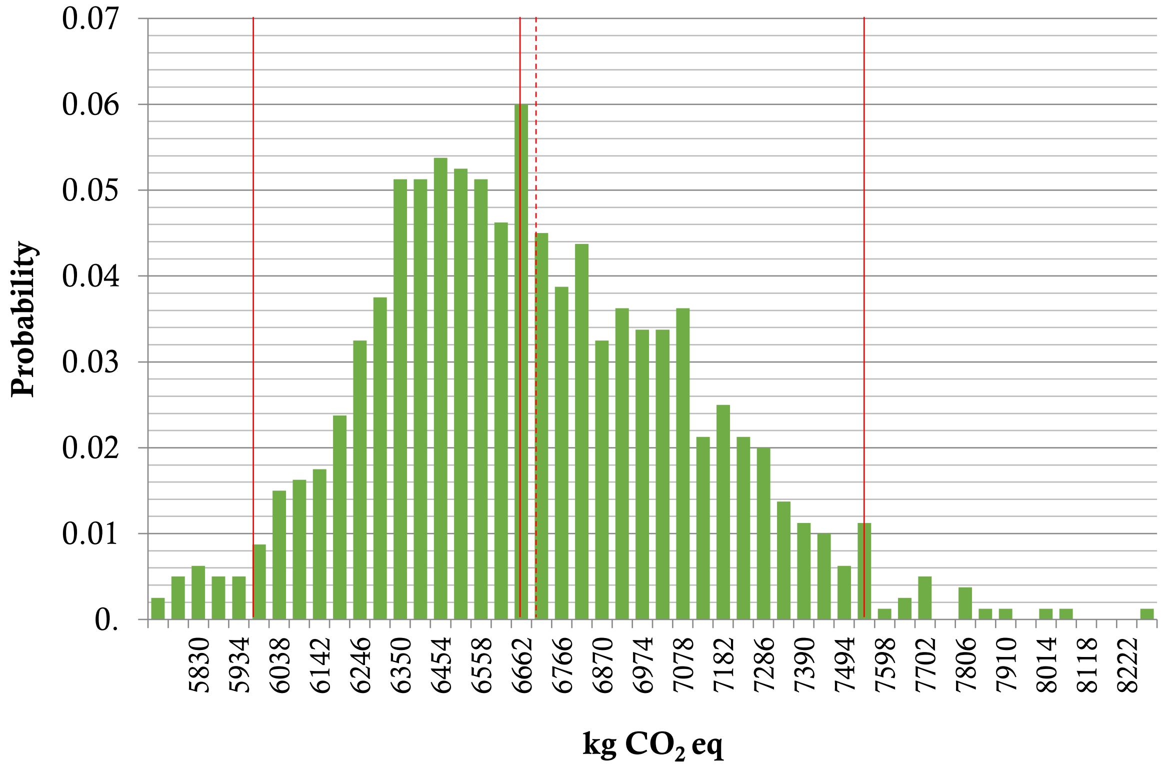

Figure 45: Corrugated board only global warming normal distribution uncertainty analysis graph

The bell-shape of the graph and the similarity of the mean and median demonstrated that the data was evenly distributed. The low coefficient of variation shows that the data was accurate and evenly distributed. The low standard error of the mean also supports the claim that the data was accurate and evenly distributed.

Stratospheric Ozone Depletion

The uncertainty analysis of the stratospheric ozone depletion impact for the corrugated board only packaging configuration exhibited a normally distributed graph (Figure 46 and Appendix B29). The mean of the data was calculated to be 0.00247 kg CFC11 eq and the median was 0.00247 kg CFC11 eq. The standard deviation of this data set was 0.000155 kg CFC11 eq and the coefficient of variation was 6.27%. The data set exhibited a standard error of the mean of 0.00000548 kg CFC11 eq.

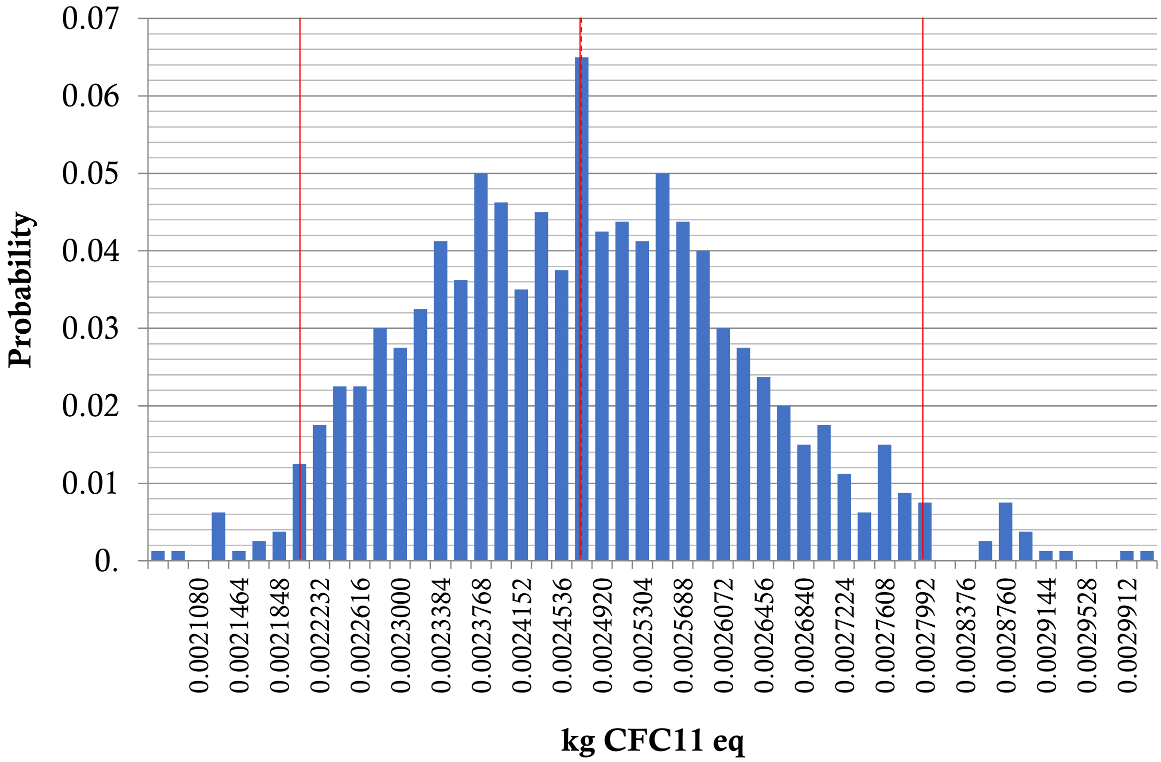

Figure 46: Corrugated board only stratospheric ozone depletion normal distribution uncertainty analysis graph

The bell-shape of the graph and the identical values of the mean and median demonstrate that the data was perfectly symmetrically distributed. The low coefficient of variation shows that the data was accurate and evenly distributed. The very low standard error of the mean also supports the claim that the data was accurate and evenly distributed.

Fine Particulate Matter Formation

The uncertainty analysis of the particulate matter impact for the corrugated board only packaging configuration exhibited a normally distributed graph (Figure 46 and Appendix B30). The mean of the data was calculated to be 10.5 kg PM2.5 eq and the median was 10.4 kg PM2.5 eq. The standard deviation of this data set was 0.541 kg PM2.5 eq and the coefficient of variation was 5.16%. The data set exhibited a standard error of the mean of 0.0191 kg PM2.5 eq.

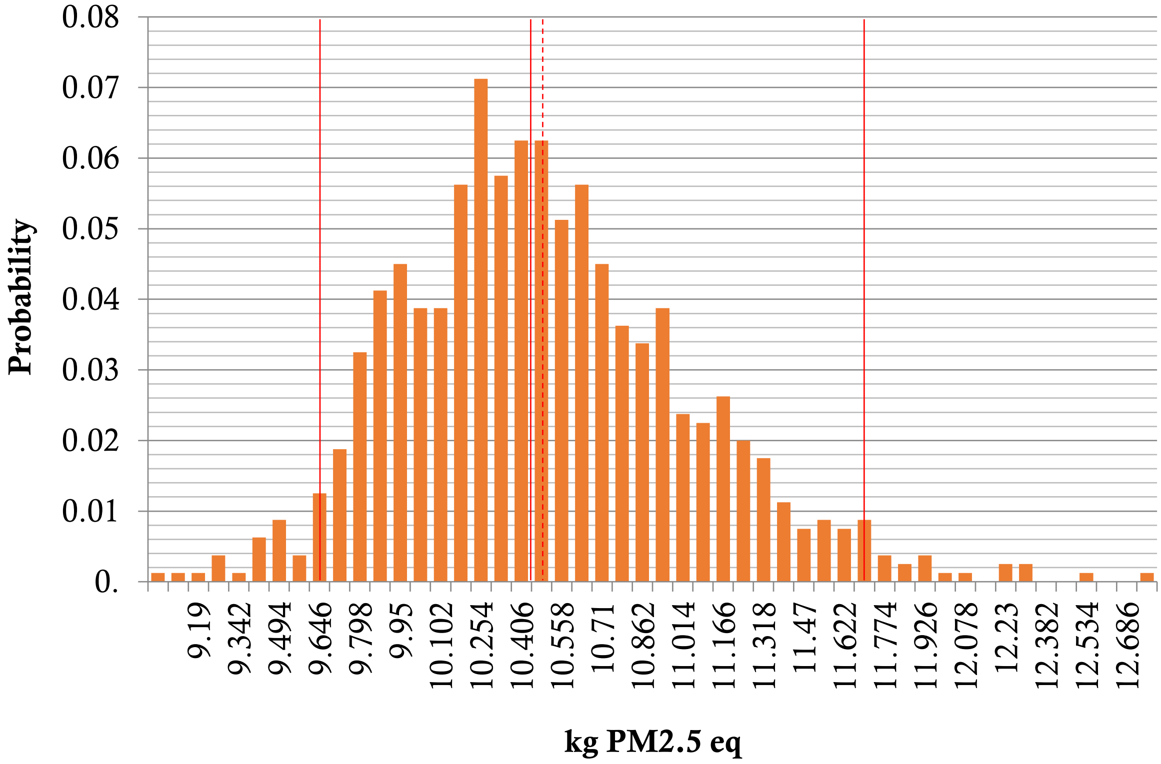

Figure 47: Corrugated board only fine particulate matter formation normal distribution uncertainty analysis graph

The bell-shape of the graph and the similarity of the mean and median demonstrates that the data was evenly distributed. The low coefficient of variation shows that the data was accurate and evenly distributed. The very low standard error of the mean also supports the claim that the data was accurate and evenly distributed.

Freshwater Ecotoxicity

The uncertainty analysis of the freshwater ecotoxicity impact for the corrugated board only packaging configuration exhibited a normally distributed graph screwed to the left (Figure 48 and Appendix B31). The mean of the data was calculated to be 134 kg 1,4-DCB and the median was 130 kg 1,4-DCB. The standard deviation of this data set was 35.4 kg 1,4-DCB and the coefficient of variation was 26.5%. The data set exhibited a standard error of the mean of 1.25 kg 1,4-DCB.

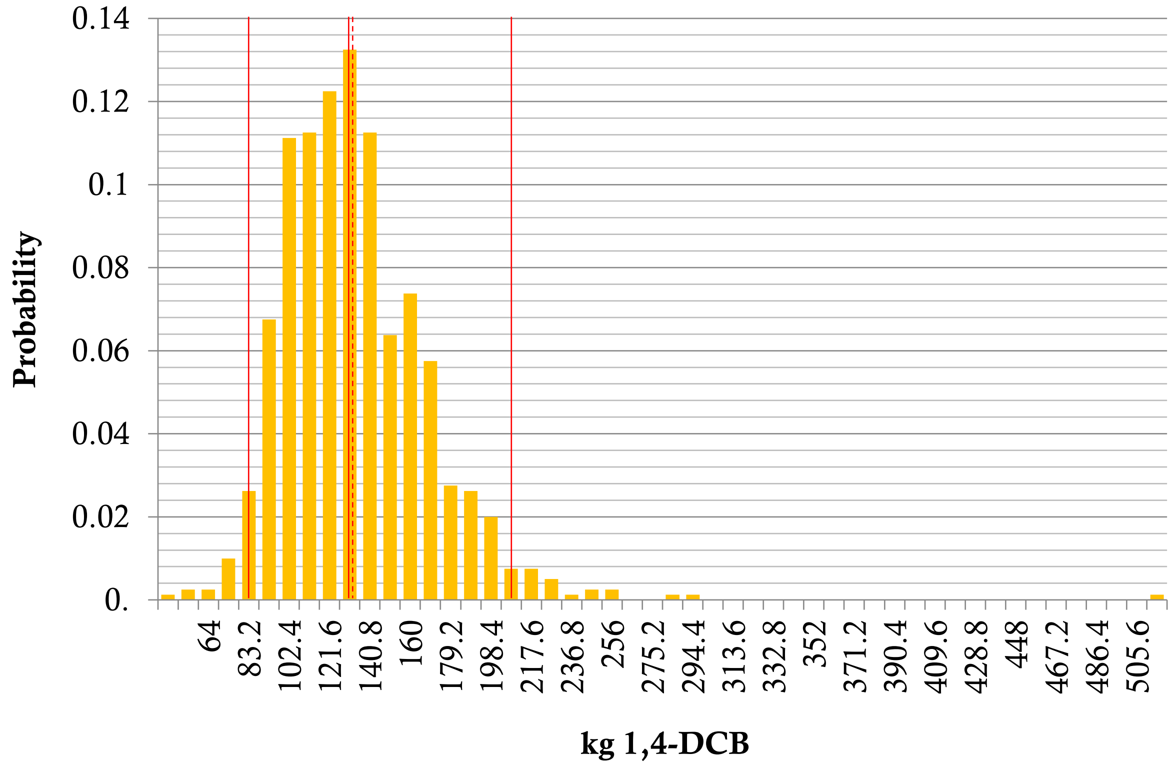

Figure 48: Corrugated board only freshwater ecotoxicity normal distribution uncertainty analysis graph

The bell-shape of the graph, although skewed to the left, and the similarity of the mean and median demonstrated that the data was evenly distributed. The moderately high coefficient of variation shows that the data had a notable degree of dispersion around the mean. The very low standard error of the mean however supports the claim that the data was accurate and evenly distributed. These differences account for the slightly larger error bar on the freshwater ecotoxicity value on the uncertainty bar chart in Figure 44 as compared to the three previous categories data that exhibited smaller errors.

Water Consumption

The uncertainty analysis of the water consumption impact for the corrugated board only packaging configuration exhibited a normally distributed graph skewed to the right (Figure 49 and Appendix B32). The mean of the data was calculated to be -20.2 m^3 and the median was 53.8 m^3. The standard deviation of this data set was 1 280 $m^3$and the coefficient of variation was -6 310%. The data set exhibited a standard error of the mean of 45.1 m^3.

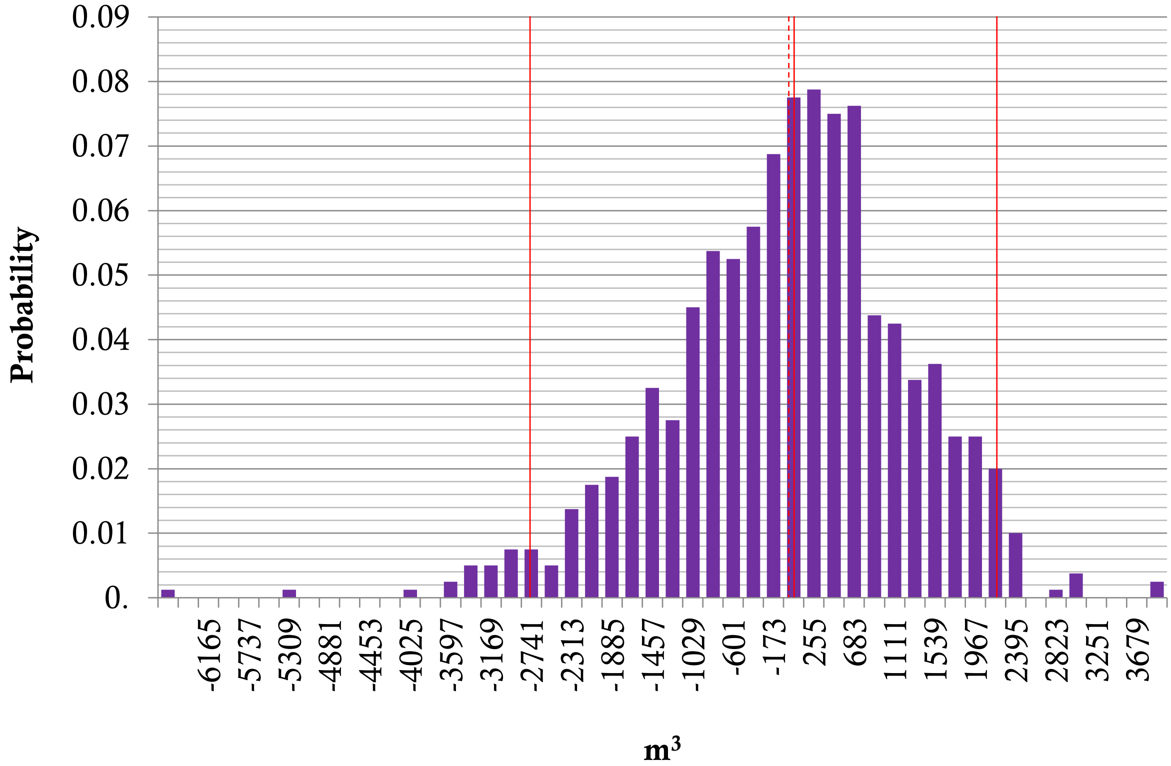

Figure 49: Corrugated board only water consumption normal distribution uncertainty analysis graph

The bell-shape of the graph, although skewed to the right, and the moderately close values of the mean and median demonstrated that the data was evenly distributed. The very high coefficient of variation does not support the claim that the data was accurate and evenly distributed as this value demonstrates that the data had a very high degree of dispersion around the mean. The high standard error of the mean also does not support the claim that the data was accurate and evenly distributed.

This data supports the very large error bar that was displayed in Figure 44 for the water consumption impact data. This very large error was likely due to the uncertainty associated with definitively determining the exact water requirements of the processes associated with all the stages in the life cycle of this packaging configuration. It can thus be said that the uncertainty data regarding the water consumption impact data suggests that the data may possible not be as accurate as other impact categories thus may be a factor to consider as it may significantly influence the modelling data for water consumption.

5.6.3. Uncertainty Analysis: Summary table

Table 12: Uncertainty analysis summary table

	Mean		**Median**		**Standard Deviation**		**Coefficient of Variation (%)**		**Standard error of the mean**	
Packaging Configuration	Heat-Shrink Plastic	Cardboard Only	Heat-Shrink Plastic	Cardboard Only	Heat-Shrink Plastic	Cardboard Only	Heat-Shrink Plastic	Cardboard Only	Heat-Shrink Plastic	Cardboard Only
Global Warming (kg CO_2 eq)	367 000	6 690	364 000	6 650	5 040	409	13.7	6.11	159	14.5
Stratospheric Ozone Depletion (kg CFC11 eq)	0.0246	0.00247	0.022	0.00247	0.0107	0.000155	43.3	6.27	0.000337	0.00000548
Fine Particulate Matter Formation (kg PM2 eq)	95	10.5	94.5	10.4	8.55	0.541	9	5.16	0.27	0.0191
Freshwater Ecotoxicity (kg 1,4-DCB)	1 020	134	860	130	642	35.4	62.9	26.5	20.3	1.25
Water Consumptio n (m^3)	157	-20.2	228	53.8	1 580	1 280	1 010	-6 310	49.8	45.1

6. CONCLUSIONS

This study compared two FMCG product packaging configurations. A comprehensive LCA was executed for both packaging configurations in isolation and then they were comparatively assessed to ascertain the configuration that offered the lowest environmental impact. A sensitivity analysis and uncertainty analysis were both then executed to analyze and assess the validity of the assumptions made at the beginning of the study and to assess the accuracy and reliability of the data with which the LCA was executed. The main conclusions drawn from each of these sections are discussed below.

6.1 Complete and Condensed Life-Cycle Impact Assessments

The LCA was first executed for each of the packaging configurations in isolation to determine the factors that resulted in the greatest contribution to the impact score in each of the impact categories. The LCA was first executed for the full eighteen category results set to ascertain general trends then focus was placed on five main impact categories that are selected based on the geographical location of the study and the research objectives.

The LCA of the heat shrink-wrap plastic packaging configuration concluded that the greatest contributing factor was the impact due to the use of electricity to run the shrink-wrap tunnels, contributing approximately 80% to most of the impact categories. The inclusion of electricity in this packaging configuration was a defining difference between the two packaging configurations. It was also noted that the plastic material which was the defining factor of this packaging configuration contributed a very small amount to all the impact scores. However, the contribution of packaging film (low-density polyethylene) in isolation was an inaccurate representation as the electrical requirement of the shrink wrap tunnel is a critical requirement of this packaging material.

The LCA of the corrugated board only packaging configuration concluded that the greatest contributing factor to the impact score in all eighteen of the impact categories was the corrugated board carton. This factor, the impact associated with the use of corrugated board, was present in both packaging configurations, however in the heat shrink-wrap plastic configuration it only contributed between 10% and 30% to most of the impact categories. Compared to the corrugated board only configurations where the corrugated board impact was between 40% and 95%. Given that the mass and material inputs for this resource are identical for both configurations this comparison emphasizes how large the contribution was that electricity generates towards the impact score for the heat shrink-wrap plastic configuration.

The exclusion of long-term emissions demonstrated that the corrugated board only configuration demonstrated very marginal variations compared to the heat shrink-wrap plastic configuration which demonstrated more significant changes when the timeline of exposure is adjusted.

6.2 LCA Comparison

A comparative LCA was then executed to directly compare the two packaging configurations. This comparison was executed for the full eighteen LCA categories and focus was then placed on the five chosen impact categories. The full eighteen category comparison determined that the corrugated board only configuration offers a lower impact score in every category irrespective of whether long-term emissions are accounted for or not.

Focusing on the five chosen categories, the corrugated board only configuration demonstrated an impact score an average of 83% lower, when long-term emissions were included, and 79.6% lower, when long-term emissions were excluded, than the comparative heat shrink-wrap plastic configuration.

6.3 Sensitivity Analyses

Sensitivity analysis assesses the validity and impact that certain assumptions made during the execution of the LCA have on the results. The outcomes of the sensitivity analyses to ascertain the impact of utilizing the industry standard recycle rates of packaging film and corrugated board concluded that very little variation in the impact score was evident because of variable recycle rates. For the heat-shrink plastic packaging configuration the only focus category that demonstrated variation in the impact result with varying recycle rate was the freshwater ecotoxicity category. With a difference of only 6.1% between the impact score of 0% recycle rate vs that for 100% recycle rate. The other four focus categories demonstrated the same impact score irrespective of whether the plastic is recycled or not. For the corrugated board only packaging configuration the global warming category was the only focus category that demonstrated noticeable variation between recycling rates. The impact score decreased approximately 4% for every 20% increase in recycle rate of corrugated board.

The industry standard recycling rate of 42.8% for packaging film offered an ideal average impact score across the range of recycle rates that were analyzed. The packaging film recycle rate sensitivity analysis concluded that the corrugated board only configuration achieved a lower LCA impact score compared to the heat shrink-wrap plastic configuration irrespective of the rate of recycling of packaging film.

The industry standard recycling rate of 61.4% for corrugated board offered an ideal average impact score across the range of recycle rates that were analyzed. The corrugated board recycle rate sensitivity analysis concluded that the corrugated board only configuration achieved a lower LCA impact score compared to the heat shrink-wrap plastic configuration irrespective of the rate of recycle of corrugated board.

Both sensitivity analyses concluded that the recycle rates utilized were representative of the population and did not influence the conclusions drawn from the primary comparative analysis.

6.4 Uncertainty Analyses

Unlike sensitivity analysis which assesses the validity and impact of assumptions, uncertainty analysis assesses the data used to execute the LCA and the associated possible errors or unreliability in the data. The results of uncertainty analyses determined that the data utilized to calculate the impact scores in four of the five chosen categories for both packaging configurations offered very low uncertainty. The data was evenly distributed, exhibiting very low levels of dispersion about the mean and a close representation of the true value of the population outside of the sample size. The only category that demonstrated a high degree of uncertainty was the water consumption category owing to the difficulty in definitively determining the exact water requirements of the systems under analysis. The uncertainty analysis concluded that the results and conclusions yielded from the primary comparative analysis remain valid due to low degrees of uncertainty in the impact data.

7. RECOMMENDATIONS

7.1. Current Study

This study may be improved by more in-depth analysis into a greater number of impact categories and secondly broaden the geographical relevance of the study to include coastal areas with marine considerations. Similarly, this study may benefit from a greater analysis into the significant uncertainty ascertained for the water consumption of both packaging configurations. In a similar manner, owing to the significant impact that electricity has on the environmental impact score of the heat shrink-wrap plastic configuration an uncertainty analysis of the electricity data may prove beneficial in expanding the current study to consider reliability of the electricity data.

This study may benefit from analyzing a greater number of packaging alternatives to broaden the options available to the trade based on the resources available and the trade requirements. Similarly, the conclusions drawn from this study may be more beneficial if further engagement with the retailers was initiated to broaden the scope of packaging configurations to mitigate environmental impacts as much as possible. This may extend to eliminating double packaging products which creates unnecessary waste or changing selling unit quantity to better fulfil shelves in store to reduce the frequency of stock drops thus reducing the environmental impact realized due to transport processes.

7.2. Future Studies

Although the corrugated board only configuration was concluded to be the packaging configuration that offers lower LCA impact scores it would be beneficial to investigate how this configuration could be further improved. Future studies may consider investigating alternatives to utilizing packaging tape such the use of staples, glue, strapping, or interlocking shippers that require no additional 'closure' material or mechanism.

When examining the heat shrink-wrap plastic packaging configuration owing to the significant impact contribution that electricity makes to the LCA score it would be beneficial to investigate alternatives to using shrink-wrap tunnel technology that are more energy efficient. An investigation into alternative materials to group products in a similar manner such as paper, may also be beneficial as it may mitigate the requirement for inefficient shrink-wrap tunnels entirely.

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APPENDICES

Appendix A: SimaPro simulation setup

Appendix A1: Heat shrink-wrap plastic configuration industry average standard

Products				
Outputs to Technosphere: Products and co-products	**Amount**	**Unit**	**Quantity**	**Allocation**
Shrink Wrapped (61.4% Cardboard Recycle 42.8% Plastic Recycle)	*1*	*Year*	*Time*	*100%*
Inputs				
Inputs from Technosphere: materials/fuels	**Amount**	**Unit**		
Folding boxboard carton (RoW) | market for folding boxboard carton | Cut-off, U	*1845.35*	*kg*		
Polyvinylchloride, bulk polymerized (GLO) | market for | Cut-off, U	*26.17*	*kg*		
Packaging film, low density polyethylene (GLO) | market for | Cut-off, U	*191.15*	*kg*		
Synthetic Rubber (GLO) | market for | Cut-off, U	*19.12*	*kg*		
Inputs from Technosphere: electricity/heat	**Amount**	**Unit**		
Electricity, medium voltage (ZA) | market for | Cut-off, U	*26.96*	*MWh*		
Outputs				
Outputs to Technosphere: Waste treatment	**Amount**	**Unit**	**Distribution**	**SD**
Waste polyvinylchloride (ZA) | market for waste polyvinylchloride | Cut-off, U	*26.17*	*kg*	*Normal*	*3*
Waste polyethylene (ZA) | market for waste polyethylene | Cut-off, U	*109.34*	*kg*	*Normal*	*3*
Waste paperboard (ZA) | market for waste paperboard | Cut-off, U	*712.30*	*kg*	*Normal*	*3*

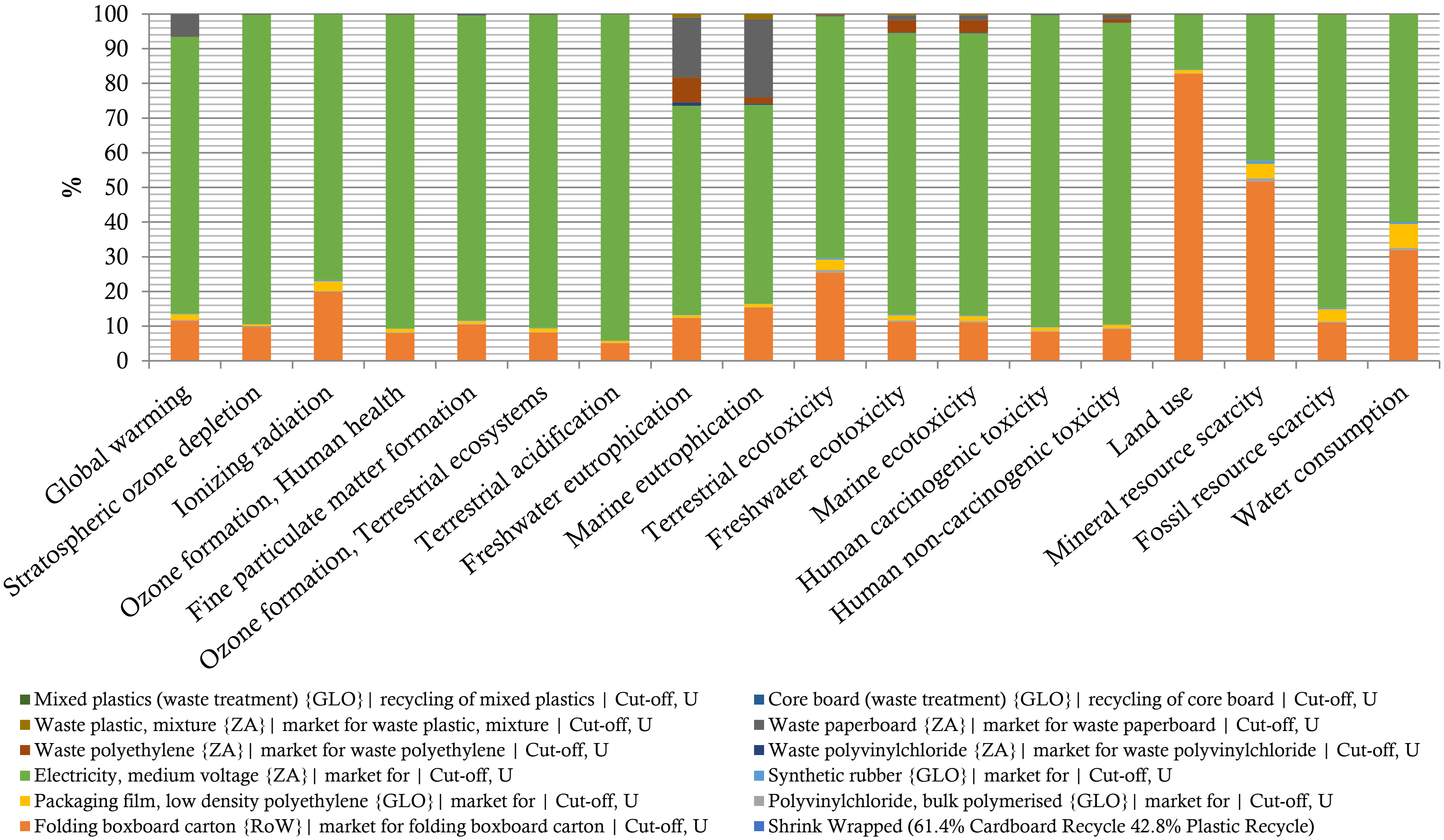
Waste plastic, mixture (ZA) | market for waste plastic, mixture | Cut-off, U	*19.12*	*kg*	*Normal*	*3*
Core board (waste treatment) {GLO} | recycling of core board | Cut-off, U	*1133.05*	*kg*	*Normal*	*3*
Mixed plastics (waste treatment) {GLO} | recycling of mixed plastics | Cut-off, U	*81.81*	*kg*	*Normal*	*3*

Appendix A2: Corrugated board only configuration industry average standard

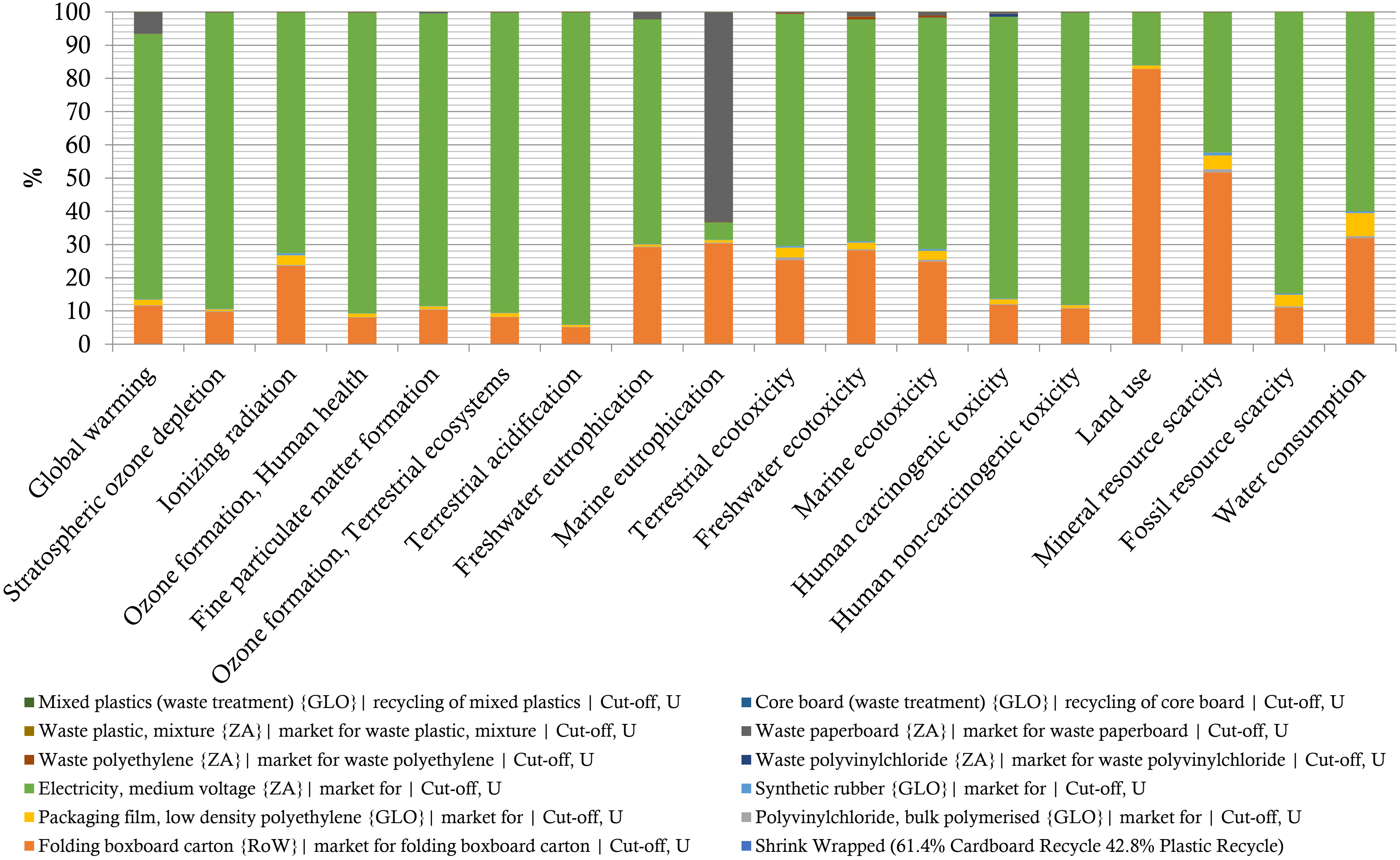
Products				
Outputs to Technosphere: Products and co-products	**Amount**	**Unit**	**Quantity**	**Allocation**
Cardboard Shipper Only (61.4% Cardboard Recycle)	*1*	*Year*	*Time*	*100%*
Inputs				
Inputs from Technosphere: materials/fuels	**Amount**	**Unit**		
Folding boxboard carton (RoW) | market for folding boxboard carton | Cut-off, U	*1845.35*	*kg*		
Polyvinylchloride, bulk polymerized (GLO) | market for | Cut-off, U	*26.17*	*kg*		
Outputs				
Outputs to Technosphere: Waste treatment	**Amount**	**Unit**	**Distribution**	**SD**
Waste polyvinylchloride (ZA) | market for waste polyvinylchloride | Cut-off, U	*26.17*	*kg*	*Normal*	*3*
Waste paperboard (ZA) | market for waste paperboard | Cut-off, U	*712.30*	*kg*	*Normal*	*3*
Core board (waste treatment) {GLO} | recycling of core board | Cut-off, U	*1133.05*	*kg*	*Normal*	*3*

Appendix B: SimaPro results graphs and tables.

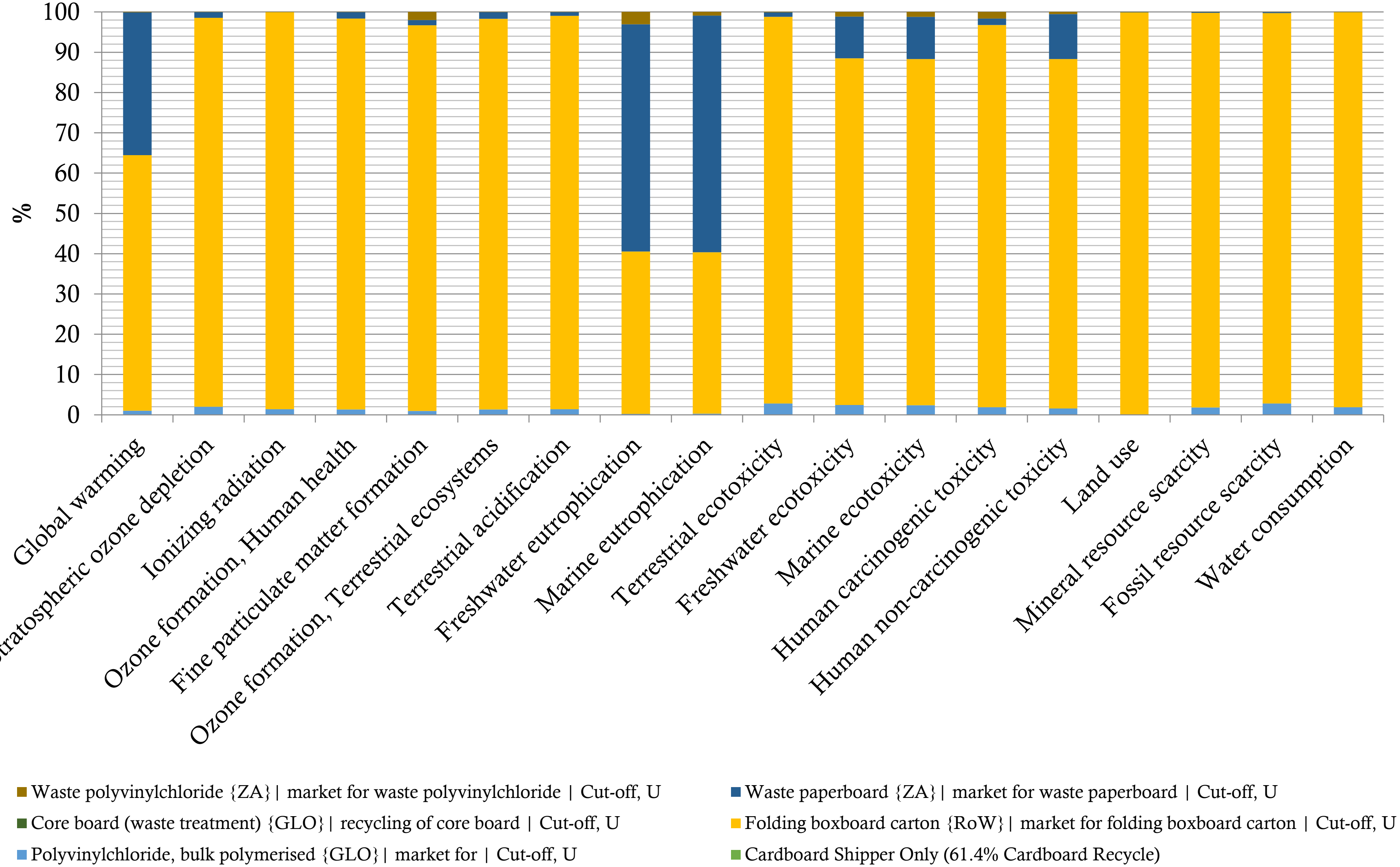
Appendix B1: Shrink-Wrapped Configuration Complete 18 Category Results



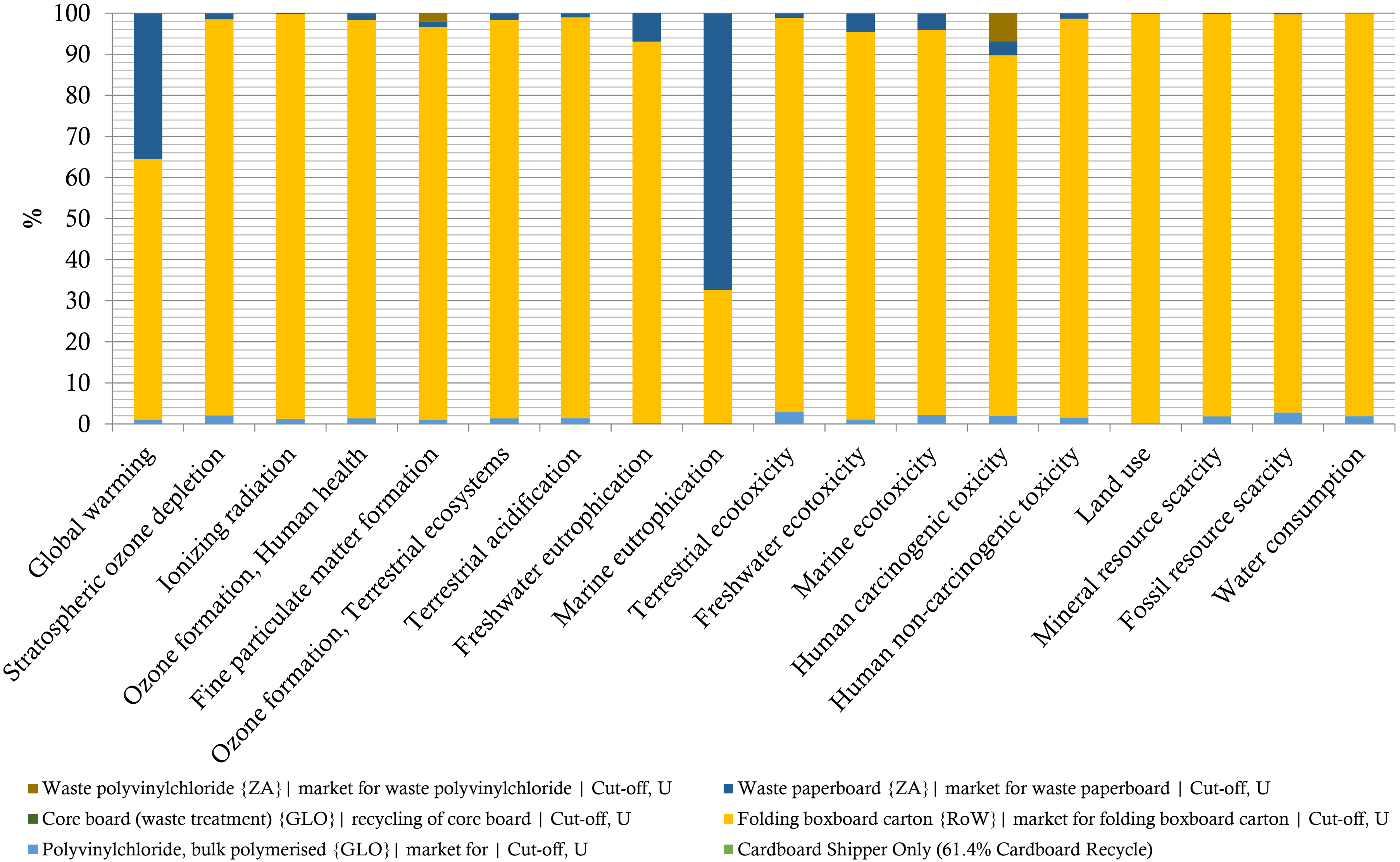
Appendix B2: Shrink-Wrapped Configuration Complete 18 Category Results Excluding Long-Term Emissions



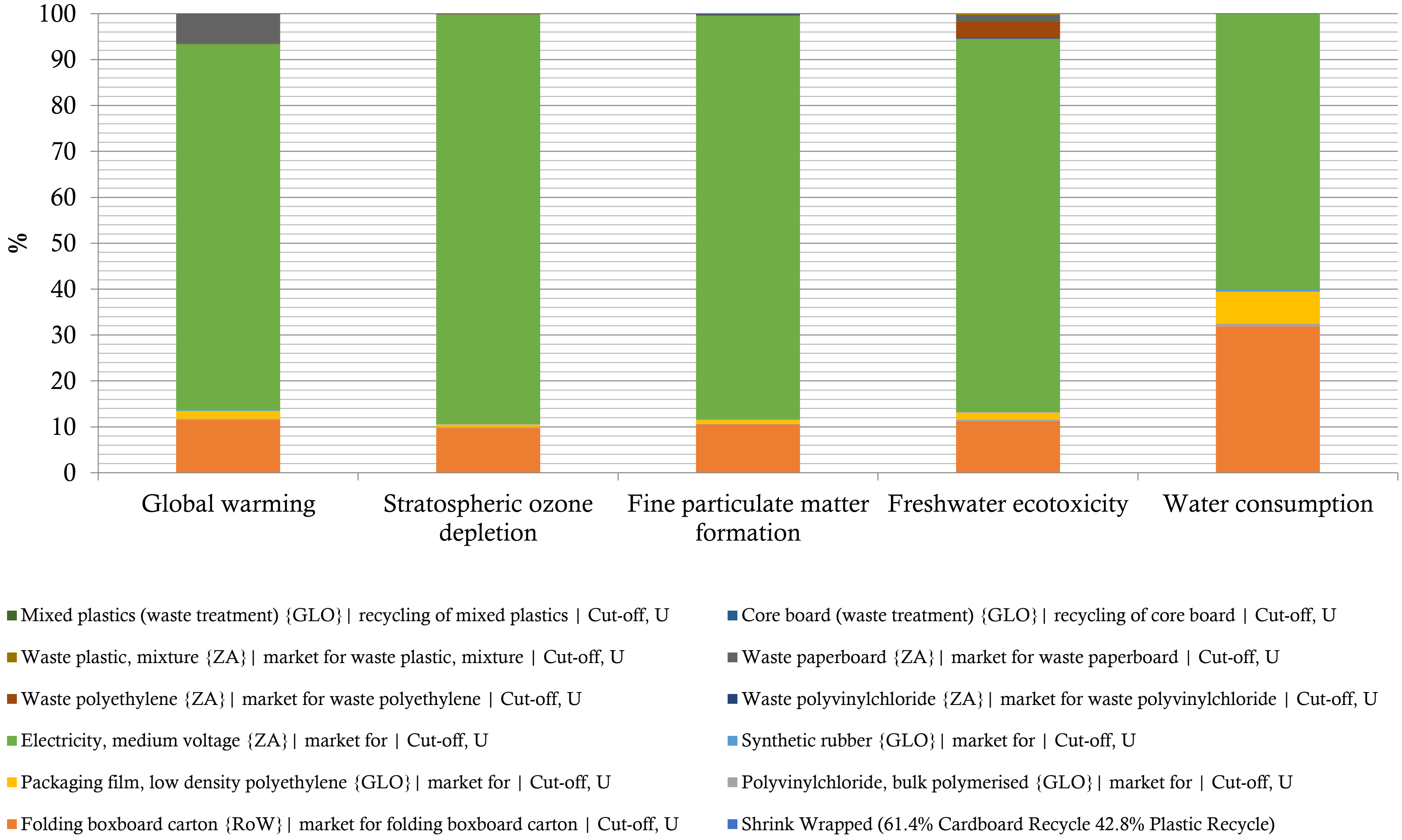
Appendix B3: Corrugated Board Configuration Complete 18 Category Results



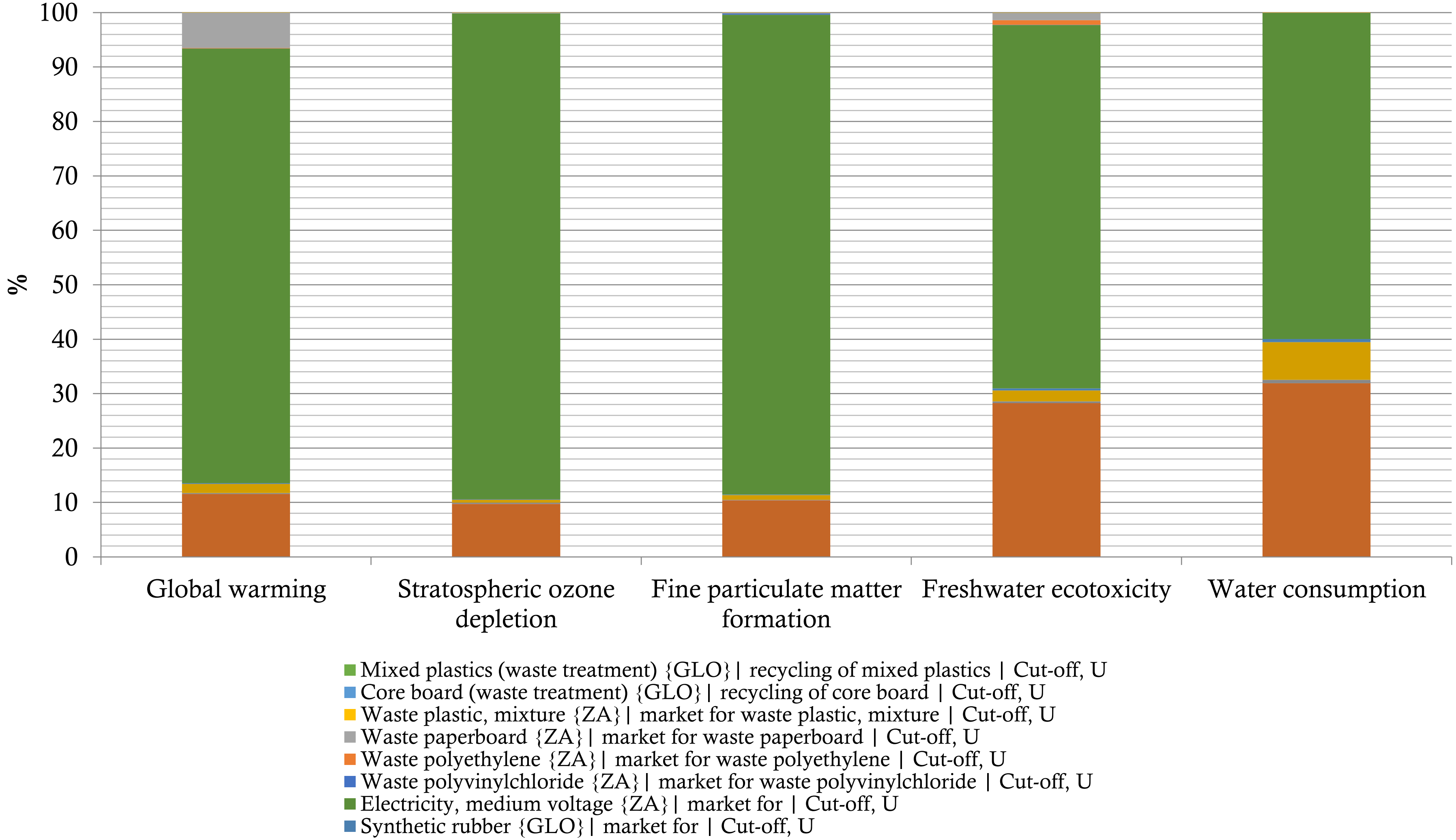
Appendix B4: Corrugated Board Configuration Complete 18 Category Results Excluding Long-Term Emissions



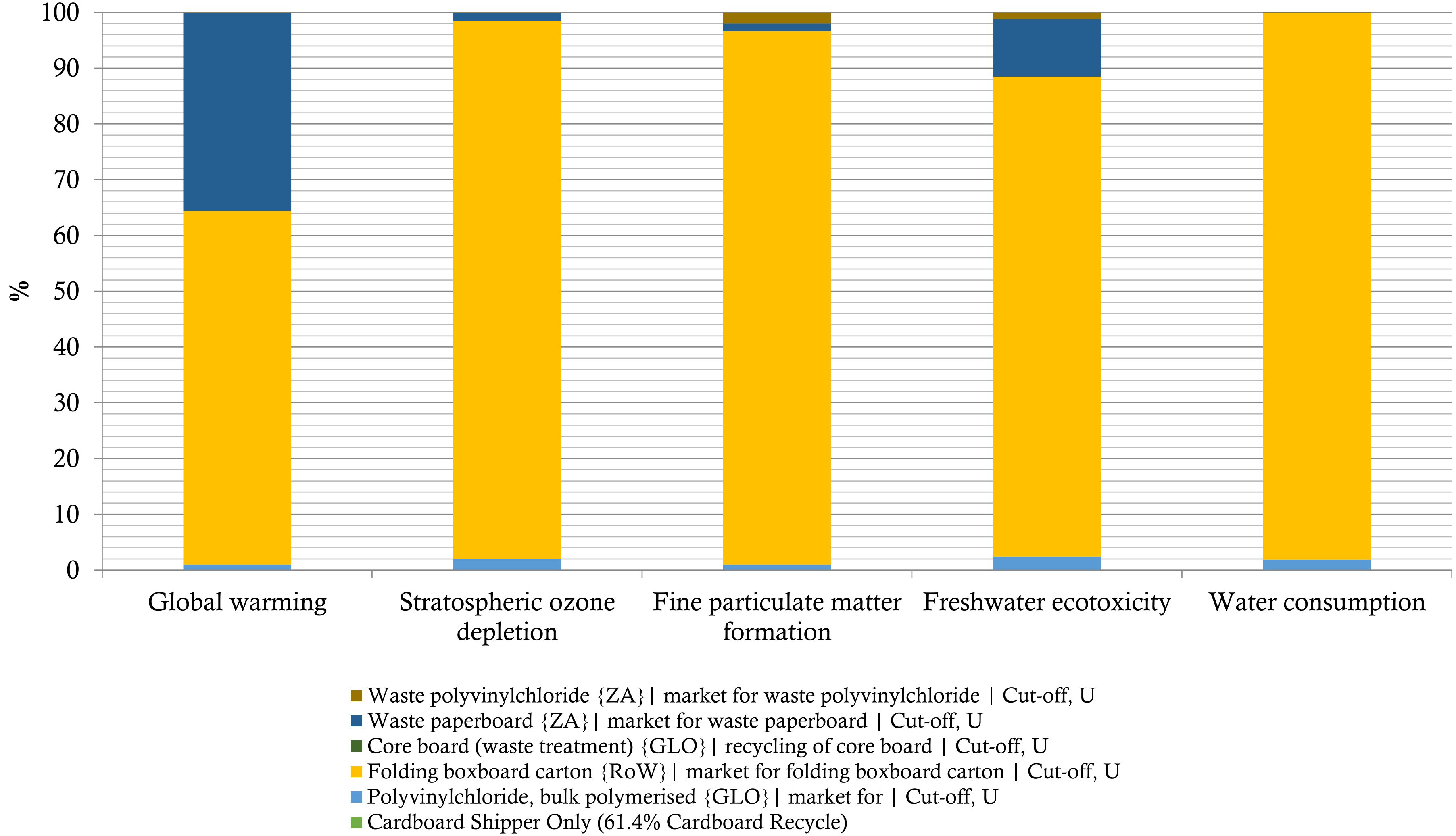
Appendix B5: Condensed Shrink-Wrapped Configuration Results



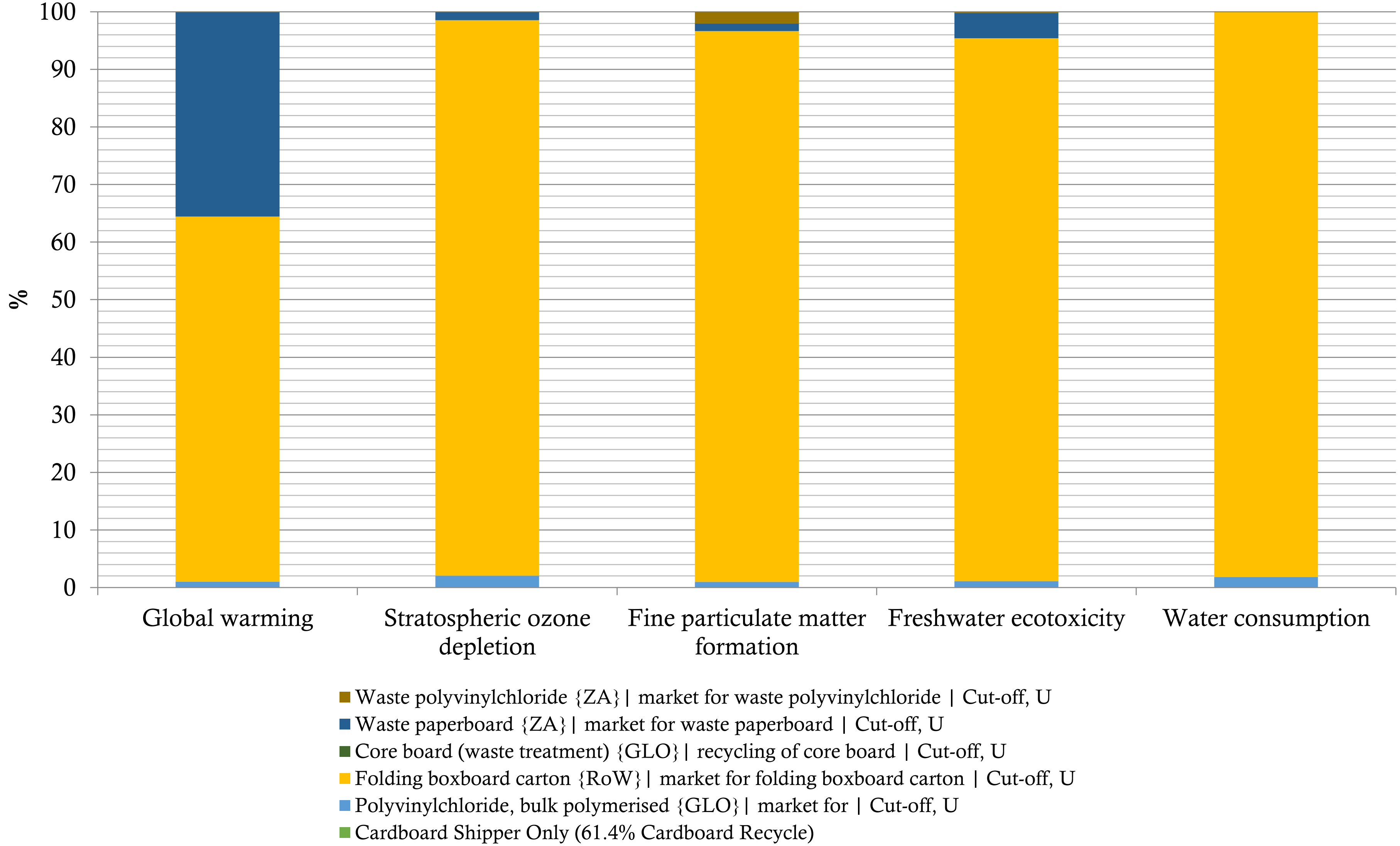
Appendix B6: Condensed Shrink-Wrapped Configuration Results Excluding Long-Term Emissions



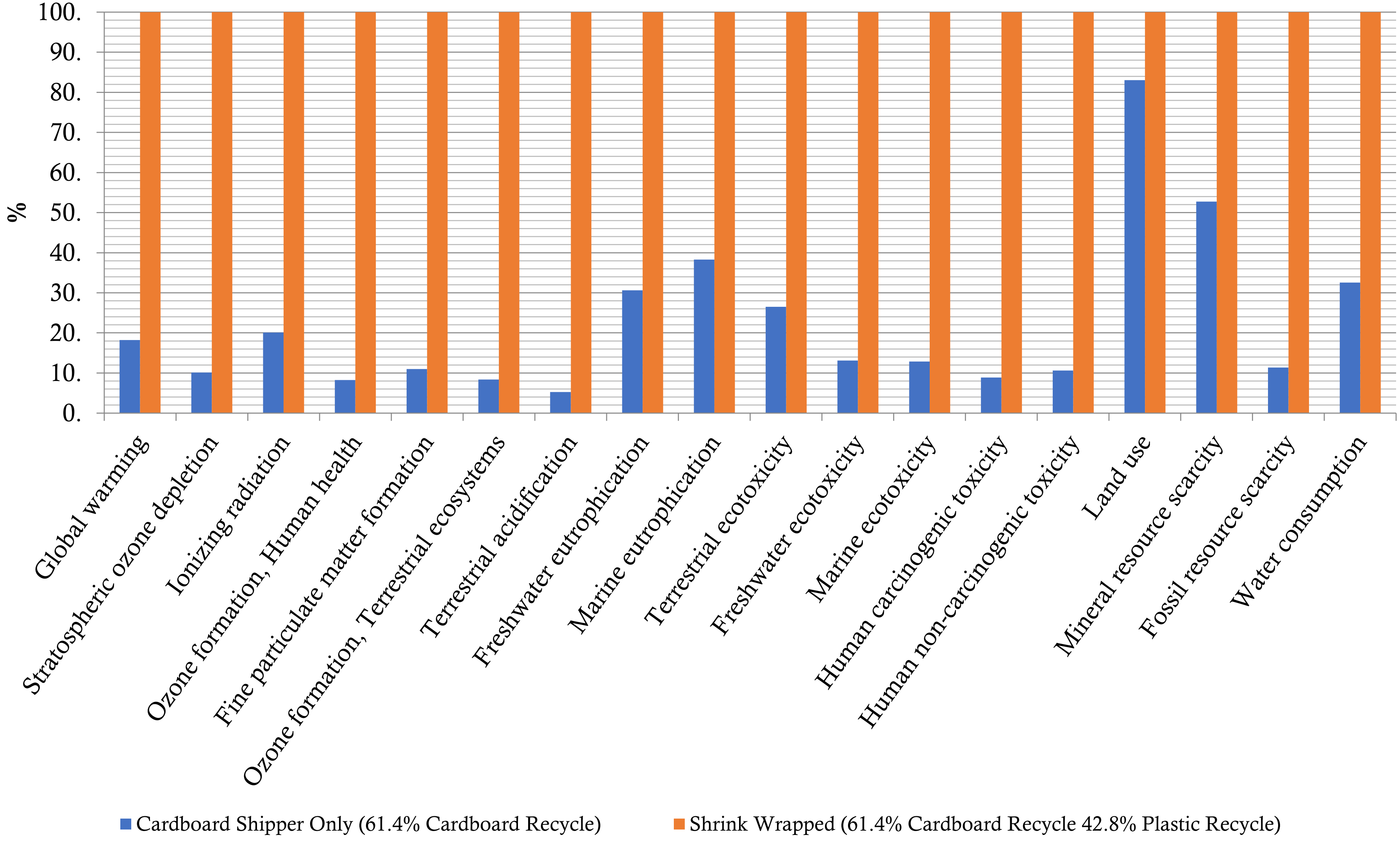
Appendix B7: Condensed Results Corrugated Board Configuration Results



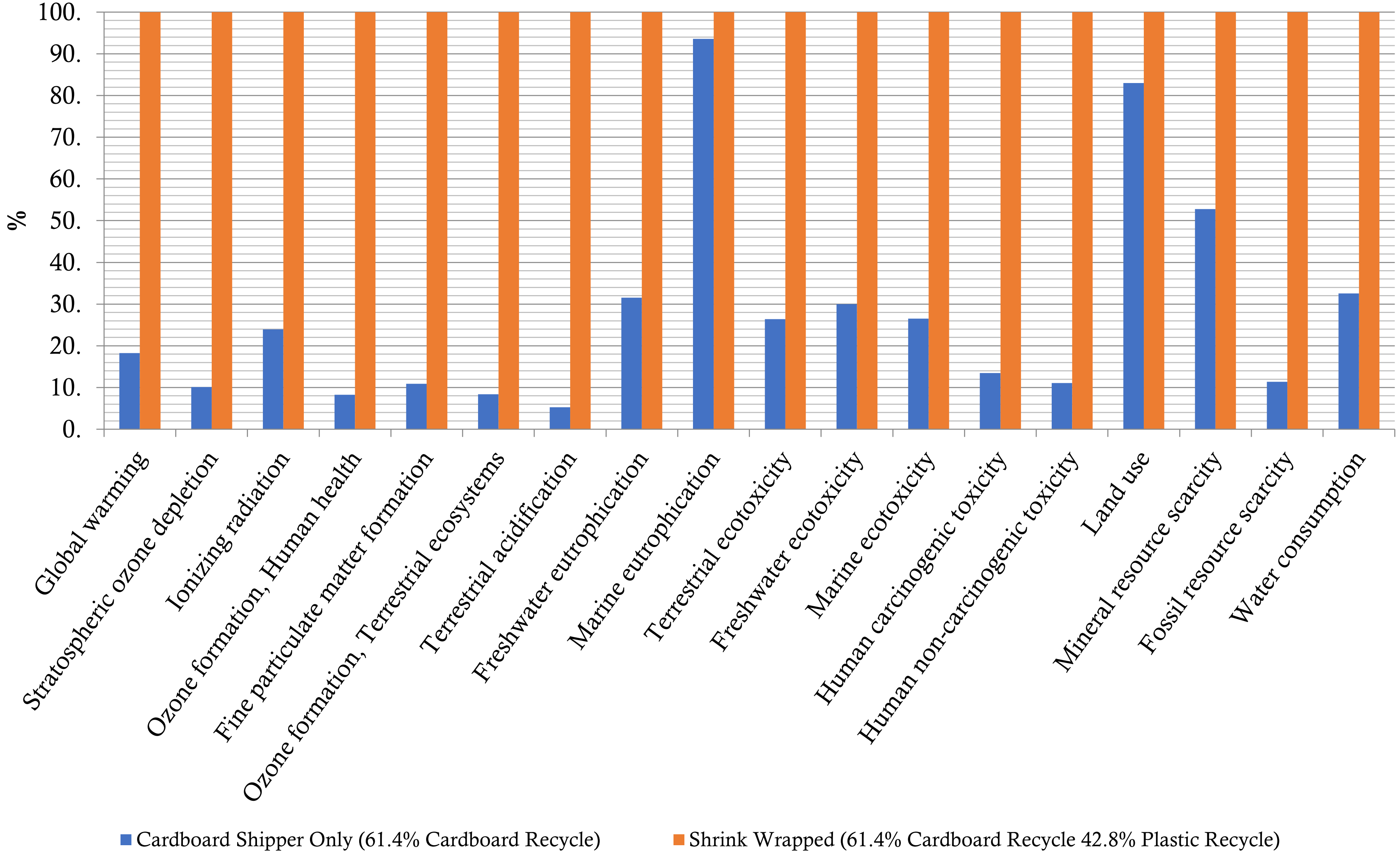
Appendix B8: Condensed Results Corrugated Board Configuration Results Excluding Long-Term Emissions



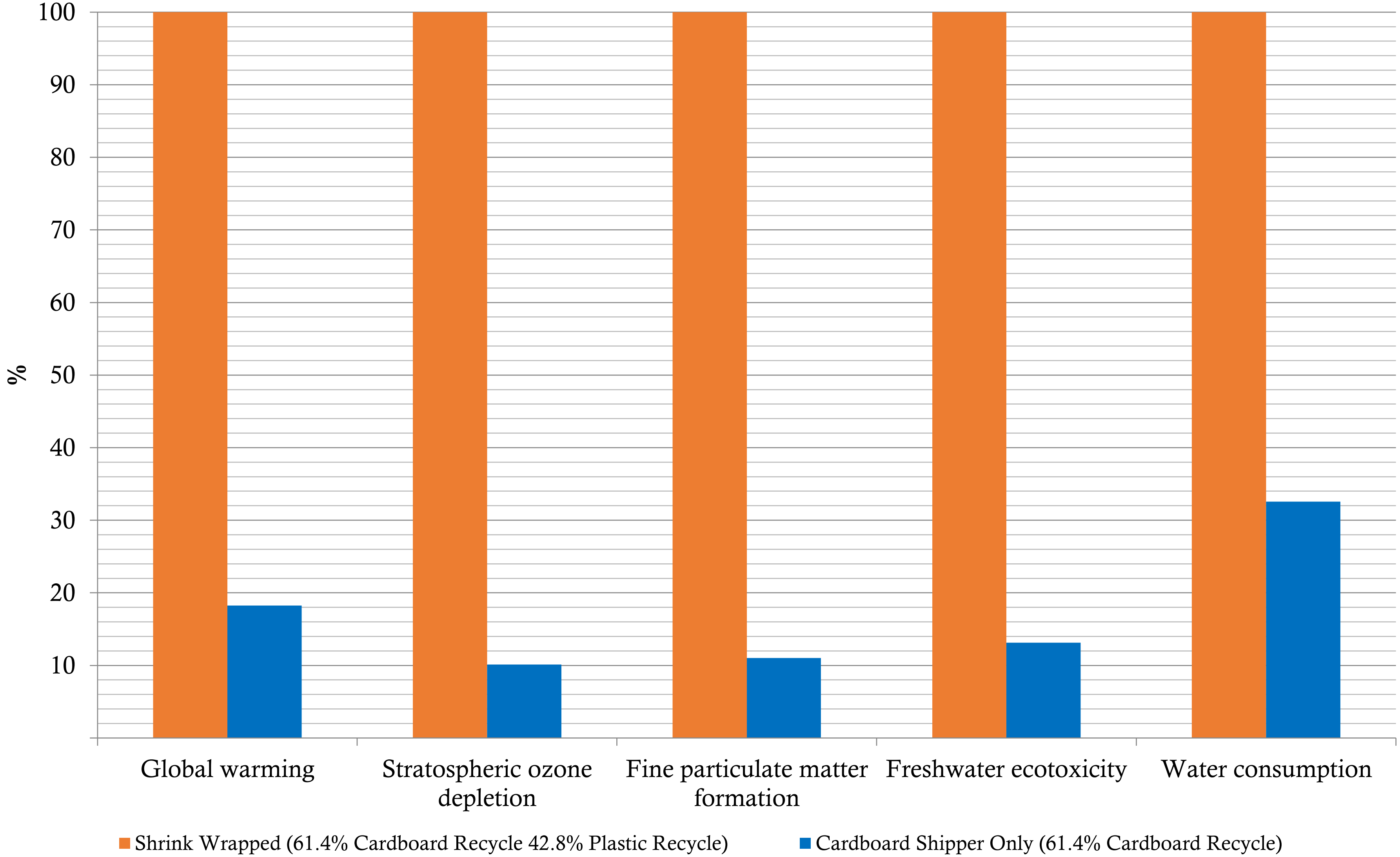
Appendix B9: Complete 18 Category LCA Comparison Results



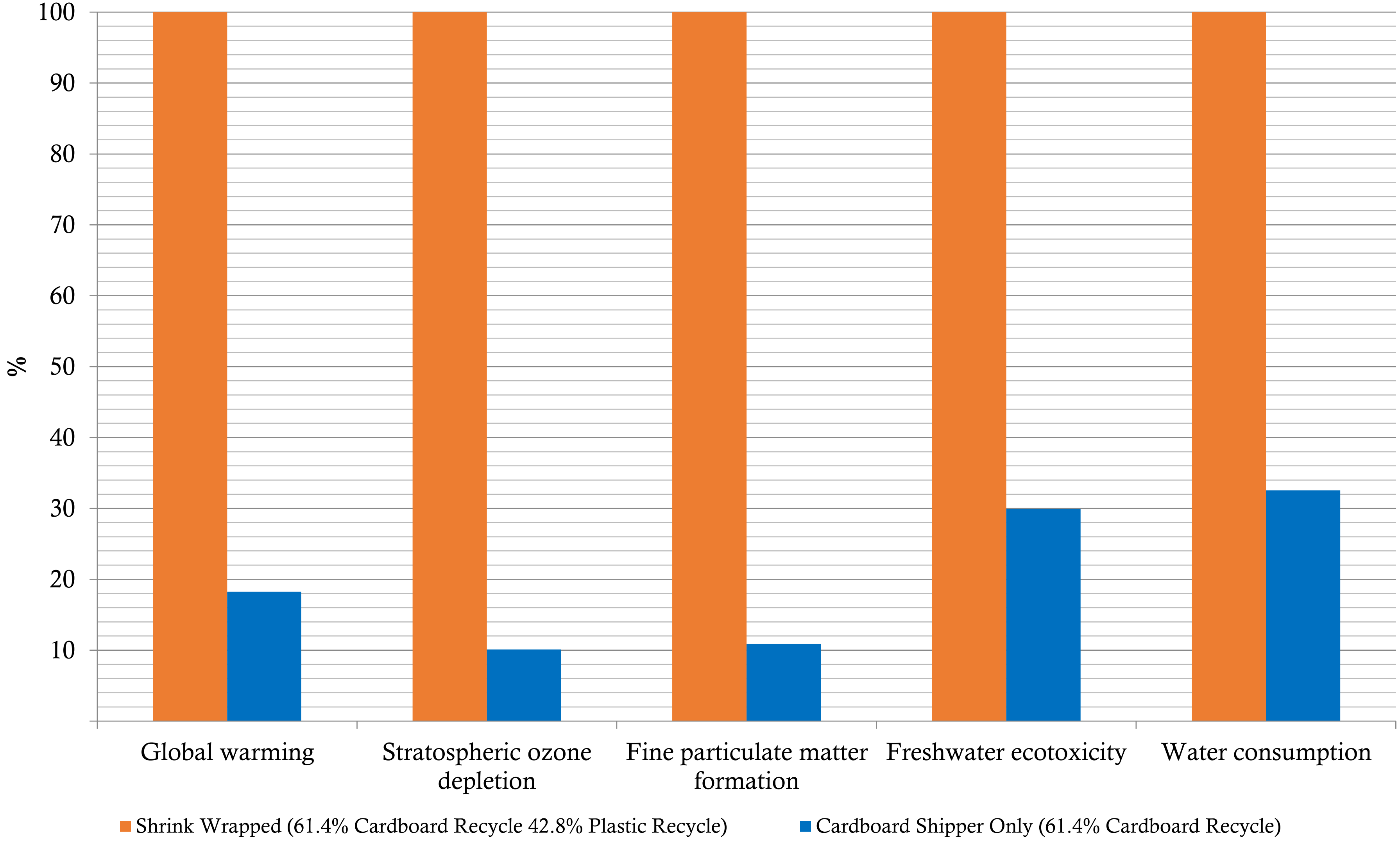
Appendix B10: Complete 18 Category LCA Comparison Results excluding Long-Term Emissions



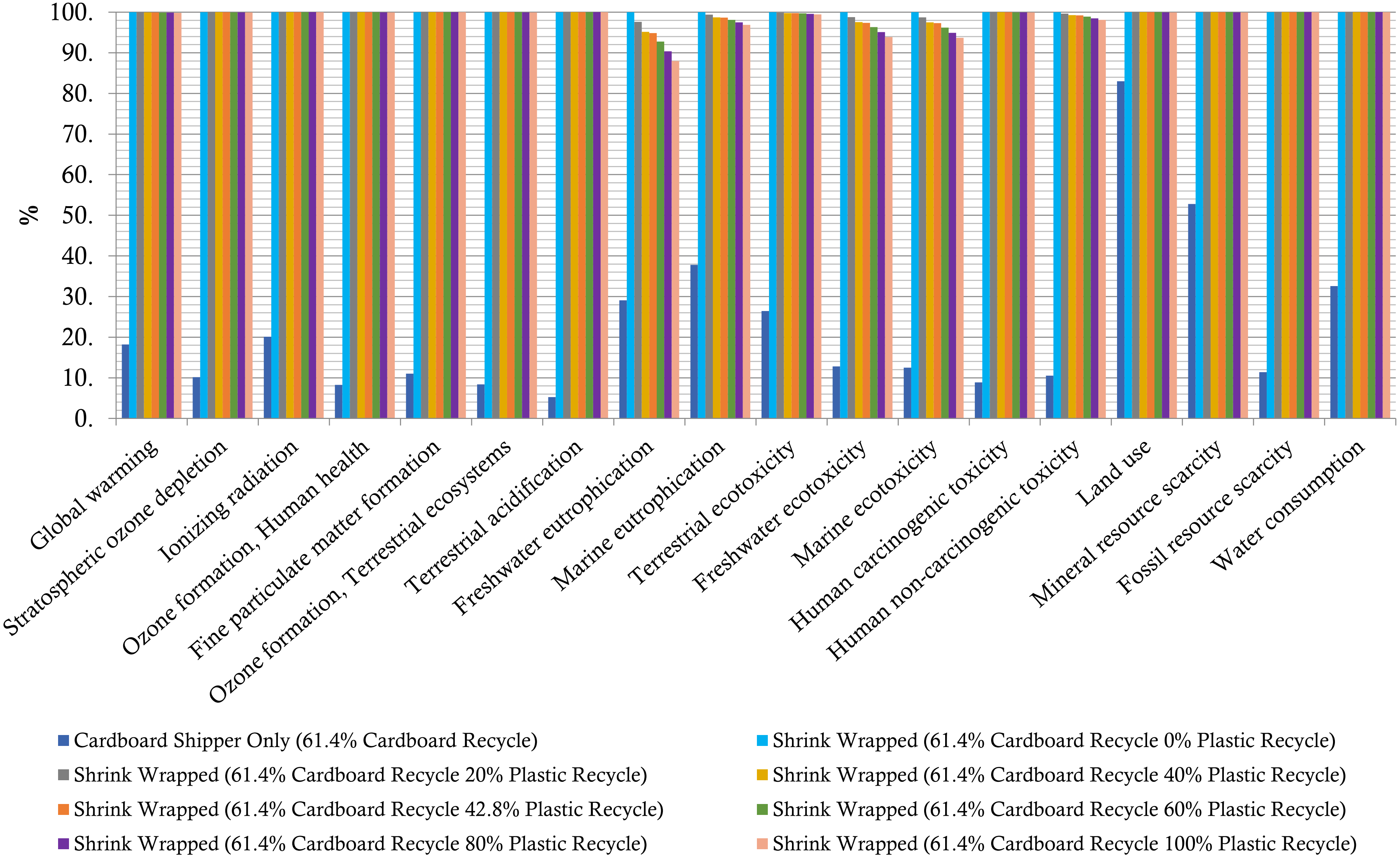
Appendix B11: Condensed LCA Comparison Results



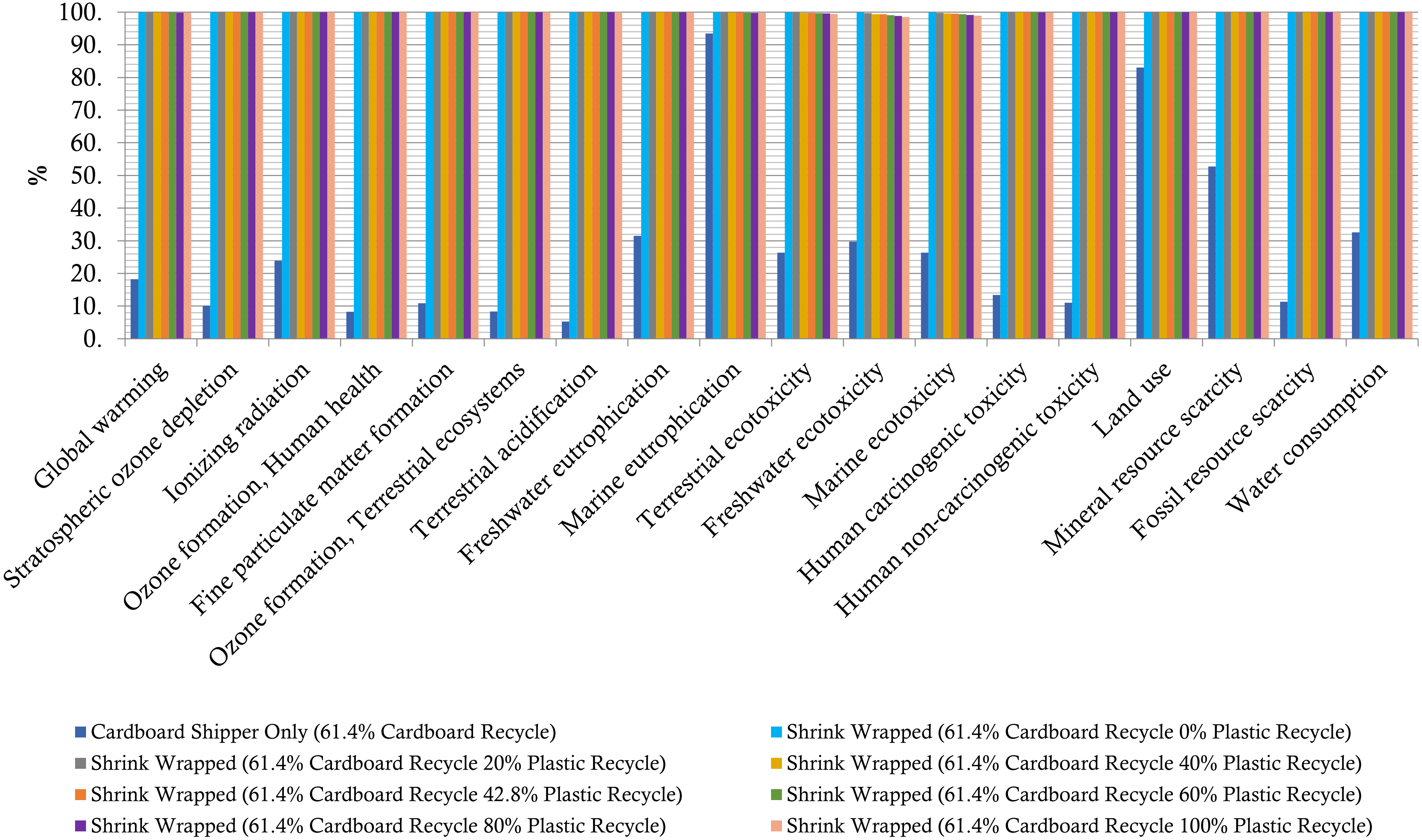
Appendix B12: Condensed LCA Comparison Results excluding Long-Term Emissions



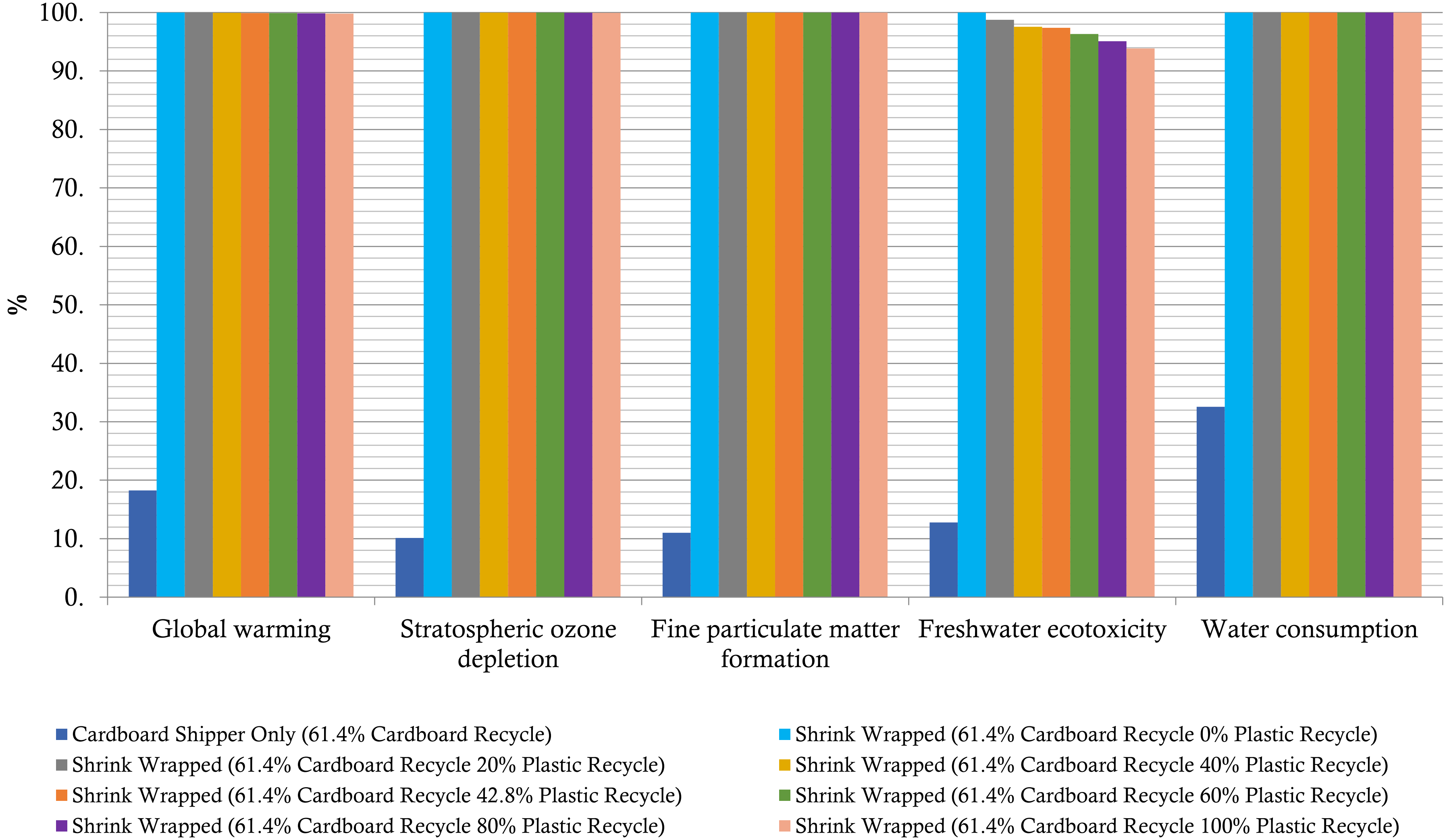
Appendix B13: Sensitivity Analysis Complete Results of Shrink-Wrap Plastic Recycle Rate



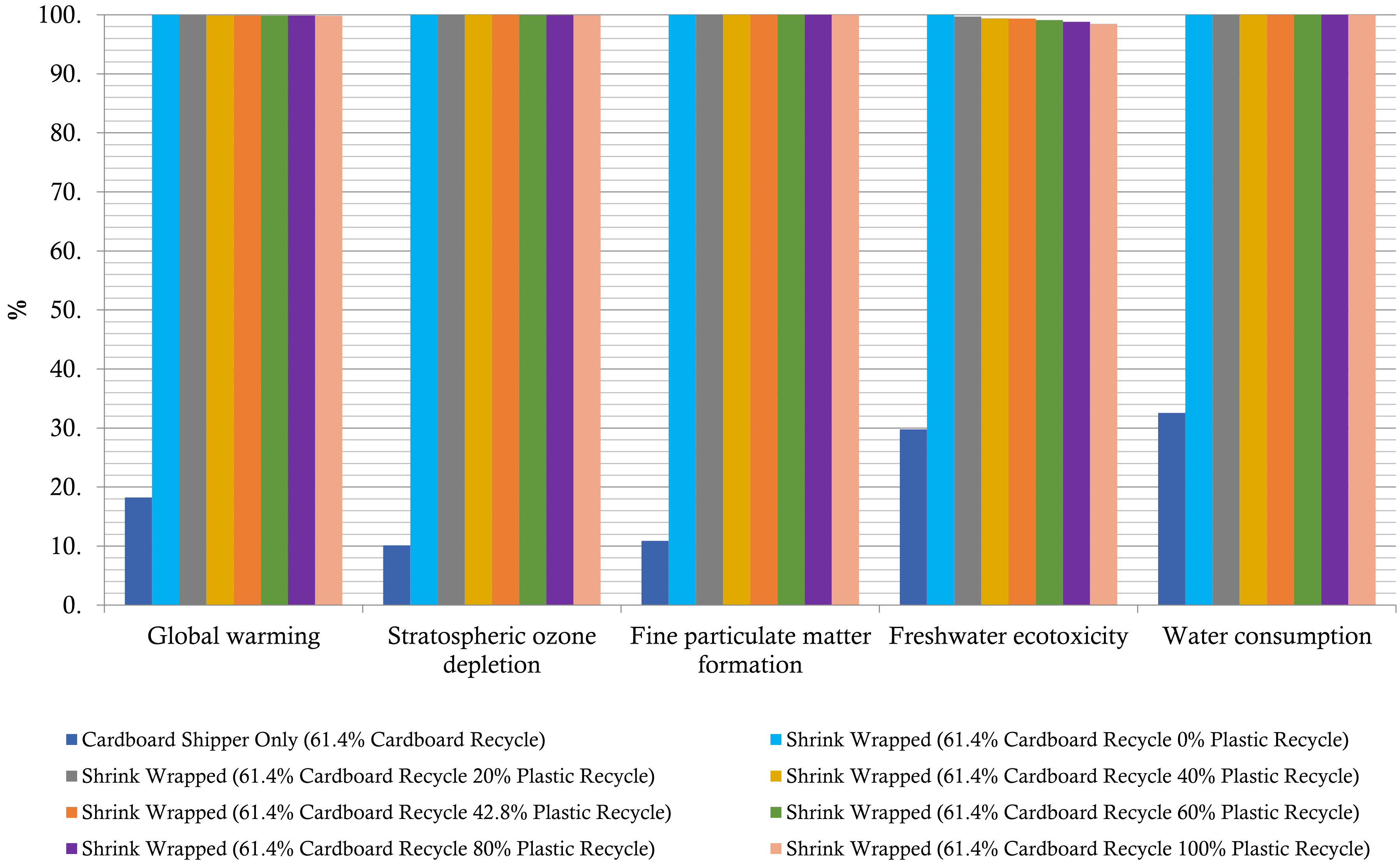
Appendix B14: Sensitivity Analysis Complete Results of Shrink-Wrap Plastic Recycle Rate excluding Long-Term Emissions



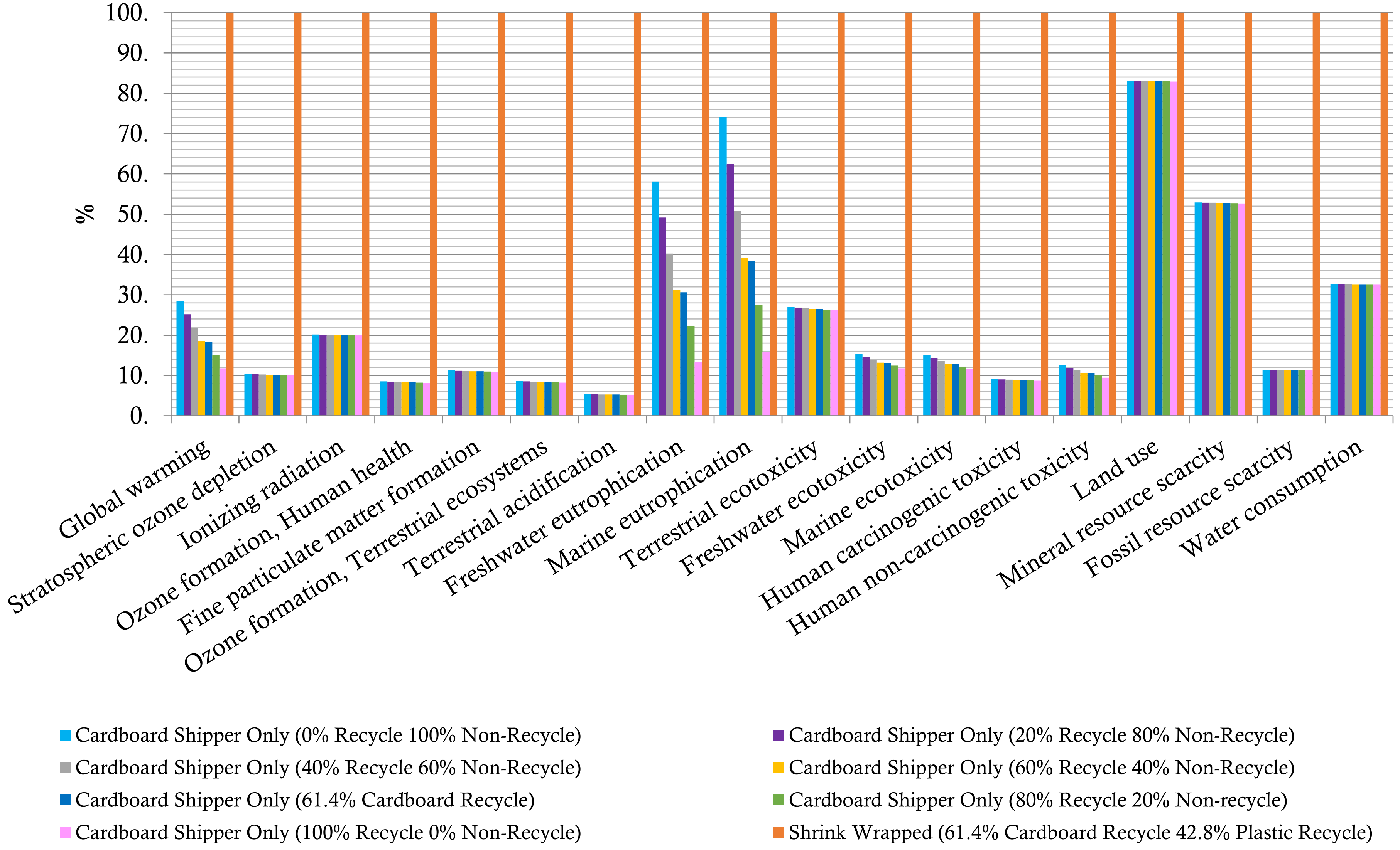
Appendix B15: Sensitivity Analysis Condensed Results of Shrink-Wrap Plastic Recycle Rate



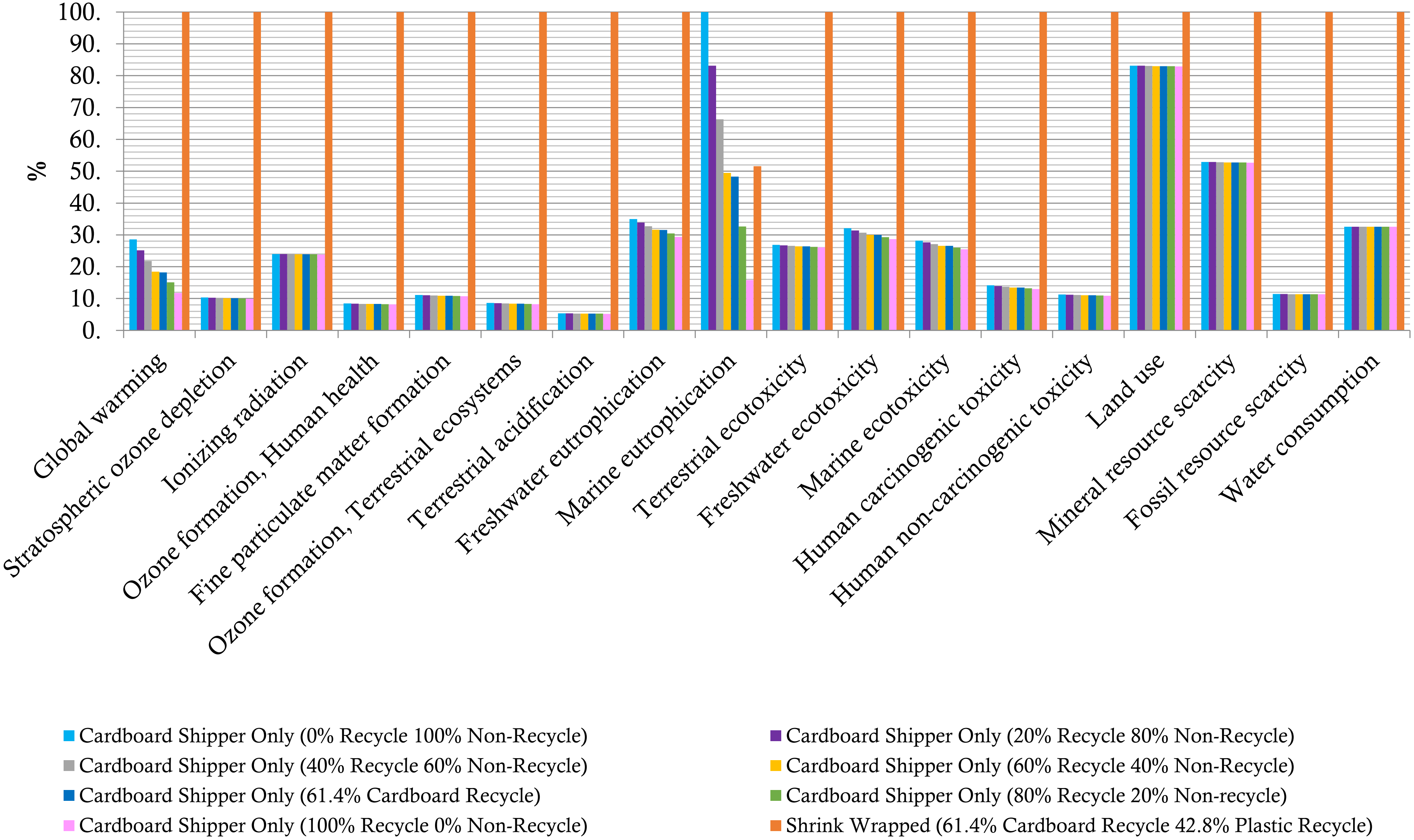
Appendix B16: Sensitivity Analysis Condensed Results of Shrink-Wrap Plastic Recycle Rate excluding Long-Term Emissions



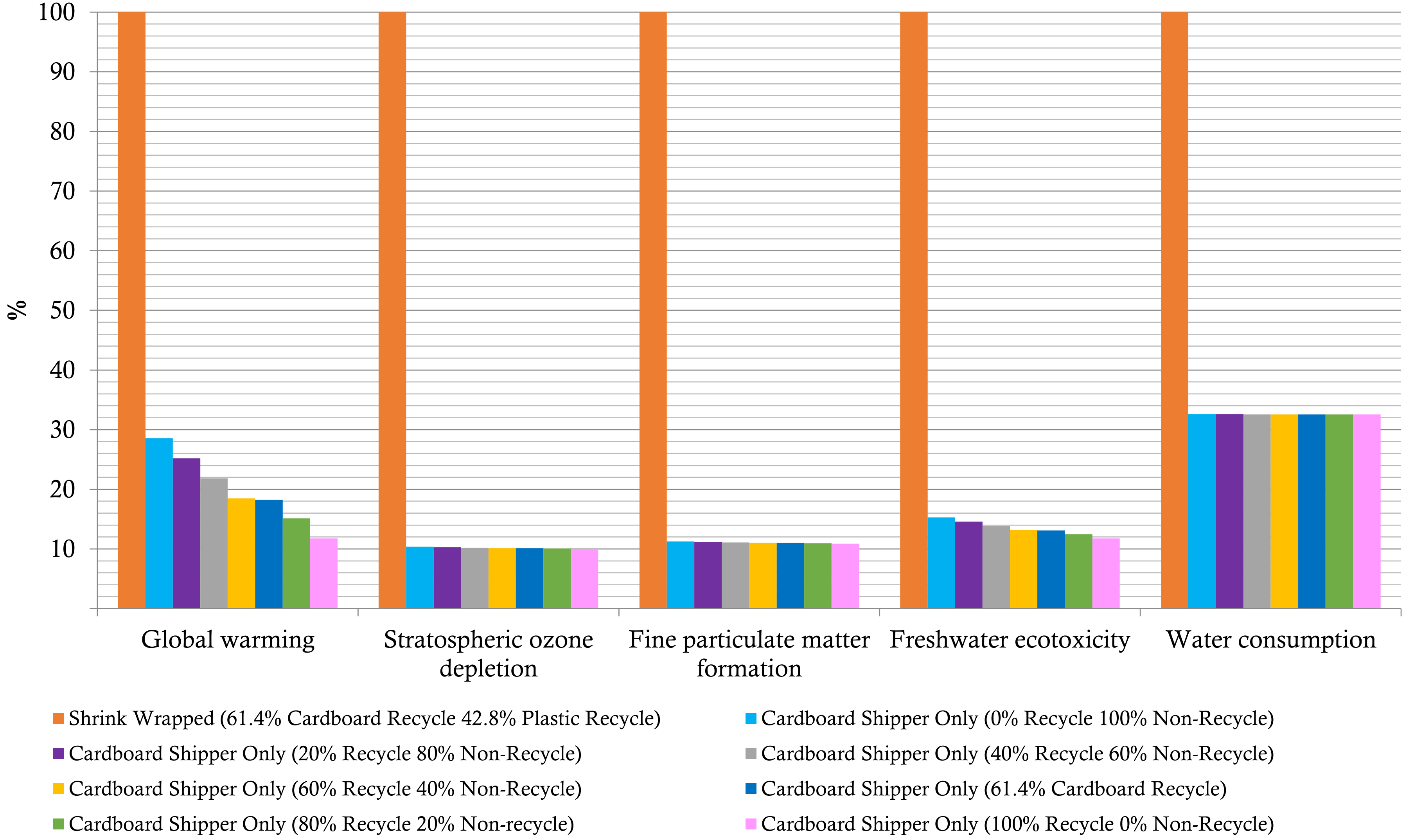
Appendix B17: Sensitivity Analysis Results of Corrugated Board Recycle Rate



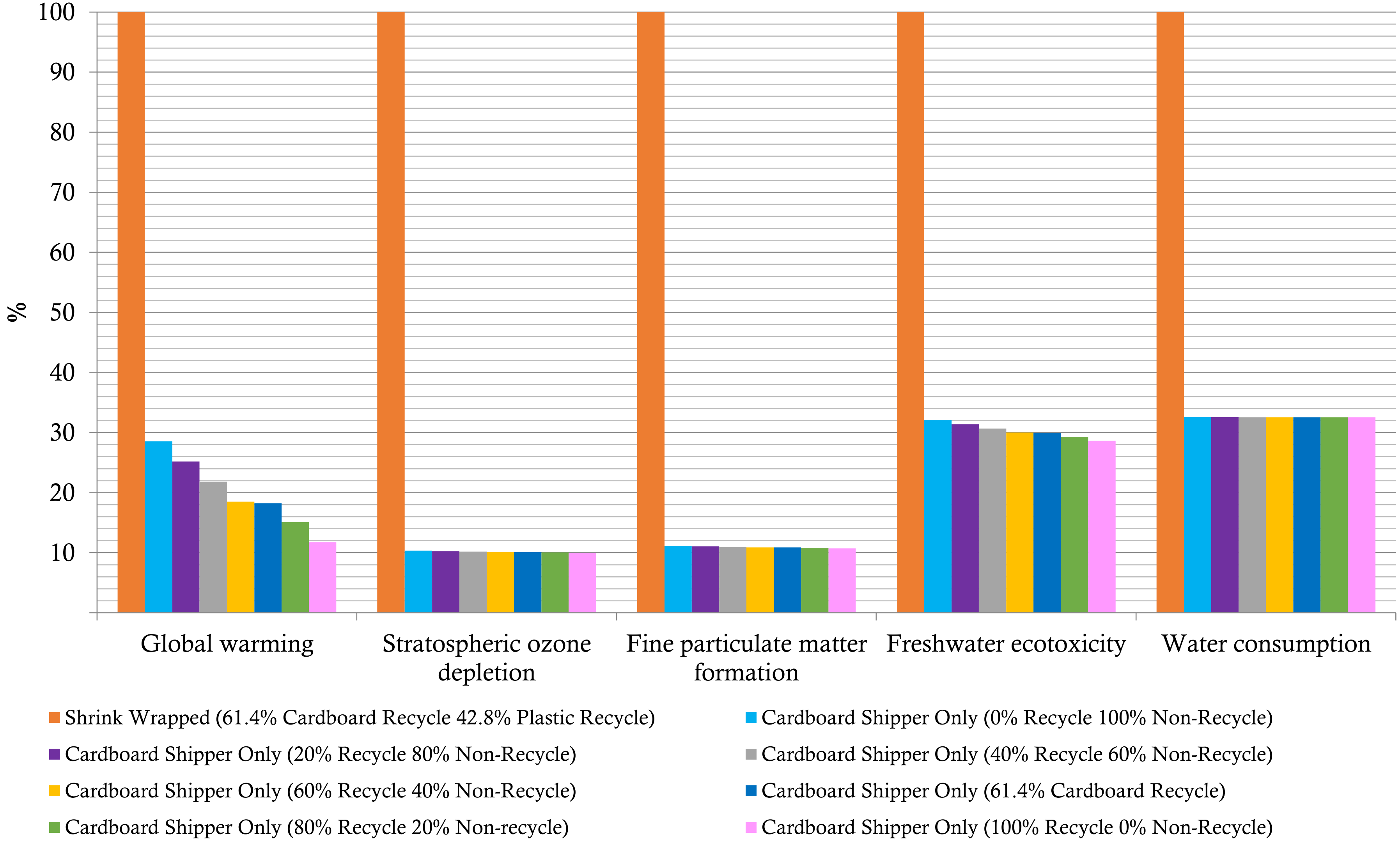
Appendix B18: Sensitivity Analysis Results of Corrugated Board Recycle Rate excluding Long-Term Emissions



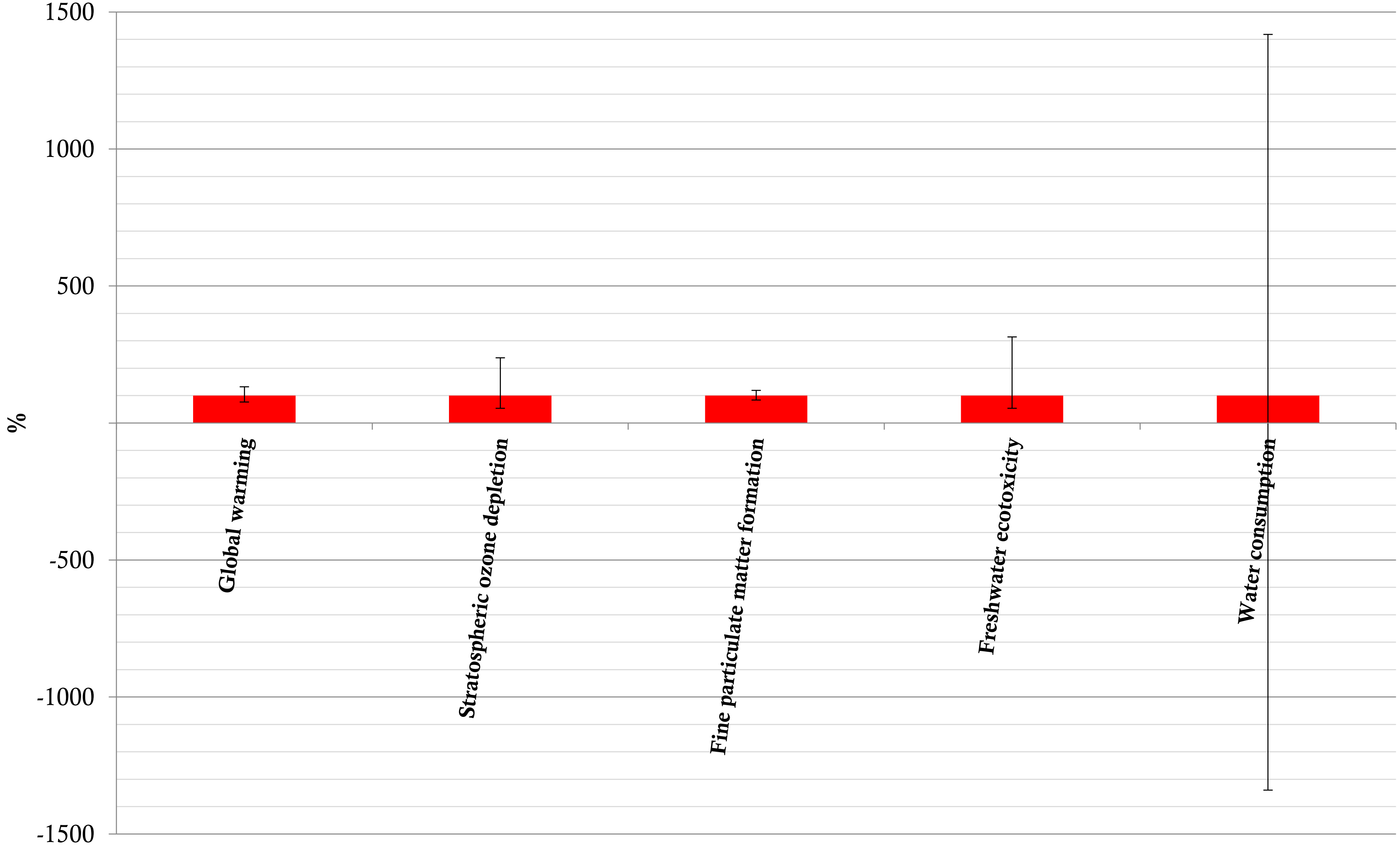
Appendix B19: Sensitivity Analysis Condensed Results of Corrugated Board Recycle Rate



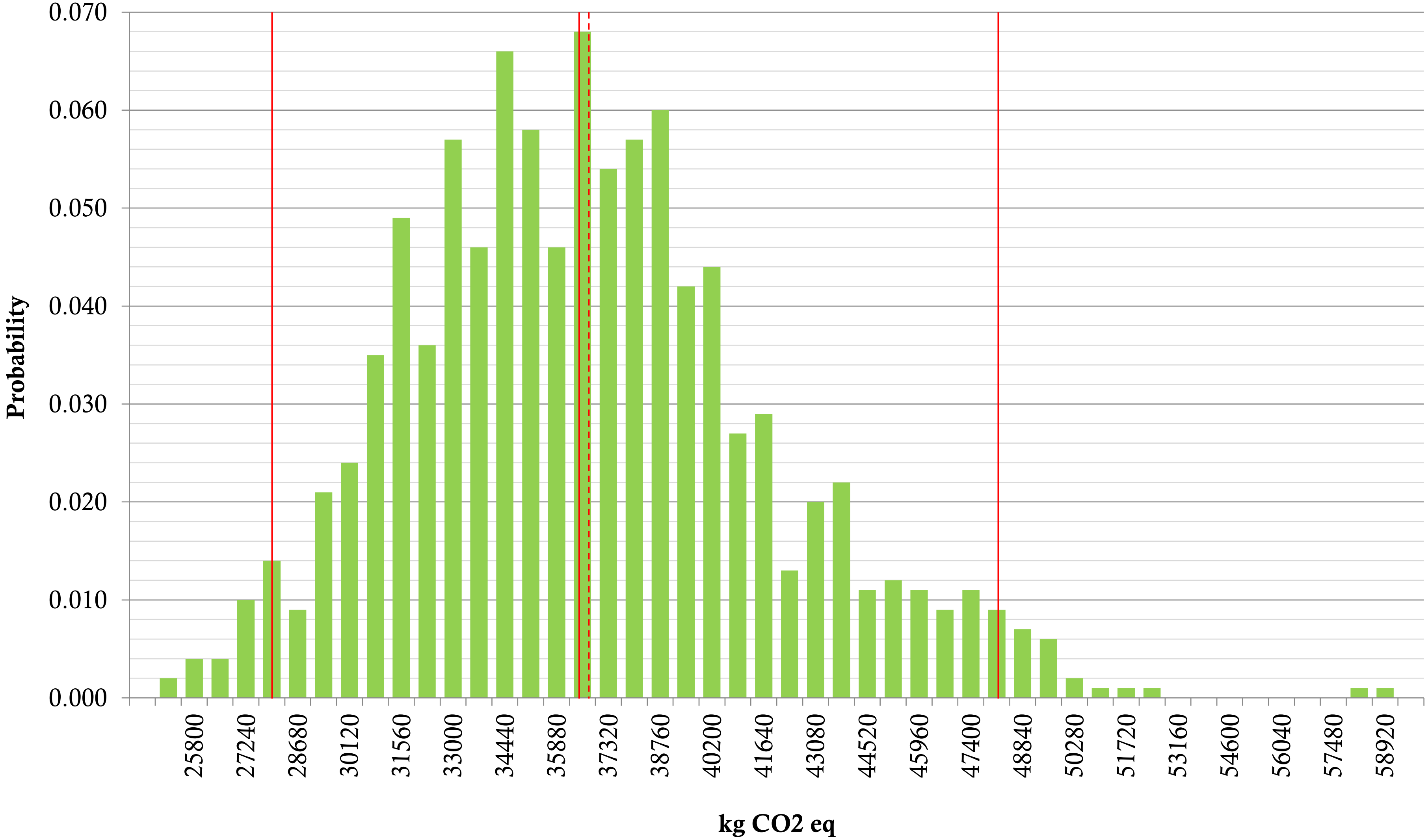
Appendix B20: Sensitivity Analysis Condensed Results of Corrugated Board Recycle Rate excluding Long-Term Emissions



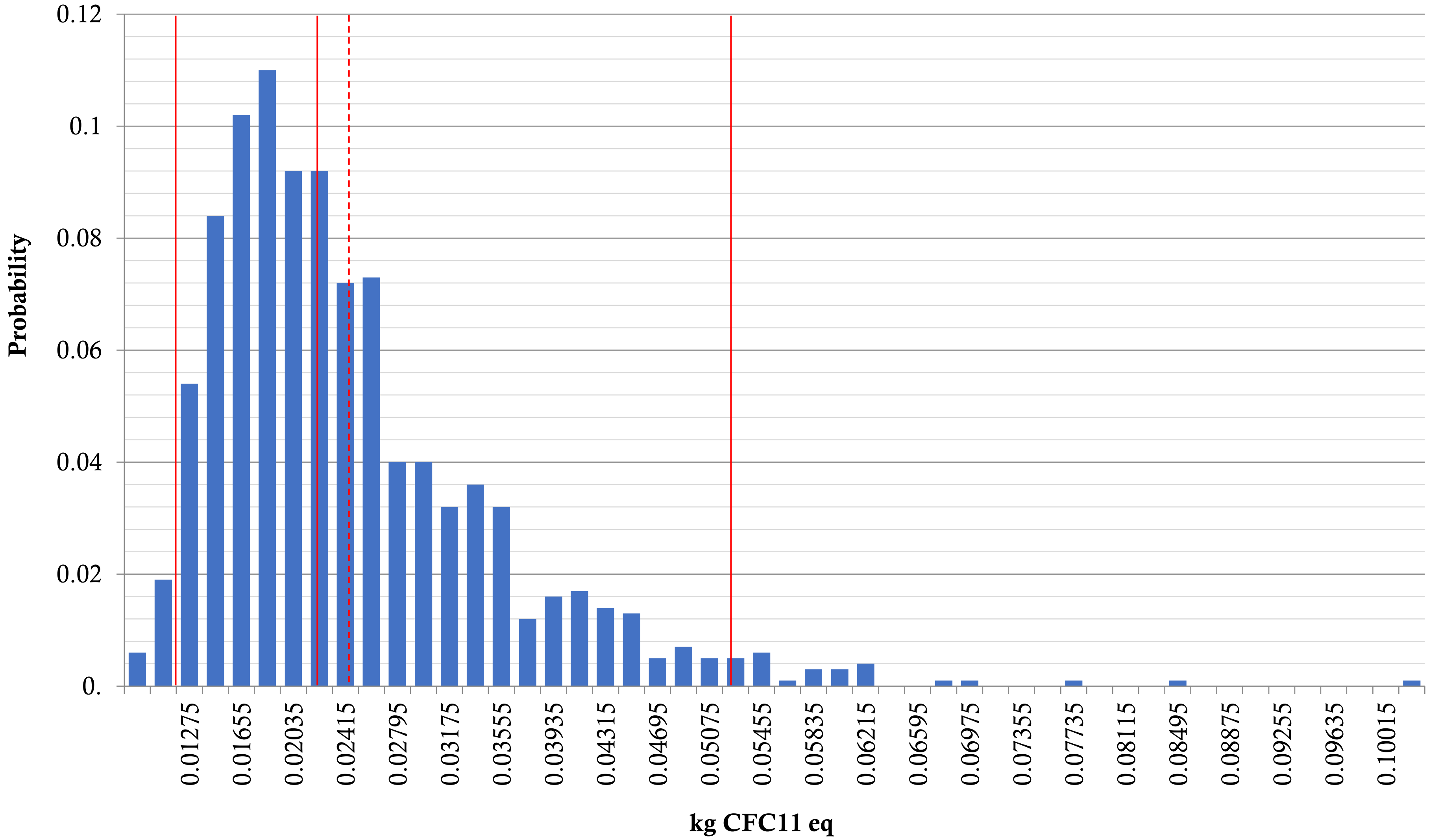
Appendix B21: Uncertainty Analysis Heat Shrink-Wrap Plastic Bar Chart



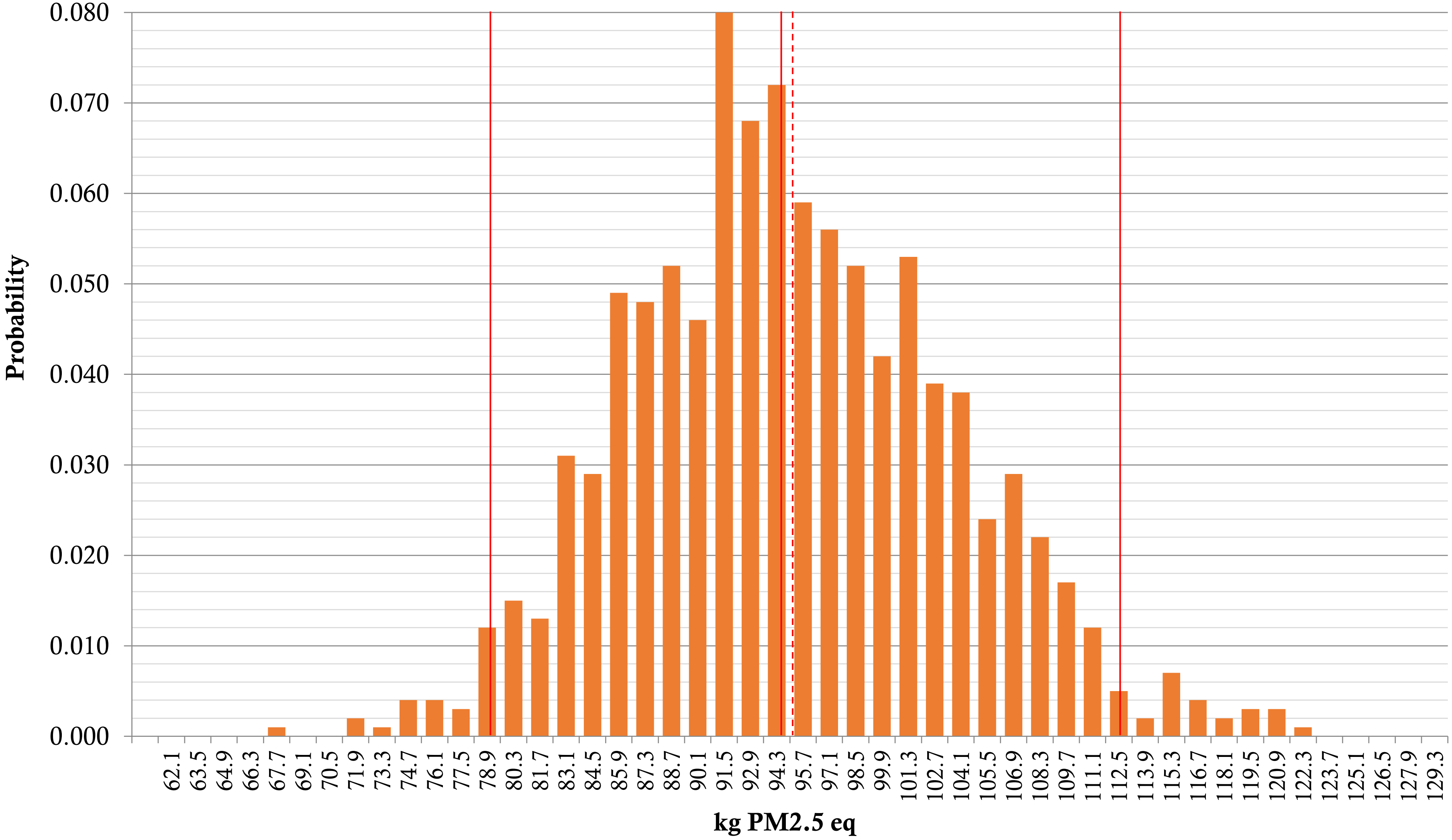
Appendix B22: Uncertainty Analysis Heat Shrink-Wrap Plastic Global Warming



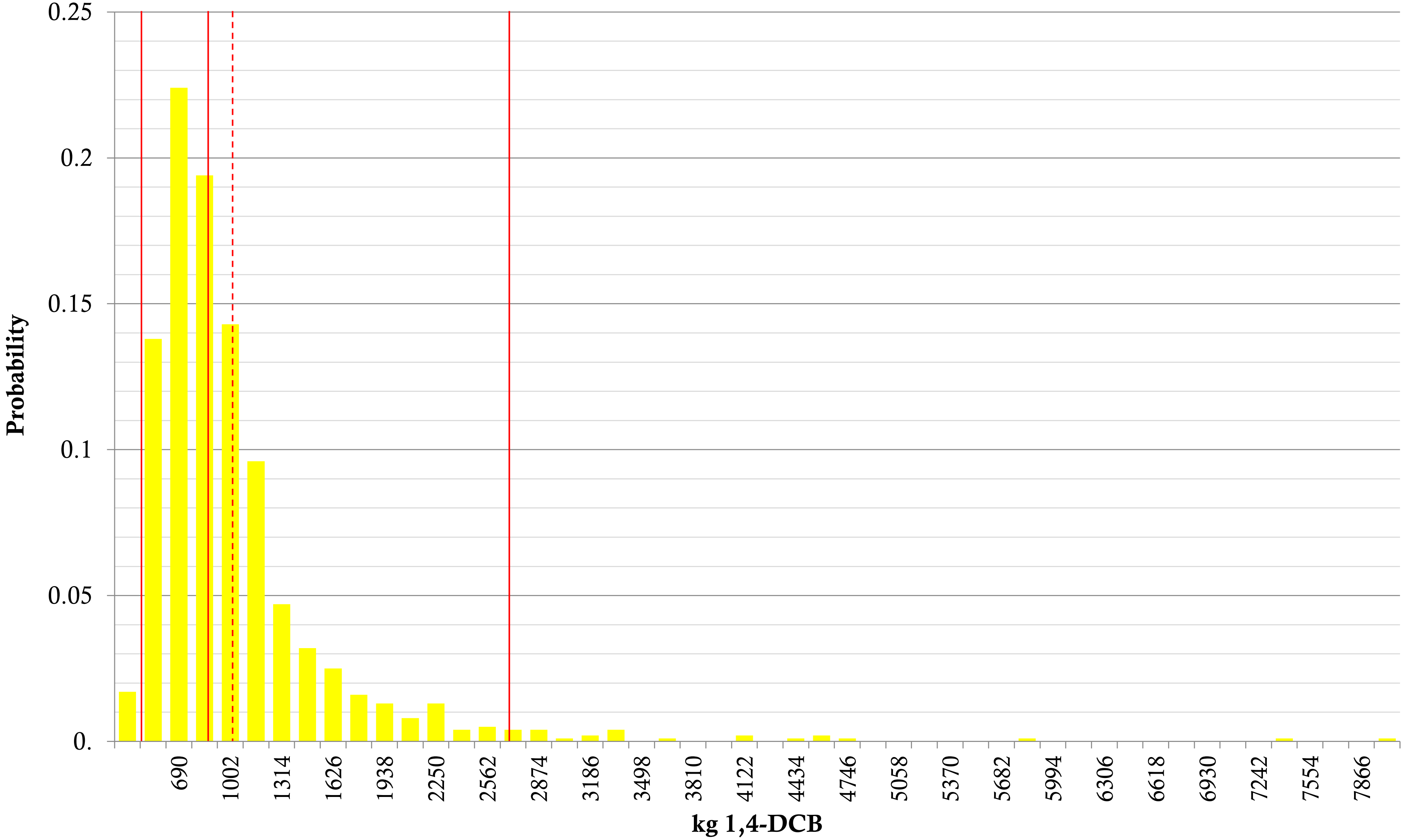
Appendix B23: Uncertainty Analysis Heat Shrink-Wrap Plastic Stratospheric Ozone Depletion



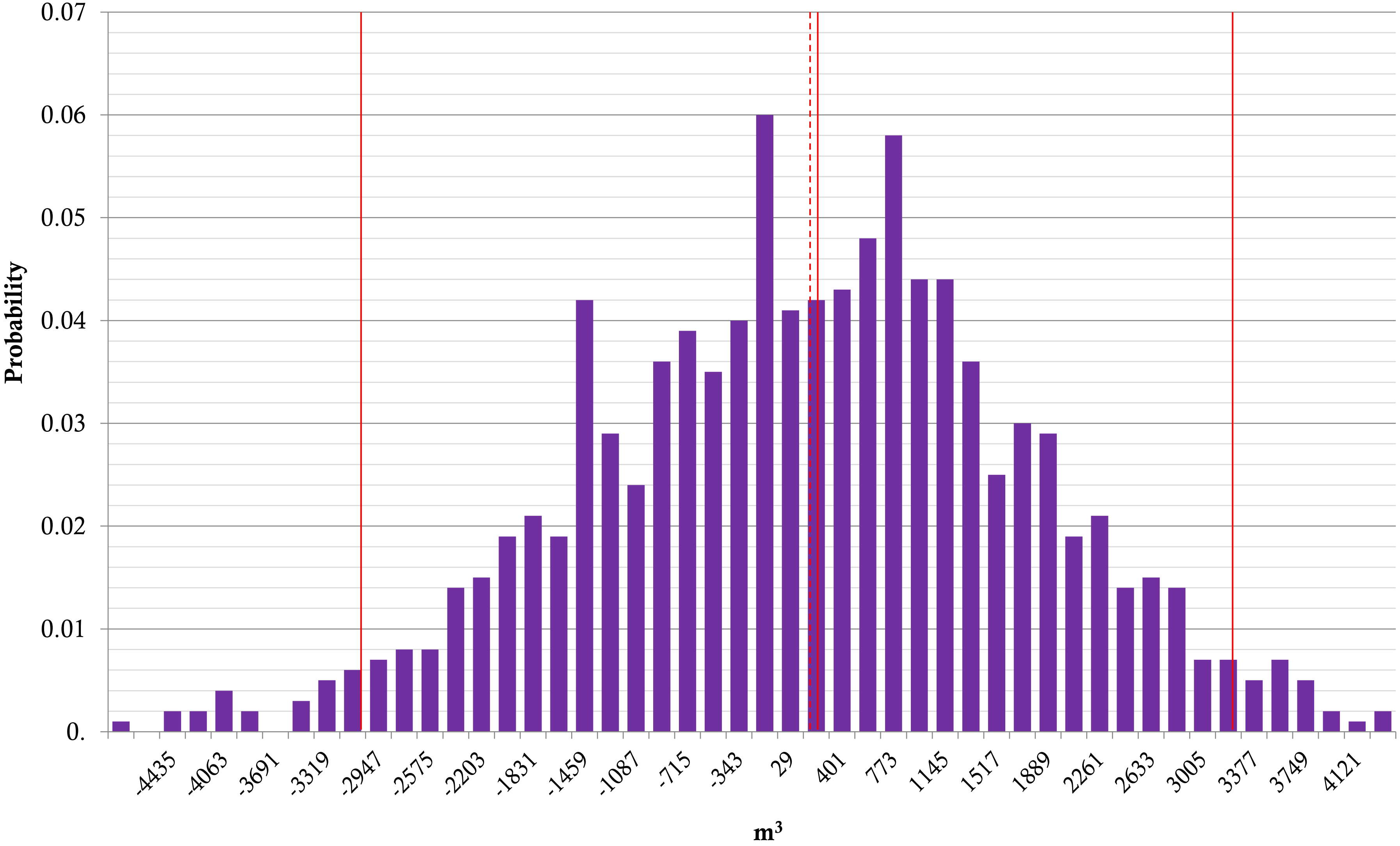
Appendix B24: Uncertainty Analysis Heat Shrink-Wrap Plastic Fine Particulate Matter Formation



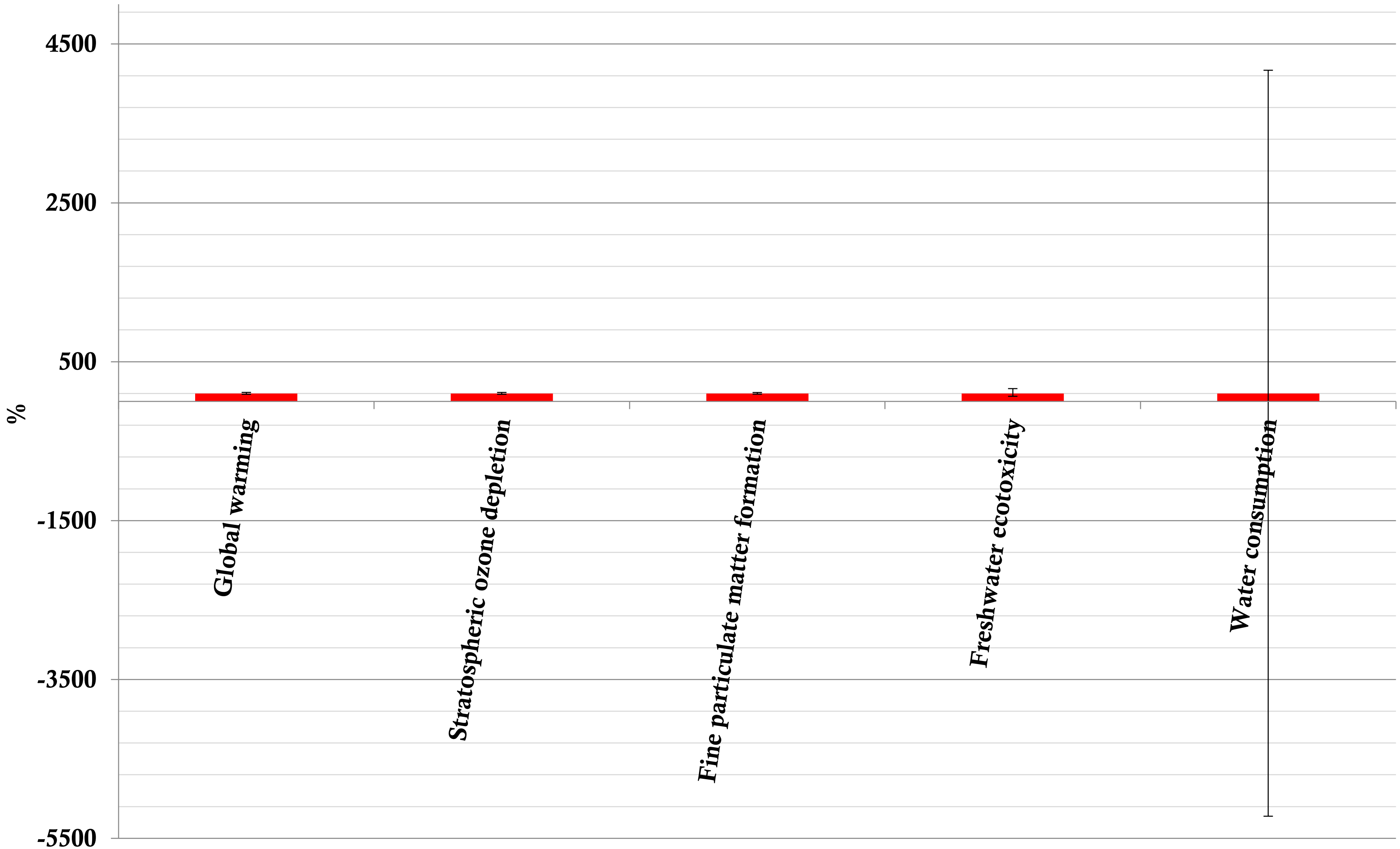
Appendix B25: Uncertainty Analysis Heat Shrink-Wrap Plastic Freshwater Ecotoxicity



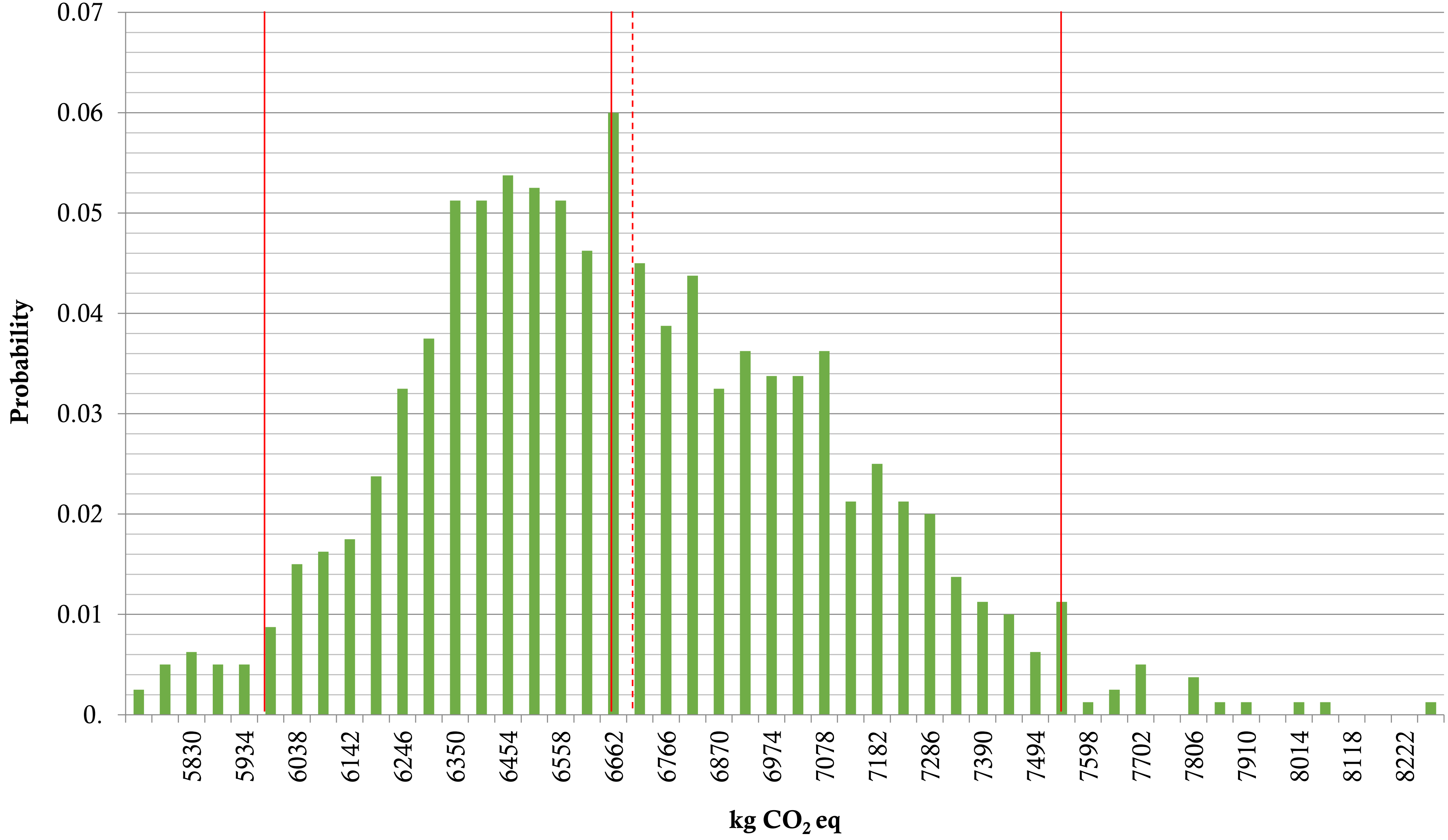
Appendix B26: Uncertainty Analysis Heat Shrink-Wrap Plastic Water Consumption



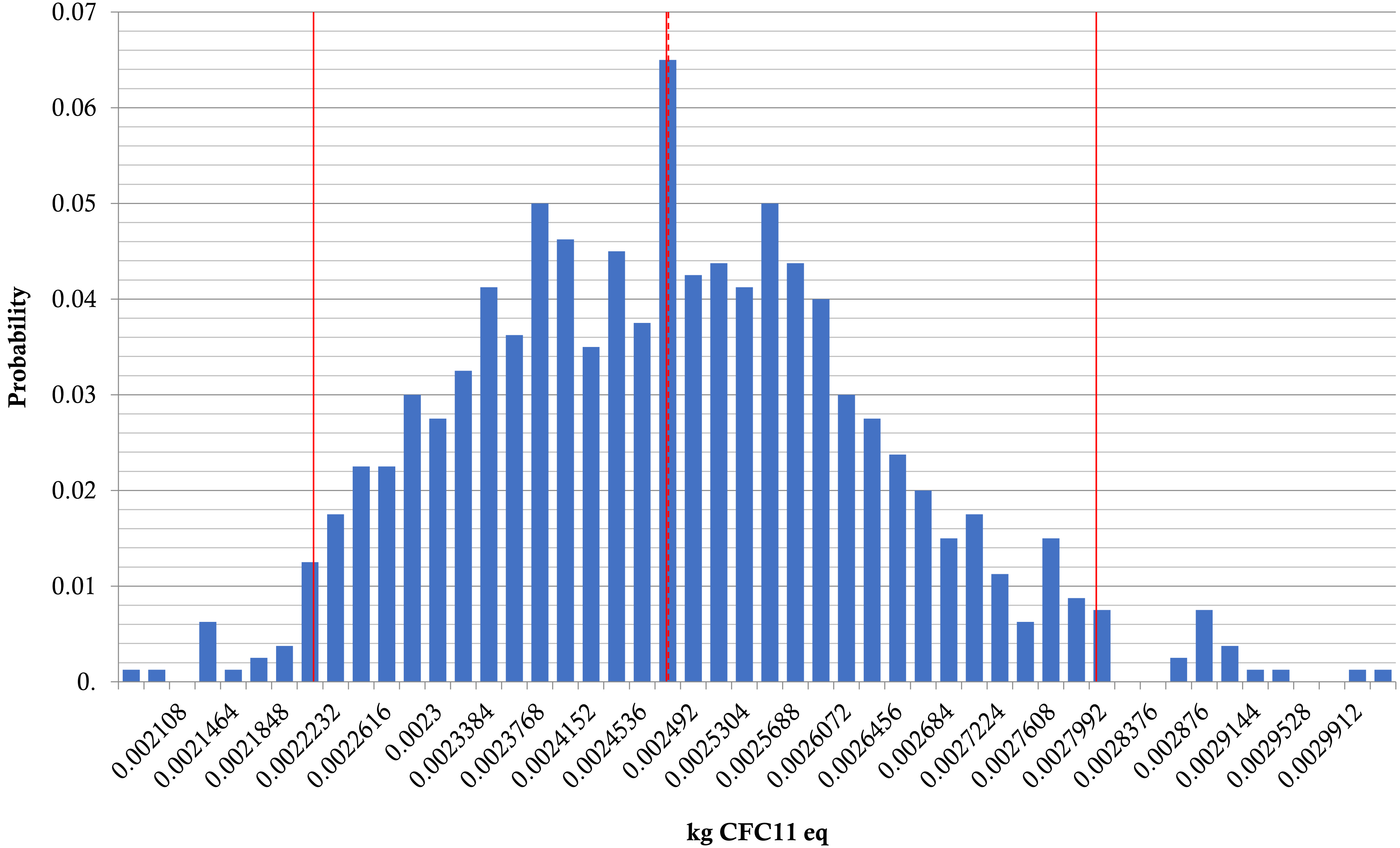
Appendix B27: Uncertainty Analysis Corrugated Board Bar Chart



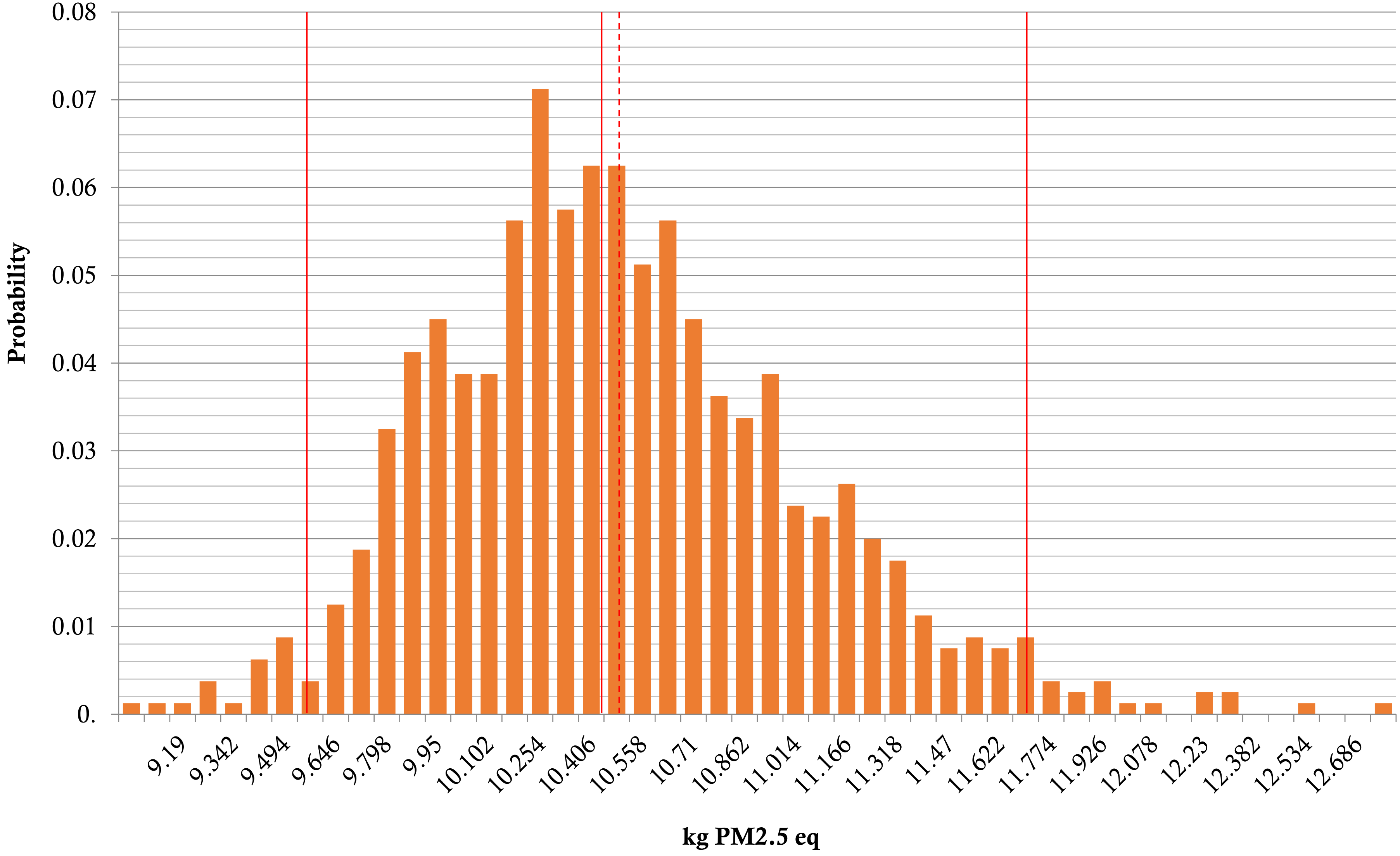
Appendix B28: Uncertainty Analysis Corrugated Board Global Warming



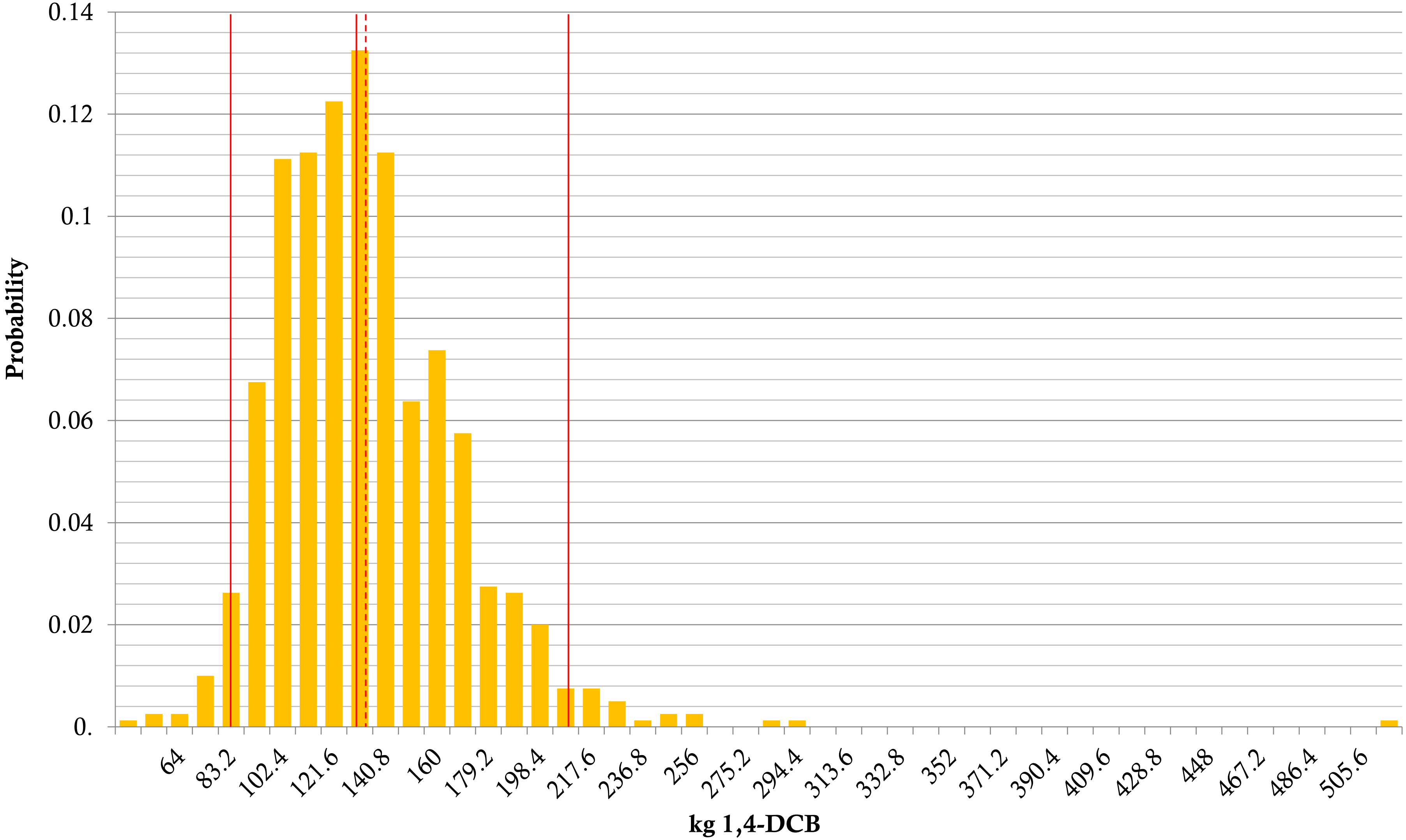
Appendix B29: Uncertainty Analysis Corrugated Board Stratospheric Ozone Depletion



Appendix B30: Uncertainty Analysis Corrugated Board Fine Particulate Matter Formation



Appendix B31: Uncertainty Analysis Corrugated Board Freshwater Ecotoxicity



Appendix B32: Uncertainty Analysis Corrugated Board Water Consumption