

# **Optimizing Sustainability in Jordanian Detergent Manufacturing: A Life Cycle Analysis Approach**

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## **Abstract**

Jordanian manufacturing is facing an increasingly high level of pressure to reduce environmental damage and implement more sustainable processes of production. Life Cycle Assessment (LCA) is a very popular method used to assess the environmental hazards that come with products and processes across their life cycle. This research applies a gate-to-gate LCA to evaluate the environmental performance of liquid laundry detergent production in Jordan. The evaluation looks at the mixing, filling, and packaging stages of the system using a functional unit of 1 kg of liquid detergent produced. Primary data were gathered from a local detergent manufacturing facility using site visits and questionnaires, and secondary data were found from literature sources and life cycle inventory databases. Midpoint indicators like Global Warming Potential (GWP), Human Toxicity Potential (HTP), Marine Ecotoxicity (MET), as well as Eutrophication Potential (EP) were used to assess environmental impacts. The results show that the packaging stage is the main contributor to the environmental assessed impacts as carton board packaging corresponds to the highest source of impacts across all categories. The HDPE bottle emerged as the second most significant contributor, and electricity consumption and water use had relatively smaller impacts in the selected system boundary. Based on the results, there were identified some improvement options such as reducing the packaging material, increased use of recyclable materials, improved energy efficiency, followed by improving the waste management procedures. The study stresses the importance of packaging optimization in minimizing the environmental impact of detergent production. Future research should extend the system boundary to take a cradle-to-grave view as well as provide Jordan-specific inventory information improving the reliability and completeness of these results.

## **Keywords**

Life Cycle Assessment (LCA), Sustainable Manufacturing, Environmental Impact Assessment, Production Optimization.

## **1. Introduction**

Laundry detergents are common household essentials in countries all around the world. With the advancement and development of different products across the supply chain, the demand for detergents is consistently rising. According to Jordan Exports, in 2019 alone, EU imports of detergents from Jordan reached approximately EUR 1.6 million, which shows the size of the detergent market on a global level (Guide *et al.*, 2021). The demand growth has led to an increased production scale to meet the growing demand, which comes with bigger impacts on the environment. The increased pressure on the environment from the manufacturing industry calls for methods that can optimize these processes and reduce their impact. Life Cycle Assessment is pivotal in identifying the environmental hotspots, which are the highest contributors to the total environmental impact of a product, and optimizing them to reduce their impact. While sustainability awareness in the manufacturing sector has increased over the past decade, there is still a lack of transparent identification of process hotspots and actions that address them. This results in higher waste, unoptimized process emissions, and a bigger impact on the environment.

## **1.1 Objectives**

This study aims to establish standard procedures, concerning improved sustainability, that can be adopted by manufacturing facilities in Jordan. Through a comprehensive LCA framework, the paper analyzes and assesses the environmental impact of laundry detergent production and recommends operational adjustments to mitigate identified hotspots.

**Research Questions:** What hotspots are there in the laundry detergent manufacturing? How do operational decisions in the production process of detergents affect the environment? What procedures and strategies should be implemented to target the identified hotspots to optimize the manufacturing process?

## **2. Literature Review**

### **2.1 Manufacturing Process Overview**

The detergent manufacturing process consists of several stages, including obtaining and processing the raw materials, formulation of the solution, post-processing, quality control tests, and finally packaging and storage. The main raw material used in detergents is the surfactant, which is the cleaning agent that breaks down the surface tension between the dirt particles and the clothing, allowing them to be washed away by the water. The choice of surfactant type can affect foaming, cleaning efficiency, and the type of water that can be used. Most surfactants, particularly anionic surfactants, cannot function effectively in hard water because the minerals in the water interact with the surfactant, affecting its overall performance. Therefore, builders, such as zeolites and phosphates, are essential for softening water, as they react with the minerals in hard water. However, phosphates remain in the water and act as fertilizers, causing excessive algae growth, known as eutrophication, which leads to water pollution. Due to the environmental impacts of phosphates, studies report that 32% of European powder detergents use zeolites as builders, since the resulting residue is harmless (Bajpai and Tyagi, 2007). Other common materials used in the detergent production are enzymes, such as protease, amylase, and lipase, which break down stains, in addition to fillers, such as sodium sulfate, which add bulk to the product. Additives, like optical brighteners, anti-redeposition agents, and fragrance ingredients, vary by the facility's product formula.

The raw materials go through processing, including sulfonation, a process that combines petrochemicals with sulfur trioxide ( $\text{SO}_3$ ) to produce anionic surfactants, and ethoxylation, a process where ethylene oxide is added to a fatty alcohol to create nonionic surfactants. These chemical processes require specific temperatures and pressures to achieve the final products, which is energy-consuming.

Following preparation, the raw materials are formulated in industrial mixers, where surfactants form 25-50% of the detergent formula, while other ingredients account for varying percentages depending on the product's desired properties, such as viscosity and cleaning performance. Afterward, in the case of powdered detergents, the formed solution undergoes a process called spray drying, where it is made into a liquid slurry, then sprayed through atomizers into a hot air tower, which causes the water to evaporate instantly, resulting in uniform, free-flowing granules. Furthermore, quality control tests are performed to check cleaning efficiency, pH levels, foam performance, and stability, which are necessary for standards compliance, and have a considerable effect on production waste.

The final stages in the laundry detergent production are packaging and storage. Packaging differs by facility, but most facilities use HDPE plastic bottles for liquid detergents and cardboard boxes for powder detergents, leading to several environmental impacts upon disposal. Moreover, better stability and longer shelf-life of the detergents require cool, dry conditions along with controlled humidity and no direct sunlight. Maintaining optimal storage conditions of the product and preserving its efficiency reduces the volume of consumption and product waste.

Based on the reviewed process, several environmental hotspots can be identified across the different stages, namely, the harmful by-products of the chemical processes, the high energy consumption for the spray drying, and recycling concerns regarding packaging material, in addition to the choice of materials used, like phosphate building agents causing eutrophication, all contributing to impacts regarding carbon footprint, energy use, water use, waste, and pollution.

### **2.2 LCA Methodology and Approaches**

Life Cycle Assessment (LCA) is a framework used to define and quantify the environmental impacts of a product or process from raw material extraction, through the production and use, to product disposal. LCA acts as a tool to

identify environmental hotspots, which are stages or processes that contribute the most to the environmental impact, based on several indicators, helping decision-makers optimize the specific stages and improve the sustainability performance. The four main phases of LCA are defining the goal and scope of the study, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and interpreting the results (Curran, 2013; “ISO 14040:2006/Amd 1:2020 - Environmental management — Life cycle assessment — Principles and framework — Amendment 1”, n.d.). The first step of LCA, defining the goal and scope, includes defining the process being analyzed, defining the purpose of the analysis, setting a functional unit for measurement, and setting the system boundaries. LCA system boundaries define which unit processes, like the delivery of raw materials, life cycle stages, like product manufacturing and product disposal, and material and energy flows are included in the assessment. Selecting the system boundaries helps focus the analysis on the desired stages of the process and determine the data that must be collected, which is time and resource-efficient. In the case of laundry detergent manufacturing, the LCA system boundary is shown in Figure 1, which clearly displays each stage of the life cycle, as well as the system’s inputs and releases.

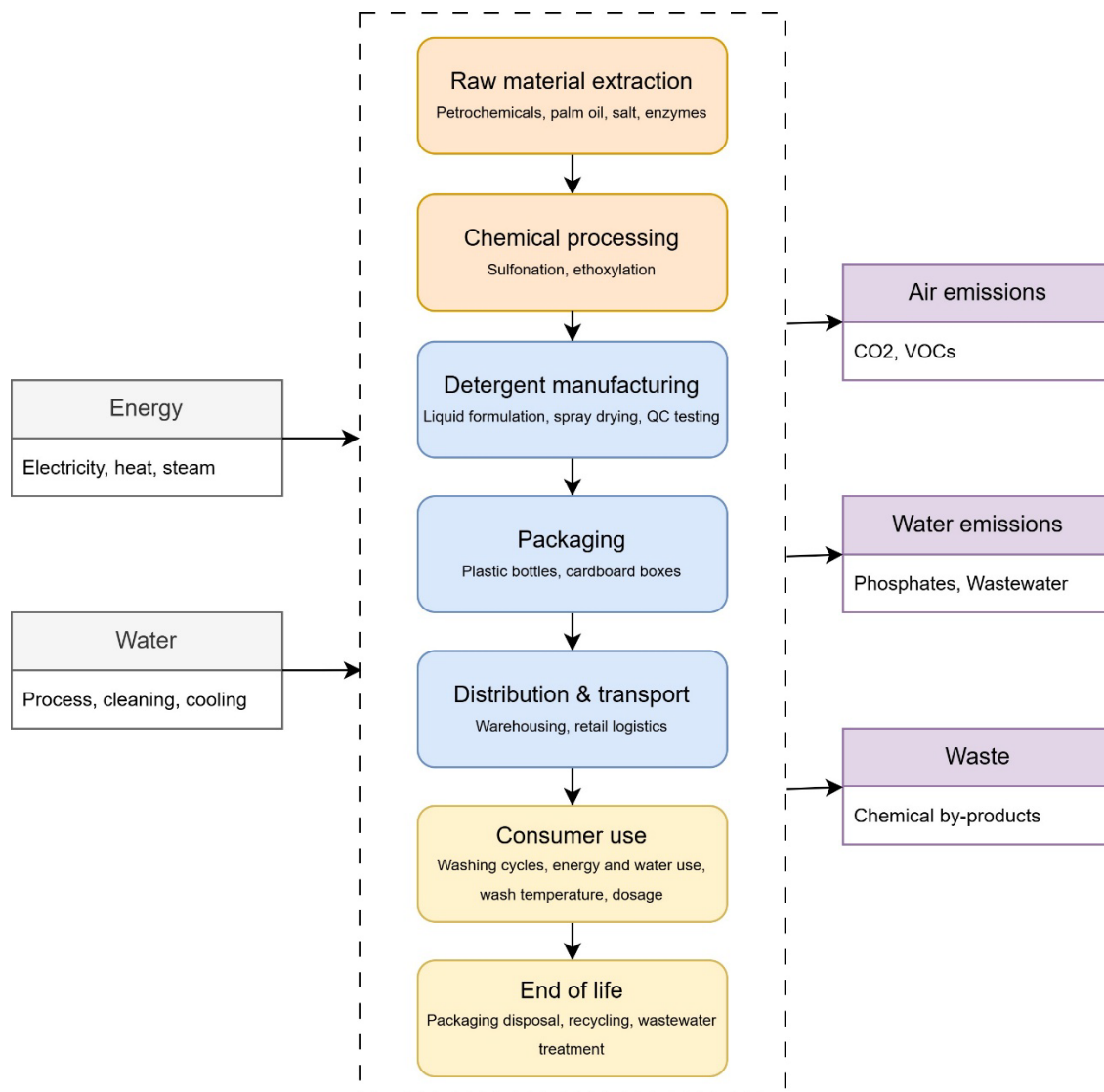


Figure 1. System Boundary Diagram for Laundry Detergent Life Cycle

The next phase of LCA is the Life Cycle Inventory (LCI) Analysis, which involves compiling an inventory of inputs, including material and energy, and releases, like emissions and waste, of each process. LCA data systems are classified into 2 systems: foreground and background. The foreground system, consisting of primary data, covers processes that are under the direct control of the decision-maker, for example, the manufacturing and assembly processes in a factory.

The background system, consisting of secondary data, covers processes that are out of the decision-maker's direct control, such as material extraction. This separation aids in the acquisition of the process data, as foreground systems require primary data to be collected from the factory floor, whereas background systems require secondary data from existing LCI databases. Moreover, the data quality and uncertainty distribution of the parameters must be collected and specified, this is to ensure a more accurate evaluation.

A study on the developments in the field of LCI compared different LCI data generation methods and their accuracy based on their uncertainty, time requirements, and manufacturing readiness (Köck *et al.*, 2023). Evaluation results showed that collecting data directly from the plant and LCI databases had the highest accuracy, lowest uncertainty, and highest manufacturing readiness; however, it had the highest time requirement, which shows these two methods to be the best approaches in the case of no time constraints. Other methods, like process simulation tools and advanced process calculations, were recommended as less accurate, but also less time-consuming methods for data generation. After compiling the relevant data, a Life Cycle Impact Assessment (LCIA) is performed, where the collected data is classified, characterized, and then optionally normalized, weighted, and aggregated. The classification step involves assigning inventory flows, which are the inputs and releases, to impact categories, for example, eutrophication, which are used to group environmental burdens. As for the characterization step, the flows are quantified and aggregated into category indicators using impact units, such as kg CO<sub>2</sub> -eq, to represent their relative contribution to each category (Hauschild *et al.*, 2013). Next, normalization is performed to calculate the magnitude of the category indicators by dividing the value by a reference value, for example, changing the kg CO<sub>2</sub> -eq unit into a dimensionless ratio like person-year impact. Lastly, the results are weighted using relative importance factors, which are subjective according to the company's priorities, and aggregated to reach a single indicator (Andrea *et al.*, 2025).

The last phase of LCA is the interpretation of the results, where the environmental hotspots are identified, developing different solutions to minimize their impact, and comparing alternatives. It is important to consider the assumptions and quality of data while making decisions based on the results.

## 2.3 Review of LCA Applications in Manufacturing

Several studies were reviewed where Life Cycle Assessment was applied to the detergent manufacturing industry to identify hotspots and assess optimization solutions. The ISO 14040 was commonly followed, but each study had different system boundaries, used different software tools and assessment methodologies, and provided varying solutions to address the derived environmental impacts.

### 2.3.1 Methodologies and Assessment Approaches

The variability in LCA results can be due to the differences in the system boundaries, methodologies, and software used for the analysis, as shown in Table 1. One study used the GaBi version 8.0 software, along with the CML 2016 methodology, which focuses on the midpoints and assigns impact categories. Another paper used the Ecoinvent database to calculate the impacts, and utilized the ReCiPe methodology, where 12 impact categories were calculated and aggregated into 3 endpoint impacts, which are human health, ecosystems, and resources surplus cost. The study evaluating enzymatic detergent also used the Ecoinvent database plugged into the OpenLCA software, and used 5 calculation methodologies, including CML Baseline, ReCiPe Midpoint (H), IPCC 2013 GWP 100a for carbon footprint calculations, AWARE for water scarcity calculations, and Cumulative Energy Demand (CED) for energy consumption calculations.

All of the reviewed studies relied on primary data from local facilities for manufacturing processes, while detergent consumption patterns were collected through questionnaires filled out by consumers. LCA databases, such as Ecoinvent, were used to derive data that were difficult to obtain directly from manufacturers or consumers.

Table 1. Summary of Studies Applying LCA on Detergent Products

| Study                                                        | Ref                           | Product/<br>Process | Software/<br>Database | Method-<br>ology | System<br>Boundar<br>y | Outcome                                                         |
|--------------------------------------------------------------|-------------------------------|---------------------|-----------------------|------------------|------------------------|-----------------------------------------------------------------|
| The Environmental Impacts of Bar Soap Production: Uncovering | (Gaurav <i>et al.</i> , 2023) | Bar soap            | GaBi V8.0             | CML 2016         | Cradle-to-grave        | Raw material extraction and chemical processing contributed the |

|                                                                                                                                                                                |                                                   |                                         |                                 |                                                                   |                 |                                                                                                                                                                                |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------|-----------------------------------------|---------------------------------|-------------------------------------------------------------------|-----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Sustainability Risks with LCA Analysis                                                                                                                                         |                                                   |                                         |                                 |                                                                   |                 | highest to most impact categories, due to heating and chemical treatment.                                                                                                      |
| A compilation of life cycle studies for six household detergent product categories in Europe: the basis for product-specific A.I.S.E. Charter Advanced Sustainability Profiles | (Gols teijn <i>et al.</i> , 2015)                 | Powder and tablet laundry detergents    | Ecoinvent v2.2                  | ReCiPe                                                            | Cradle-to-grave | The water heating during the use phase accounted for around 95% of most categories. Ingredient sourcing contributed to the remaining impacts, like land use and eutrophication |
| Ecodesign coupled with Life Cycle Assessment to reduce the environmental impacts of an industrial enzymatic cleaner                                                            | (de Lapu ente Díaz de Otazu <i>et al.</i> , 2022) | Enzymatic all-purpose cleaner detergent | OpenLCA; Evoinvent 3.7 database | CML Baseline; ReCiPe Midpoint (H); IPCC 2013 GWP 100a; AWARE; CED | Cradle-to-grave | 0.76 kg CO <sub>2</sub> -eq per kg of packaged detergent, upstream chemical ingredients and downstream transportation identified as the main hotspots.                         |

### 2.3.2 Environmental Hotspots

The study performing an LCA on the production of bar soap in the context of India has found that the raw material extraction and chemical processing, including fats, oils, fragrances, and preservatives, had the most significant environmental impacts. Specifically, concerning the global warming potential (GWP), eutrophication, ozone depletion, and human toxicity (HTP) indicators. These impacts were linked with the energy-intensive heating and chemical treatment processes. Moreover, the study emphasized the impact of the use phase on the environment, particularly on the water consumption, eutrophication from the grey water being dumped into rivers, and marine & terrestrial toxicity from chemicals in wastewater. Notably, packaging was shown to have an insignificant impact on the environmental indicators compared to the other stages (Gaurav *et al.*, 2023).

According to the study of detergent products in Europe, the heating of washing water during the use phase accounted for between 46% and 95% in most impact categories, such as climate change, particulate matter formation, and fossil depletion. Additionally, both tablet and powder detergents consumed 64-68% of the Cumulative Energy Demand (CED) during their use. Moreover, the choice of ingredients had notable impacts on land use, with 86% driven by surfactants, as well as marine eutrophication and metal depletion, where over 50% of the impact was from the builders used in the formula (Golsteijn *et al.*, 2015).

Recent LCA literature highlights the environmental impacts across the upstream, core, and downstream phases of detergent manufacturing. The raw material extraction and chemical processing, specifically of ingredients like the 3-butoxy-2-propanol and ethoxylated alcohols, showed the highest Cumulative Energy Demand (CED). This calls for the substitution of raw materials with environmentally friendly alternatives. Moreover, the core manufacturing processes, particularly the waste management, contributed the most to the water scarcity footprint (WSF), accounting for around 48% of the water consumption in the core phase. As for the downstream phase, the transportation during product distribution was identified as the main hotspot, being the highest contributor in six out of the seven impact categories. The study recommended switching to railway transport to mitigate this impact (de Lapuente Díaz de Otazu *et al.*, 2022).

### 2.3.3 Optimization Strategies

The reviewed papers recommended several solutions for different stages of the detergent manufacturing process, as shown in Table 2, to target the identified environmental impacts. The strategies were evaluated and compared.

Table 2. Summary of Sustainable Solutions Mentioned in Published Literature

| <b>Solution</b>                                                        | <b>Targeted Impact</b>                                                       | <b>Improvement</b>                                                                                 | <b>Limitation</b>                                                     |
|------------------------------------------------------------------------|------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|
| Solar heating                                                          | High energy consumption.                                                     | Utilizing renewable energy instead of power from limited resources.                                | Subject to the variance in sunlight and different weather conditions. |
| Consumer education to use a lower dosage and less washing frequency    | Water pollution; energy and fresh water consumption.                         | Lowers water and energy consumption from the “Use” phase, which accounts to 95% of the impact.     | Consumers might ignore the instructions.                              |
| Proper wastewater drainage, adding membrane arrangements (Muthu, 2015) | Eutrophication; water depletion.                                             | The greywater from washing is recycled and reused into fresh water; prevents contamination.        | High initial cost (CAPEX).                                            |
| Circular economy solutions for plastic packaging, pyrolysis            | Resource depletion; waste generation.                                        | Diverts waste from landfills and replaces the extraction of resources.                             | High energy consumption.                                              |
| Produce concentrated detergents                                        | Energy and material consumption during packaging, production, and transport. | Reduces volume and weight of the detergent, less packaging material needed.                        | Risk of consumers using the regular dose; and other safety hazards.   |
| Set criteria for maximum level of packaging materials per job          | Resource consumption, end of life impacts of packaging.                      | Prevents the overconsumption of packaging materials, less weight during transportation.            | Compromises the sturdiness of the packaging.                          |
| On-pack guidance towards sustainable use                               | Eutrophication; water and energy consumption.                                | The guidance on the packaging encourages the consumer to use correct dosage and water temperature. | Might get ignored by the user.                                        |
| Higher volume packaging                                                | Global warming potential; Eutrophication potential.                          | Reduces overall impact by 8% to 38%; cuts GWP impact by 25%.                                       | Higher volume packs cost more per purchase.                           |
| Switching to railway transport                                         | Global warming potential; abiotic depletion potential of fossil fuels.       | Reduces GWP by 14%, reduces ADP for elements by 95%.                                               | Requires secondary transport due to fixed physical infrastructure.    |

## 2.4 Critical Analysis and Research Gap

The reviewed literature consistently identified the detergent manufacturing and packaging processes as significant contributors to environmental impacts, mainly due to energy consumption and waste generation. Despite the material extraction and the use phases being emphasized as the highest contributors by many studies, few of them provided insight on the potential operational optimization of the production and packaging processes. Additionally, while each study used different methodologies and approaches, all the results pointed to the importance of packaging, such as adding measuring cups and washing instructions, on reducing the impacts of the use stage by guiding the consumer to a more sustainable use of the product. Therefore, this study aims to conduct a gate-to-gate Life Cycle Assessment (LCA) on the laundry detergent manufacturing industry in Jordan, specifically the manufacturing and packaging processes.

### 3. Methods

#### 3.1 Research Approach

This study implements the Life Cycle Assessment (LCA) to evaluate the environmental impacts of the laundry detergent manufacturing and packaging processes in Jordan. This approach focuses on identifying the environmental hotspots within the selected system boundary and proposing optimization strategies aimed to sustainable production.

#### 3.2 Goal and Scope Definition

The goal of this study is to evaluate and assess the environmental impacts associated with detergent manufacturing and packaging stages, and identify optimization strategies to address them. Therefore, a gate-to-gate system boundary was selected, focusing on the manufacturing processes, including the detergent formulation, steam generation, machine operation, and factory waste, as well as the packaging process, as shown in Figure 2. Upstream operations, such as raw material processing and transportation, and downstream activities, like distribution, customer use, and end of life, are excluded. The defined processes from the selected facility are mixing, filling, and packaging, which are created using the LCA software, along with their inputs and outputs. For instance, the mixing process involves a 5-ton industrial mixer controlled by SCADA, where raw materials, electricity, and water are input, and then the mixed detergent is output. Moreover, for the filling process, the mixed detergent, plastic bottles, and electricity for the filling and labelling machines are input, then the filled bottles are output. Finally, the packaging process includes the cartons, tape, and the sealing tool as the inflows, and the packaged detergent cartons are the outflow.

A functional unit was defined for this study as the production and packaging of 1 kg of laundry detergent. Each bottle of detergent contains 3.15 kg, assuming a 1.05 g/mL density (Elements, n.d.), and around 21,600 kg of detergent is produced per day.

#### 3.3 Impact Assessment

For the impact calculations, OpenLCA software was used, along with the OzLCI 2019 and ELCD 3.2 databases. Data on the product formulation, electrical consumption, water use, and material waste were collected directly from a local facility. The database was used for all data unattainable from the facility. For the Life Cycle Assessment phase, the ReCiPe midpoint (H) methodology was used to evaluate the environmental impacts. The impact categories used for this research include Global Warming Potential (GWP), Human Toxicity Potential (HTP), Marine Ecotoxicity (MET), Eutrophication Potential (EP), and Acidification Potential (AP).

### 4. Data Collection

The data for this study were directly collected from a local laundry detergent manufacturing facility. A form was developed to gather information regarding the manufacturing processes, machinery and equipment used, energy consumption, water usage, packaging material, waste generation, and emissions. The data collection process focused on identifying the inputs and outputs of each process, specifically those with a significant contribution to the environmental impacts. The databases were used for secondary data, in addition to numbers from published literature. Assumptions based on engineering estimations were also made to complete the inventory analysis, which may slightly lower the accuracy of the calculations.

### 5. Results

#### 5.1 Numerical Results

Table 3. Characterized midpoint environmental impact results per 1 kg of laundry detergent produced, calculated using ReCiPe 2016 Midpoint (H) methodology in OpenLCA, using OzLCI 2019 and ELCD 3.2 databases.

| Impact Category                                      | Unit                  | Result                 |
|------------------------------------------------------|-----------------------|------------------------|
| Global Warming Potential (GWP)                       | kg CO <sub>2</sub> eq | $3.886 \times 10^{-1}$ |
| Human Toxicity Potential (carcinogenic) (HTP-c)      | kg 1,4-DCB eq         | $6.710 \times 10^{-4}$ |
| Human Toxicity Potential (non-carcinogenic) (HTP-nc) | kg 1,4-DCB eq         | $1.078 \times 10^{-2}$ |
| Marine Ecotoxicity Potential (MET)                   | kg 1,4-DCB eq         | $1.780 \times 10^{-4}$ |
| Eutrophication Potential (EP)                        | kg N eq               | $1.530 \times 10^{-5}$ |
| Acidification Potential (AP)                         | kg SO <sub>2</sub> eq | $9.095 \times 10^{-4}$ |

## 5.2 Graphical Results

### 5.2.1 Observations

The results, as shown in Figure 2, show that the Global Warming Potential (GWP) has the a significant impact score, reaching 0.389 kg CO<sub>2</sub> eq per kg of detergent produced. The carton board material used during the packaging process seems to be the biggest contributor to all of the impact categories, with the HDPE bottle having the second highest contribution in some of the categories, including GWP, with a 14% contribution, and AP, with a 15.4% contribution. For the GWP category, which had the highest score among the impact categories, the plastic material used in the cap, as well as the electricity consumed during the mixing and filling processes, contributed approximately 0.6% respectively.

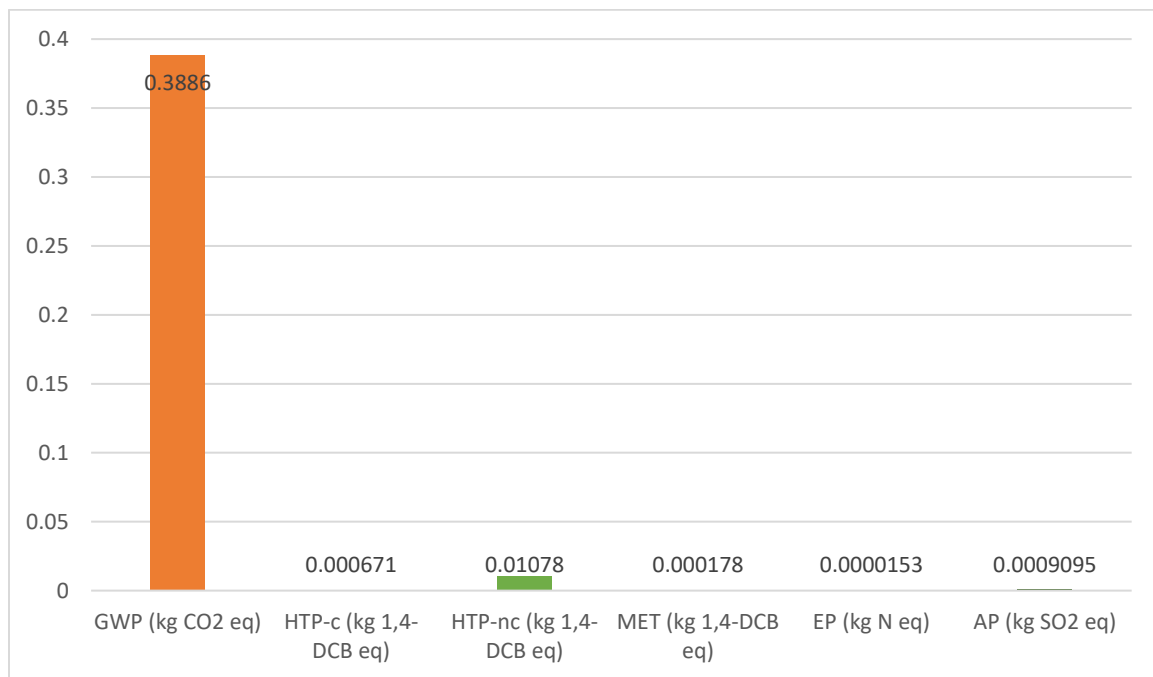
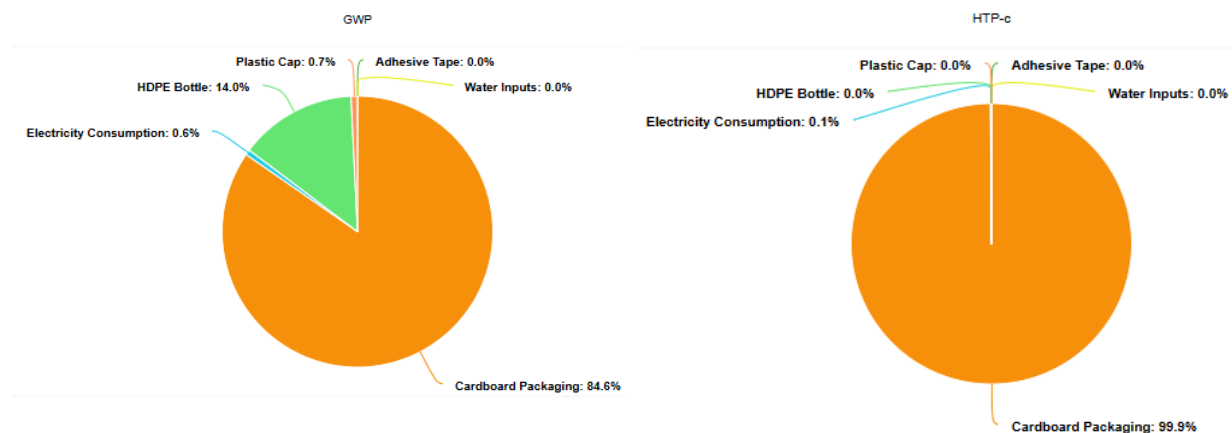
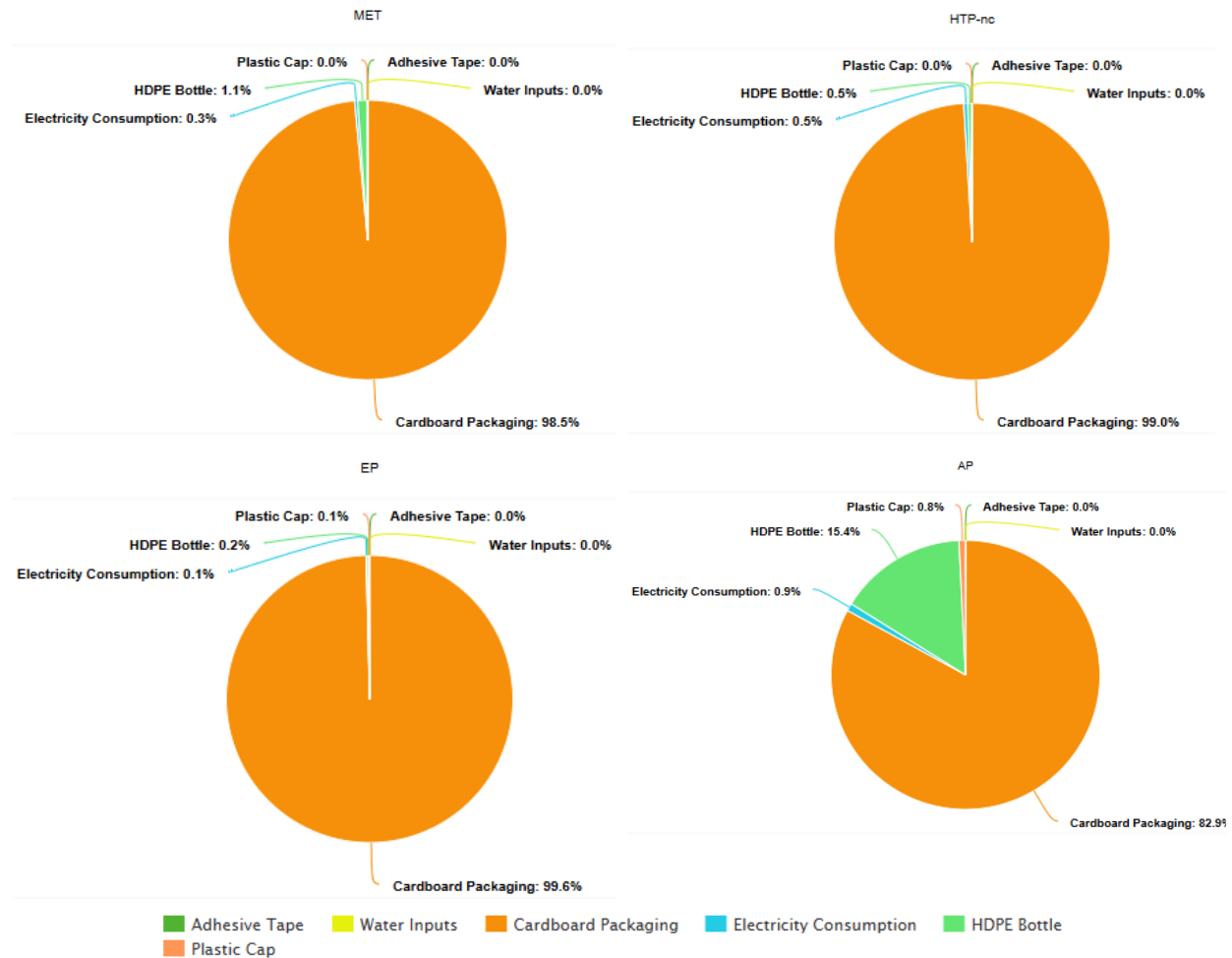


Figure 2. Characterized midpoint environmental impact results per 1 kg of laundry detergent produced.

This reflects the low carbon intensity of the electricity consumption during the manufacturing phase in comparison with the other factors. However, since the Finnish grid emission factor is 0.021 kg CO<sub>2</sub> per kWh (“Real-time CO<sub>2</sub> emissions estimate - Fingrid”, n.d.), which is much lower than the Jordanian emission factor, equivalent to 0.5425 kg CO<sub>2</sub> per kWh (Ministry of Environment in Jordan and UNFCCC, 2021), the actual value is realistically higher than the calculated value.





Figures 3-8. Contributions of material and energy processes to Global Warming Potential, Human Toxicity Potential, Marine Toxicity, Eutrophication Potential, and Acidification Potential.

The two Human Toxicity Potential categories reported are the non-carcinogenic, with a score of  $1.078 \times 10^{-2}$  kg 1,4-DCB eq, and the carcinogenic HTP, as shown in Table 3. The non-carcinogenic HTP has a score that is around sixteen times higher than the carcinogenic category. The carton board material is the highest contributor for both categories, accounting for approximately 99.9% percent in the carcinogenic HTP, while the HDPE bottles contribute to around 0.5 in the non-carcinogenic HTP. These results show the environmental burden of the secondary packaging in the packaging process.

For the Marine Ecotoxicity and Eutrophication Potential, the carton boards are also the biggest contributors, with the HDPE bottle contributing around 1.1% to MET, and the electricity contributing 0.1% to EP. Notably, the water input shows a 0% contribution to almost all of the categories, as shown in Figures 3 to 8.

### 5.2.2 Discussion of findings

The results show the packaging stage of the Liquid Detergent manufacturing process as the highest contributor to all of the environmental impact categories, particularly the use of cartons in secondary packaging, whereas the HDPE bottle represented the second largest contributor in most categories. Additionally, the energy consumption by the mixers and filling machines showed slight contributions in the Global Warming Potential (GWP), Human Toxicity Potential (HTP), and Eutrophication Potential (EP) categories, where the relevant contribution was between 0.2% to 0.6%. This is due to the majority of electricity being supplied by the facility's PV system, which reduced the environmental impacts of the non-renewable energy consumption.

The observations provided by the facility manager mentioned that the packaging stage generated the most waste, which is consistent with the assessment findings. Moreover, despite the results showing a low environmental contribution of energy consumption, the manager noted the mixing process to be the most energy-intensive in the operation. However, the calculated environmental impact may be underestimated due to the use of European datasets, where the characterized electricity emissions are relatively low.

Notably, the water consumption showed 0% contribution to all of the impact categories, despite the significant volumes used for mixing and cleaning, likely due to limited data in the used datasets. Furthermore, even with the wastewater constituting 1% of the monthly consumption, the results showed no calculations of the environmental impact associated with the generated wastewater. This is a major flaw in the assessment, as this wastewater contains chemicals such as phosphates that are discharged into the sewage systems, undoubtedly contributing to eutrophication and toxicity. Other types of waste generated, particularly the packaging material, are returned to suppliers through reverse logistics. In addition, the carton packaging and adhesive tape material used are recyclable, facilitating material recovery and circular economy practices.

### **5.2.3 Comparison with Literature**

Although the scope and datasets used in this study are different from existing literature, the findings are consistent. The reviewed literature identified the packaging and the use phase as the hotspots in the detergent lifecycle, which is similar to the current study. Additionally, existing literature have proposed several solutions that can mitigate the impact of the packaging stage, including circular economy solutions for plastic packaging, in addition to set criteria on that limit packaging material use.

Conversely, differences in the identified hotspots were observed. While the current study identified the packaging stage as the biggest contributor to environmental impact, published literature determined the chemical ingredients, such as surfactants and oils, as the main environmental hotspots. This is due to differences in the identified scopes, as the current scope excludes impact of the detergent formula from calculations. Moreover, the gate-to-gate analysis conducted by this study, in contrast to the cradle-to-grave boundary adopted by previous studies, focused on the environmental impacts associated with the manufacturing, filling, and packaging stages of the detergent lifecycle.

### **5.3 Proposed Improvements**

Several opportunities were recognized for the previously identified hotspots.

First, the quantity of packaging material used must be reduced, including carton material used in secondary packaging, as well as the plastic material used in the primary packaging. Material use can be reduced through strategies such as the optimization of carton dimensions, reducing material thickness, and increasing the recycled content of the primary packaging material. This will significantly decrease environmental impact across all of the assessed categories.

Second, since the manager noted the need for improving energy efficiency during the mixing stage, energy optimization strategies are necessary. This includes replacing current motors in the mixers with high-efficiency alternatives, installing the impellers with a less resistant design, and integrating automated process control to lower the speed when the desired consistency is achieved. Additionally, the integration of SCADA technology facilitates the implementation of predictive maintenance to maintain maximum machine efficiency.

Third, the current waste management approach by the facility, where packaging material is returned to suppliers through reverse logistics, must be maintained. However, the discharge of wastewater into sewage systems, although not environmentally assessed, must be replaced by safer approach. Existing literature has proposed that the use membrane arrangements can potentially reduce the environmental impacts of wastewater by 50% (Muthu, 2015). The membranes recovers most of the leftover detergent in the water, preventing discharge of toxic chemicals, while creating opportunities for reusing the water, which outweighs the additional electricity consumption from the filters. Finally, the implementation of lean manufacturing principles is beneficial for eliminating process waste and increasing operational efficiency, leading to decreased overall environmental impact of the whole detergent production.

## **6. Conclusion**

### **6.1 Summary of Findings**

This study evaluated the environmental impact of the liquid laundry detergent manufacturing in Jordan. A Life Cycle Assessment (LCA) was conducted in a gate-to-gate scope to evaluate the impact associated with the manufacturing,

filling, and packaging processes. The functional unit used was 1 kg of detergent produced, and the environmental impact was assessed across ReCiPe midpoint categories, including Global Warming Potential (GWP), Human Toxicity Potential (HTP), Marine Ecotoxicity (MET), and Eutrophication Potential (EP).

The results revealed the packaging process as the biggest environmental hotspot, contributing significantly to all the impact categories. Particularly, the carton board used in secondary packaging was the major contributor. Additionally, the HDPE bottle had the second highest contribution, while electricity consumption showed slight contribution in some categories. Finally, the water consumption showed zero contribution to all categories, which was due to the lack of inventory data during the analysis.

Moreover, based on assessment results and observations collected from a local facility, several improvement strategies were proposed. This includes optimizing packaging material consumption, increasing recycleable content in the HDPE bottles, improving energy efficiency in the mixing process through updating machinery and implementing predictive maintenance, and lastly, installing arrangement membranes for the treatment of wastewater.

## **6.2 Limitations**

Several limitations need to be considered when interpreting the assessment results. This includes the small scope of the study, which excludes raw material extraction and processing, transportation, product use, and end-of-life stage. Additionally, the inventory data used was limited, therefore assumptions based on literature values were used, which reduces the certainty of the calculated scores. Moreover, the used datasets are based on European values, leading to values that may not represent local operating conditions in Jordan. Specifically, the resulted electricity impact values seem to be underestimated, and are likely significantly higher using Jordanian values. Finally, due to limited time, primary data was collected from a single facility, and may vary across other detergent manufacturing facilities in Jordan.

## **6.3 Future Studies**

Future studies should expand the assessment scope to include upstream and downstream processes. Additionally, the studies must use inventory data that is relevant to Jordanian manufacturing, as well as the local electricity generation data, which will improve data accuracy and certainty. Furthermore, a sensitivity analysis on the proposed optimization strategies may be done to determine their effectiveness in supporting sustainable manufacturing.

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