



Eco-efficiency assessment of liquid dishwashing detergents

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Abstract

Cleaning products changed the relation between humans and the environment. Its production and market demand are increasing annually in the world which increases these products' assessment relevance. Its inappropriate use impacts, negatively, in the environment and human health problems. The Eco-efficiency assessment is a tool to identify the life cycle hotspots and to propose technically feasible improvements. This study was done based in the NBR ISO 14045:2014 for three detergents produced in Teresina-Piauí-Brazil, namely products A, B and C. Primary and secondary data regarding inputs, outputs and selling prices were collected from three different manufacturers, the Ecoinvent database and patents. The selling price was the product system value indicator. The results were related in an Eco-efficiency matrix. The assessed products had high environmental impacts in the categories of acidification, eutrophication, scarcity of fossil and mineral resources and water use. The use stage had the greatest impacts within the referred categories due to water consumption and wastewater treatment. For the product system value, detergents A and C had a lower selling prices than product B. All detergents had high environmental impacts, then the product system value was decisive for them to occupy the matrix quadrants' three or four. Detergent C was the best choice among the three products due to its lower environmental impacts in the selected categories and selling price. Through the sensitivity analysis, it was proposed environmentally viable changes in the product's critical points, as changes in the product formula, for manufacturers, and water consumption reduction equipment, for users.

Keywords Cleaning products · Environmental impact · Household cleansers · Life cycle assessment · NBR ISO 14045 · Sustainability

Introduction

The use of cleaning products has promoted important changes in the relation between humans and the environment around them. Additionally, factors, such as industrialization, population growth and the increase in the life quality, have influenced these changes. Therefore, there were an increase in the demand of such products, which, consequently, led

to the emergence of regulations in this sector (Sakač et al. 2021). In Brazil, for example, the market for liquid dishwashing detergents moved, in 2021, more than three million Brazilian Reals (BRL). It is an increase of approximately 40% in the national production per liters and in the industry performance value in BRL by this product between 2020 and 2021 (Associação Brasileira das Indústrias de Produtos de Higiene, Limpeza e Saneantes de Uso Doméstico e de Uso Profissional—ABIPLA 2022).

The main characteristic of detergents is the presence of surfactants in their formula, which creates the detergency phenomenon. These represent long-chain heterogeneous molecules containing a hydrophilic part and a hydrophobic one (Bajpai and Tyagi 2007). This is crucial in the cleaning process as it reduces the water tension by generating an amphipathic system. It connects the fats of the dirt (lipophilic part) to the water (hydrophilic part) (Sakač et al. 2021). There are four types of surfactants (anionic, cationic, nonionic, and amphoteric), that vary according to their electric charge and have different abilities to remove dirt. For

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this reason, a combination of surfactants is usually used in products formulation to meet different purposes (Bajpai and Tyagi 2007).

In this context, cleaning product manufacturers should consider developing dishwashing detergents that are more environmentally sustainable. This stems from the negative impacts on the environment related to detergents, such as bioaccumulation and biodegradation (Giagnorio et al. 2017). In addition, phosphorus enrichment is one of the most worrying impacts, as it generates the eutrophication of rivers and lakes and is recurrent worldwide (Chen et al. 2022).

Thus, environmental management tools, such as the Eco-efficiency, are appropriate for identifying the negative environmental and economic impacts of detergents. This also support the searching for feasible improvements. The demand for environmental studies in detergents stems from pressing issues, such as climate change, the environmental footprint of products, and pressures from social, regulatory, and commercial interests. Managing the interests of different stakeholders develops a leadership movement of companies towards sustainable development (American Cleaning Institute—ACI 2019).

Some studies have been assessing the environmental performance of detergents at different stages of their life cycle, through the Life Cycle Assessment tool. There are studies about the raw materials, mainly surfactants (Thannimalay and Yusoff 2014; Schowanek et al. 2018), the detergent's production process (Giagnorio et al. 2017), the packaging (Kim and Park 2020), the distribution (Nessi et al. 2014) and the use by consumer stage (Paloviita and Järvi 2018). These can underpin initiatives for Eco-efficiency assessment, communication of environmental indicators (Environmental Labeling), manufacturers' commitment to sustainability, and life cycle management improvements (Schowanek et al. 2018).

In turn, the Eco-efficiency is among the principles of the industrial ecology, that stimulates the sustainable development. This is done through the relation of the environmental and the economic pillars of sustainable development (Qalase and Harding 2022). An Eco-efficiency study results are reliable information for the decision-making process of industries, the government and the consumers. Industries can use it to promote product changes, the government to institute regulations aligned to the current environmental challenges, and the consumers to be aware of their environmental footprint.

This research assessed three different liquid dishwashing detergents that are produced in Teresina, Piauí, Brazil, in the first semester of 2022. It is noteworthy that the representativeness, temporal, geographic and technological coverage of the data was comprehensive and adequate to the research scope. Its goal was to identify the life cycle stage with the greatest environmental impacts and most critical

sub-processes of the product system. In addition, it was possible to propose technically feasible improvements, based on the sensitivity analysis. The relevance of this work lies in the lack of Eco-efficiency and environmental assessment studies of locally produced detergents. It also uses this tool to indicate possible feasible product improvements.

Materials and methods

The Eco-efficiency assessment was carried out using the NBR ISO 14045:2014 standard, which establishes the principles, requirements and guidelines for this type of assessment. This study followed the five steps defined by the standard, namely goal and scope definition, environmental assessment, product system value assessment, Eco-efficiency quantification and interpretation (Associação Brasileira de Normas Técnicas—ABNT 2015).

We searched for cleaning products producers registered in the Federal Revenue of Brazil database, using as a criterion the National Classification of Economic Activities (CNAE)¹ of manufacturing synthetic soaps and detergents (2061-4/00) and manufacture of cleaning and polishing products (2062-2/000). The manufacturers with companies located in Teresina were identified. Then, the goal and scope definition stage was carried out in order to define the basic parameters for the assessment development. At this stage, the Eco-efficiency standard allows the authors to define their product system, which for this study the liquid detergents were chosen. They are from three different brands/manufacturers and have the same function, but their composition, production, and transport are different between them. This supported the comparability between the three products.

Primary data were collected, during the first semester of 2022, from three cleaning product manufacturers, in order to develop the Life Cycle Inventory and set the Product System Value indicator. These will support the second and third stages of the Ecoefficiency that are the environmental assessment and the product system value assessment. The local reality as well the geographical and technological coverage of the Brazilian market were represented in the collected data, in which, in the visited companies' production process, they were collected through direct observation and a checklist. The checklist covered data about the company's profile (like size, activities, number of employees and the served market), the production process (resources, emissions, production stages and transport) and economic aspects (production costs per product and selling price).

¹ Website: <https://concla.ibge.gov.br/busca-online-cnae.html?view=atividades>.

The visited companies and their respective products were named A, B and C in this research to protect their images. Company A produces household cleaning products and fragrances, and companies B and C produce household cleaning products and automotive cleaners. All of them are micro-enterprises, considering the number of employees classification, by the Brazilian Micro and Small Business Support Service (Sebrae and Dieese 2020), and their size, based in information from the register of the Federal Revenue Service. Most cleaning products manufacturers are considered micro-enterprises in the Brazilian scenario, being 84.37% of the registered companies according to ABIPLA (2022). This fact also characterizes the local scenario for cleaning products production.

Secondary data were collected from patents, labels and industry documents. To define the product A formula, as it was not provided by its company, the product label and the patents from Batchelor and Bird et al. (2018) and Pambou (2019) were used. Besides that, the modeling of the preservative Isothiazolinone was performed through the patent of Jin et al. (2013), as this substance was not available in the Ecoinvent database.

As the manufacturers did not provide information about their suppliers, to estimate the distance between the suppliers' location and Teresina, Piauí, it was consulted the Brazilian Chemicals database in the Brazilian Chemical Industry Association (ABIQUIM) website. Through the ABIQUIM website, the name, the headquarters city and the production plant location for each chemical used in detergents were identified. The distance between the suppliers' cities and Teresina was got on Google Maps and, then, a simple mean was calculated.

After the data collection, the environmental assessment was developed. Then, the Life Cycle Impact Assessment (LCIA) aimed to understand and assess the magnitude and significance of potential environmental impacts of a product system throughout the product's life cycle" (ABNT 2014). For this, the OpenLCA software version 1.11 and the Ecoinvent database version 3.7.1 were used to model the data about the defined product system in the chosen impact categories. The product system value assessment is the next stage of an Eco-efficiency study. For this, it is necessary to define the product system value. It represents the value or desirability attributed to the product system by different stakeholders. Its indicator is expressed in terms of functional or monetary aspects, among others (ABNT 2015). In this study, detergent's sale price was the product system value and it was collected during the visits. In order to improve the sales price data representativeness, a simple mean of the prices was taken. It considered the first half of 2022 and the correction was based on the Extended Consumer Price Index, available on the website of the Brazilian Institute of Geography and Statistics.² This index measures the price

variation of a basket of products and services consumed by the Brazilian population. This is a reference for the government inflation targets and to the Central Bank of Brazil decide the changes in the interest rate (Instituto Brasileiro de Geografia e Estatística—IBGE 2022).

Next, according to the NBR ISO 14045:2014, the Eco-efficiency quantification is determined through the relationship between the results of the environmental impact categories indicators (vertical axis) and the product system value indicators (horizontal axis), according to the goal and scope definition (ABNT 2015). For this, the normalized environmental and the product system value indicators were related in an Eco-efficiency matrix. In the interpretation stage, for studies with comparability between products, the Ecoefficiency standard NBR ISO 14045:2014 determines that sensitivity and uncertainty analysis must be performed. Sensitivity analysis is a procedure to understand how changes in input data and methodological choices affect the assessment results (ABNT 2015). Thus, the results indicate the hotspots on the product system, which enables the proposition of new scenarios.

The uncertainty analysis is a procedure to understand how uncertainties in the input data and the assumptions affect the reliability of the assessment results (ABNT 2015). This analysis is necessary to evaluate the input data quality as they have intrinsic uncertainties. For this, the Pedigree Matrix and the Monte Carlo Simulation, available in the OpenLCA software, were used. Input data were assessed for reliability, completeness and temporal, geographic and technological coverage on a Likert scale through the Pedigree Matrix. These data were used as input for the Monte Carlo simulation.

Results and discussion

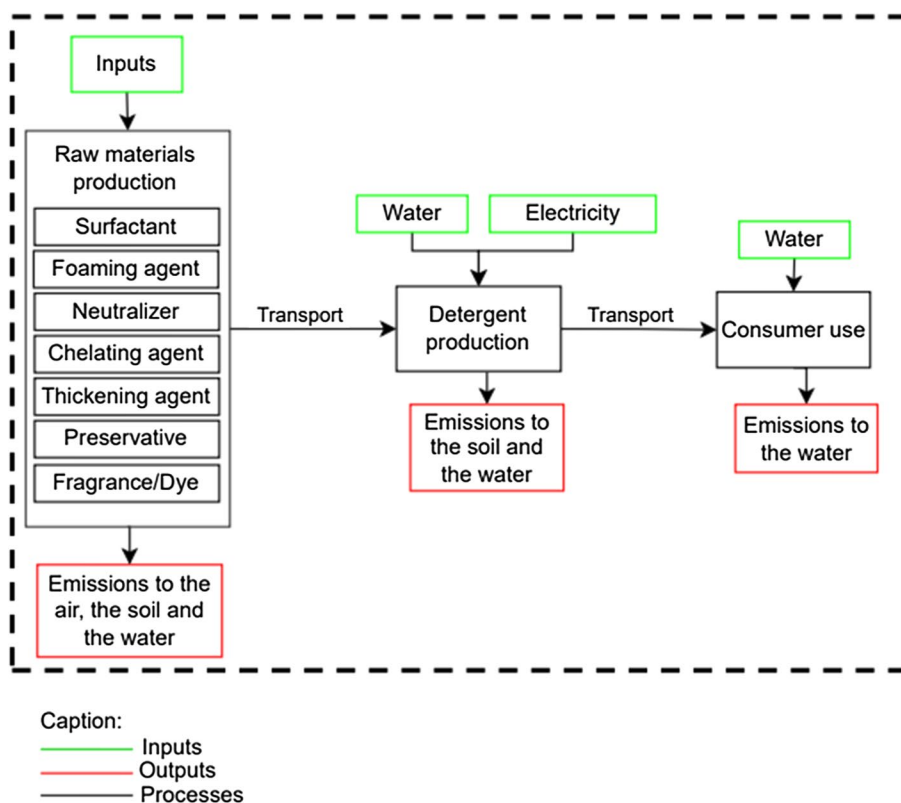
Goal and scope definition

The environmental and the economic performance of dishwashing detergents produced in Teresina were assessed in this study. Its target audience were the local and national cleaning products producers, the academic community interested in environmental assessment of products and detergent's consumers. The Eco-efficiency profile indicator were compared between the three detergents from different manufacturers, as a way to indicate the one with the best and worst Eco-efficiency. Besides that, technically feasible improvements in the products were proposed based in the sensitivity analysis.

² IBGE website: <https://www.ibge.gov.br/explica/inflacao.php>.



Fig. 1 Product system boundaries. *Source* Authors



This work product system encompassed all the elementary processes of life cycle of the liquid dishwashing detergents. It considered detergents that are unpackaged, for household use and for manual dishwashing of porcelain, glass, metal and plastic. The system boundary was from cradle to the consumer use stage, and was divided into five stages: raw materials production, transportation to Teresina-PI, detergent production, distribution, and consumer use. The production scale of the three assessed detergents is industrial. Figure 1 shows the system boundaries.

The inputs for the manufacture of each raw material are a variety of substances, that are purchased by the detergent producer companies. For example, the sulfuric acid, the benzene, the sulfur and the methanol are one of these substances got from non-renewable resources, such as oil and natural gas. They are used in the production of the surfactant (Penteadó et al. 2006), the foaming agent (Sociedade Brasileira de Química—SBQ 2022), the preservative (Jin et al. 2013) and the chelating agent (formaldehyde) (Sinex 2004) of the visited companies.

The Sodium Chloride, extracted from seawater, is part of the neutralizer (Dias 2022), and the coconut oil is the main component of the thickening agent (Peçe et al. 2016). These processes together cause gaseous emissions, liquid effluents and solid waste. These production processes cause emissions to the air, the soil and the water and they occur in different Brazilian industrial parks (São Paulo-SP, Rio de Janeiro-RJ

and Jaboatão dos Guararapes-PE). The range of these emissions goes beyond Brazil, as the country imports some of the referred substances.

The visited companies purchase the raw materials for the detergent production, which are transported from other Brazilian cities to Teresina. The water and the electricity are got from the municipal supply systems and the water from company A is got from underground sources (well). Then, the stages of detergent production, distribution, and consumer use take place in Teresina. As outputs of the production process, the companies emit effluents, from the losses during the processes, and waste, from the raw materials packaging and the labels, beyond the detergent itself. After the detergent production, there is a packaging and a labeling stage. These processes were not considered in the scope of this research, as they have potential for a specific assessment.

The distribution stage includes two detergent transport phases. The first is the transportation from the manufacturing site to the retailer, which is done by the company. The retailers are factor stores. The second phase is the transportation from the retailer to the place of use (houses or institutions), that is done by the consumer. During the use stage, the consumer dissolves the detergent in water (according to the product use instructions), applies it to the dishes (with the help of a sponge or a steel wool), and rinses the dishes to remove the dirtiness and the product. The generated liquid effluents are discharged into the municipal sewage system. It



is noteworthy that objects like sponges and steel wool were excluded of this study scope.

The assessed detergent's function is to clean dishes (plates, spoons, bowls and pans) through the phenomenon of detergency. The product is applied to the dishes generating the solubilization of the fat molecules (from contact with food) in water, and then rinsed. The functional unit represents 200 washes of four porcelain dinner plates and four stainless steel cutleries (fork and knife) with the same degree of dirt.

The reference flow is 1.2 L for product A, 1.30 L for product B and 1.33 L for product C, to meet the defined function. The consumption of product A is lower than product B and C due to its higher viscosity. This is reached with a higher proportion of thickening agent and lower proportion of water in its formula. In turn, detergents B and C have a subtle difference in the reference flow, which is from their similar formula and their different dosages.

Detergents A, B and C share the same product system (unpacked liquid dishwashing detergents life cycle processes) assessed in this work. Despite being similar, it respects the processes specificities for each product. In addition, all products perform the same dish cleaning function for the number of washes defined in the functional unit. However, the amount of detergent used (reference flow) to wash a certain number of dishes (functional unit) changes according to the product, in order to guarantee the same washing efficiency.

The Report on Recommendations for Impact Assessment Models for the Brazilian Context, from the Life Cycle Impact Assessment Research Network (RAICV), was consulted to select the impact categories. This document indicates the most relevant categories for environmental assessment of products, processes and services studies in the country (Ugaya et al. 2019). The categories of terrestrial acidification, freshwater eutrophication, abiotic resources depletion (fossil and mineral) and water scarcity were selected for this study based on that document.

Thereby, the LCIA methods were selected, namely ReCiPe 2016 Midpoint (Hierarchist), CML (baseline) and Available Water Remaining (AWARE). These methods cover the chosen categories and are recommended for Brazilian studies by the RAICV report. In addition, choosing more than one method is necessary due to the lack of a single method for the Brazilian conditions, which supports more reliable results (Piekarski et al. 2012).

The ReCiPe 2016 Midpoint (H) choice took into consideration the availability of characterization factors for a global scale. This method is also common in Life Cycle Assessment studies of detergents (papers from Van Lieshout et al. (2015), Kapur et al. (2012) and Golsteijn et al. (2015)), as shown in Table 1. It has Midpoint and Endpoint perspectives, in which impacts can be seen connected to the causes

or the consequences (Cavalett et al. 2013). Ugaya et al. (2019) recommend the terrestrial acidification category of the ReCiPe method for studies in the Brazilian context.

The CML (baseline) method was selected based on its global coverage (Mendes et al. 2015), the availability of eleven midpoint categories (mandatory and optional types, which allows comparability with other methods) (Piekarski et al. 2012) and for having specific characterization factors previously quantified for each impact category (Hauschild et al. 2010). The acidification and eutrophication impact categories of CML were chosen, because they are similar (with caveats) to those of the ReCiPe method, recommended for Brazilian studies (Ugaya et al. 2019). Furthermore, studies by Akizu-gardoki et al. (2022), Saouter and Hoof (2022), Dewaele et al. (2004) and Van Hoof et al. (2003) used this method for the environmental assessment of cleaning products, as detailed in Table 1.

It is noteworthy that the ReCiPe 2016 and the CML (baseline) methods are also recommended by Mendes et al. (2015) and Piekarski et al. (2012) for LCA studies in the Brazilian context. These authors evaluated different LCIA methodologies and identified the most appropriate methods for Brazil. They considered the methods scope and availability of characterization factors.

The AWARE method was chosen in this study because it addresses a third impact category (water scarcity) recommended for the Brazilian context. This method has a midpoint category, that considers the ecosystems water needs. It is also the recommendation of the Society of Environmental Toxicology and Chemistry for an LCIA indicator in the water scarcity category (Ugaya et al. 2019). AWARE has a database with different characterization factors for different locations and ecosystems (Kiss et al. 2018).

The product system value assessment was done through a monetary method. It is expressed as the price (in national currency) paid by consumers when purchasing the detergents. This price is presented in Brazilian real per liter of the product. Manufacturers and consumers are the most affected stakeholders in this choice of product system value.

Environmental assessment

The Eco-efficiency assessment second step is the environmental assessment, that follows the NBR ISO 14040:2014 and ABNT NBR ISO 14044:2014 standards, for the Life Cycle Inventory and its assessment. Thus, all inputs and outputs of each life cycle stage of the detergents are described and, in sequence, assessed for the selected impact categories. Table 2 shows detergent A formula (concentrated format). This is according to what was collected during the visits, obtained from the patents and, later, retrieved from the Ecoinvent database.

Table 1 Scientific papers that use the ReCiPe and CML methods

Paper title	Products	Data collected	Local
Leveraging Life Cycle Assessment to Evaluate Environmental Impacts of Green Cleaning Products	All-purpose cleaner, dishwashing liquid detergent, hand soap detergent (Method) and dishwashing liquid detergent (Ecover)	Primary data provided by the companies participating in the study (Method and Ecover)	USA
Comparative life cycle assessment of conventional and Green Seal-compliant industrial and institutional cleaning products	All-purpose cleaner and bathroom and window cleaner, both Green Seal certified and conventional (non-certified)	There was no primary data collection. Secondary data were obtained from research developed by Green Seal and from the literature	USA
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	Manual dishwashing detergent, compact detergent (powder/tablets), glass window spray, bathroom spray, acid bathroom cleaner and toilet bowl cleaner	Primary data obtained from A.I.S.E. (Henkel, Procter & Gamble and Unilever) and Eurostat	Europe
Ecodesign coupled with Life Cycle Assessment to reduce the environmental impacts of an industrial enzymatic cleaner	Enzymatic all-purpose cleaner	Primary data from A&B <i>Laboratorios de Biotecnología S.A.U</i>	Spain
A Database for the Life-Cycle Assessment of Procter & Gamble Laundry Detergents	Liquid and powder detergent for washing clothes	Data collected from secondary sources in the literature, companies, industry associations and the P&G database	Europe/Belgium
Comparative life cycle assessment study 3 cleaning products for kitchen surfaces	Kitchen surfaces cleaner in liquid, spray and wipe formats	Primary data from participating companies (P&G and Ecobilan)	France
Comparative Life-Cycle Assessment of Laundry Detergent Formulations in the UK	Ready-to-use and concentrated format of liquid, powder and tablet detergent for washing clothes	Secondary data from the literature and databases Data collected from secondary sources in the literature, industry associations, official country data, and the P&G database	Europe

Adapted from Van Lieshout et al. (2015), Kapur et al. (2012), Golsteijn et al. (2015), Akizu-gardoki et al. (2022), Saouter and Hoof (2022), Dewaele et al. (2004) and Van Hoof et al. (2003), respectively



Table 2 Detergent A formula

Component	Role in the formula	Proportion (%)
Alkylbenzene sulfonate, linear, petrochemical ^a	Surfactant	18–23
Sodium hydroxide, without water, in 50% solution state*	Neutralizer	5–10
Fatty alcohol sulfate ^b	Foaming agent	5–10
Cocamide diethanolamine	Thickening agent	10–15
EDTA, ethylenediaminetetraacetic acid**	Chelating agent	10–15
Isothiazolinone	Preservative	1–2
Chemical, organic ^c	Fragrance/Dye	1–2
Water, well, BR	Solvent	45–55

Source Authors, Batchelor and Bird et al. (2018)* and Pambou (2019)**

^aLinear Alkylbenzene Sulfonate (LAS)

^bSodium Lauryl Sulphate (SLS)

^cWater-soluble essence and dye

The Chelating agent, Ethylenediamine Tetra-Acetic Acid (EDTA), stands out in the formula of product A. Its use indicates that the water consumed in the production process is classified as hard (high mineral content). Thus, it probably comes from an underground source (well). The EDTA role in the formula is to complex the ions responsible for the hardness of the water and, then, not to impair other components action.

Among the detergent A raw materials that were retrieved in the Ecoinvent database, only the preservative (Isothiazolinone) and the fragrance/dye were not available. For the first one, the inputs and outputs of the Isothiazolinone production process was based in the patent of Jin et al. (2013). It is noteworthy that data on emissions and electricity consumption were not considered. The preservative inputs are Methyl acrylate (5–15%), Hydrogen sulfide(0–5%), Sulfur (0–5%), Sodium sulfite (10–20%), Methylamine (0–5%), Chlorine-gaseous (5–15%) and Water (50–60%) and the outputs are Sodium sulfide (40–50%), Methanol (5–15%), Hydrochloric acid, without water, in 30% solution state (5–15%) and Isothiazolinone (25–35%) (Jin et al. 2013).

The referred modeling of the preservative was used for all detergents in this study, which have this substance in the formula. For the fragrance/dye, an equivalent product comprising the broader chemical group was used. Table 3 shows detergent B formula (ready-to-use format), as collected in the researched companies and retrieved from the Ecoinvent database.

In turn, detergent B does not have a chelating agent in its formula, since it uses potable water in its production process. This water is got from the municipal water supply network. All components of detergent B were recovered in the Ecoinvent database, except the fragrance/dye. This was recovered using the same equivalent process as detergent A. Detergent C formula (concentrated format) is shown in Table 4, as collected in the researched companies and retrieved from the Ecoinvent database.

Table 3 Detergent B formula

Component	Role in the formula	Proportion (%)
Alkylbenzene sulfonate, linear, petrochemical ^a	Surfactant	2–6
Sodium hydroxide, without water, in 50% solution state	Neutralizer	1–3
Fatty alcohol sulfate ^b	Foaming agent	1–2
Cocamide diethanolamine	Thickening agent	1–2
Isothiazolinone	Preservative	1–2
Chemical, organic ^c	Fragrance/Dye	1–2
Tap water	Solvent	90–95

Source Authors

^aLAS

^bSLS

^cWater-soluble essence and dye

Table 4 Detergent C formula

Component	Role in the formula	Proportion (%)
Alkylbenzene sulfonate, linear, petrochemical ^a	Surfactant	40–45
Sodium hydroxide, without water, in 50% solution state	Neutralizer	20–25
Fatty alcohol sulfate ^b	Foaming agent	10–15
Cocamide diethanolamine	Thickening agent	1–5
Isothiazolinone	Preservative	1–2
Chemical, organic ^c	Fragrance/Dye	1–2
Tap water	Solvent	20–25

Source Authors

^aLAS

^bSLS

^cWater-soluble essence and dye



Table 5 Scope of processes recovered in Ecoinvent

Input	Process found in the Ecoinvent	Description
Surfactant	Alkylbenzene sulfonate, linear, petrochemical (from benzene and paraffins)	It included the infrastructure of the production plant, the electricity consumption and the emissions to the air and the soil. Furthermore, it excluded water consumption
Foaming agent	Fatty alcohol sulfate	It included the materials and the electricity inputs, transport, industry infrastructure and emissions into the soil, the air and the water. This process excluded the water consumption
Thickening agent	Cocamide diethanolamine	It covered electricity consumption, the production plant infrastructure and the generated emissions
Chelating agent	EDTA, ethylenediaminetetraacetic acid	It included the inputs and the materials consumed in the production process, as well as emissions to the air and the water, electricity demand and manufacturing plant infrastructure. Emissions to soil were excluded
Neutralizer	Sodium hydroxide	It included all the raw materials needed for chlor-alkali electrolysis. This, also, covered the production, purification and resaturation of brine and the final handling of chlorine and sodium hydroxide
Solvent	Tap water	The dataset included the distribution network and losses during transmission. This excluded electricity consumption for pumping in the distribution network and possible emissions to groundwater
Transport between the suppliers' production plant and Teresina-PI	Transport, freight, lorry 16–32 metric ton, EURO4	It includes the construction, operation, maintenance and end of life of vehicle and road infrastructures, as well as fuel consumption and emissions
Transport between the production and the consumption	Transport, freight, light commercial vehicle	It included inputs (as electricity and fuel consumption), emissions (including those arising from combustion) and environmental interventions due to the construction and maintenance of roads and vehicles
Domestic sewage treatment process	Wastewater, from residence	It included infrastructure materials for municipal wastewater treatment plant, transport and land use loads

Adapted from Ecoinvent (2022)

The chemicals that compose the detergents A, B and C had their production processes retrieved from the Ecoinvent database. These processes scope was from cradle to factory gate and represented the Global or European reality, with the preservative exception. Table 5 shows the description of each process recovered in Ecoinvent.

It is noteworthy that only the preservative was not directly recovered in the Ecoinvent database. As it was based on the patent, it included the inputs to the main product and the by-products production, but disregarded data on emissions and electricity consumption.

Figure 2 shows the mean distance between the city where the raw materials are produced and Teresina. It was considered the same suppliers for the three detergents, as this data was an estimate, and the chosen truck type was transport, freight, lorry 16–32 metric ton, EURO4.

Some chemicals applied in the detergent production were not available in the ABIQUIM database, consulted to identify the Brazilian suppliers. In this way, it was necessary

to search for a similar product or for its broader chemical group, whose analogies represented 33% of all raw materials presented in Fig. 2.

Detergent production is carried out in two main stages, one with a chemical reaction (the neutralization) and the other with a mixture of supporting substances. Figure 3 shows the detergents production process steps in the companies visited. It should be noted that in these companies, the entire production process takes place manually. It means that employees mix the raw materials without the aid of machines. Thus, the weighing stage was the only one that consumed energy, due to the use of an electric scale, and its referred consumption was included in the evaluation.

The detergent production starts with the dosage of the raw materials, according to the batch quantity. From this, all chemicals are weighed with a table scale, which consumes, on average of 15 watts of electricity (electricity, low voltage). This consumption depends on time length of this step, which was defined according to the quantity processed.

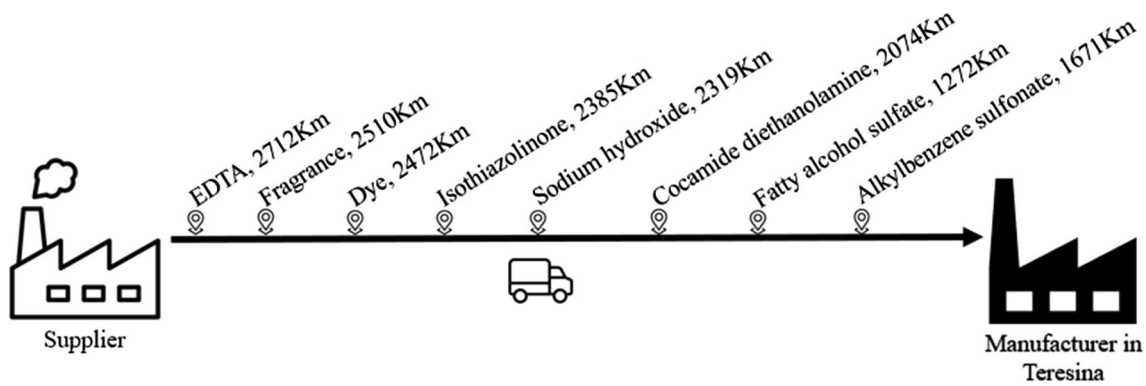


Fig. 2 Mean distance from the suppliers' production plant and Teresina-PI. Source Adapted from ABIQUIM (2023)

The surfactant, which is pasty, is dissolved in water. After that, the neutralizer is added to the mixture. The agitation is performed manually, which causes the acid–base reaction. At this stage, it is important to measure the potential of hydrogen (pH) to make sure the mixture is neutral. It means that the company meets the Brazilian National Health Surveillance Agency requirements and does not pose risks to the consumer.

The sulfonic acid and sodium hydroxide mixture forms the detergent active principle, which promotes the dish cleaning. This is the neutralization reaction, made of the interaction between the anions and cations of the acid (sulfonic acid) and the base (sodium hydroxide) forming water and salt molecules. For the detergent, the cations released by the acid must be equal to that of anions released by the base. This is called a full reaction, when the substances reach the neutral pH (Bahniuk 2014). The neutral pH guarantees the product will not harm users' hands during use.

Company A has an extra process in its production, in which the EDTA will be weighed and added to the mixture. This is added to the mixture at the same time of the other supporting substances. The fragrance and the dye are the last raw materials added in the formula. This is due to the variation according to the customer orders in the product aroma and color. At company A, small lot samples are separated to take quality tests that will support the approval/reproval decision. At company B and C, the batch compliance is done by measuring the pH directly in the mixture. After that, the processes of bottling and labeling are carried out manually.

After the production stage, the detergents are distributed to retailers (owned by the same factory owner) by road transport. In company A, the stores are located in the downtown of Teresina. Then, it was considered that the product is transported an average distance of twenty-six kilometers to the point of sale. This distribution is carried out in an Urban Cargo Vehicle (UCV), that is, a small truck with adequate dimensions for circulation in urban areas without hampering the traffic. The used UCV

model can transport up to three tons of products. Thus, the factory complies with the Teresina City Hall regulations regarding the trucks traffic in the city center during business hours (Prefeitura Municipal de Teresina—PMT 2014).

In company B, the distribution takes place in a vehicle of passenger van model. The detergent is transported to the factory's store, in the southeast area of the city, covering an average distance of seven kilometers. In turn, company C does not distribute its products, since production and sales take place in the same location.

The distance between the retailer and the consumption place (homes and/or institutions) was estimated at ten kilometers, since it was not possible to measure this distance. This is called as transport by consumer. This estimate took into account two main aspects, in which every city neighborhood has markets and supermarkets that sell detergents and consumers do not travel long distances to buy this type of product. The transport is done in a passenger car that was recovered at the Ecoinvent database using an equivalent process (transport, freight, light commercial vehicle).

The detergents use instructions vary according to the manufacturer's recommendations that depends on whether the products are ready-to-use or concentrated. Among the visited companies, only A and C sell concentrated products, while company B products are ready-to-use. The detergent: water ratio for product A is one liter of detergent to four liters of water and for product C is one liter of detergent to nine liters of water.

Dilution in water occurs in the consumer use stage, when the product is concentrated, and in the production stage, when it is ready-to-use, so both products need the solvent. Additional water consumption occurs in the manual dish-washing process due to the rinsing step. This was estimated at 768 L for products A, B and C for the defined functional unit. It was considered that the generated liquid effluents are released into the municipal sewage collection system (wastewater, from residence).

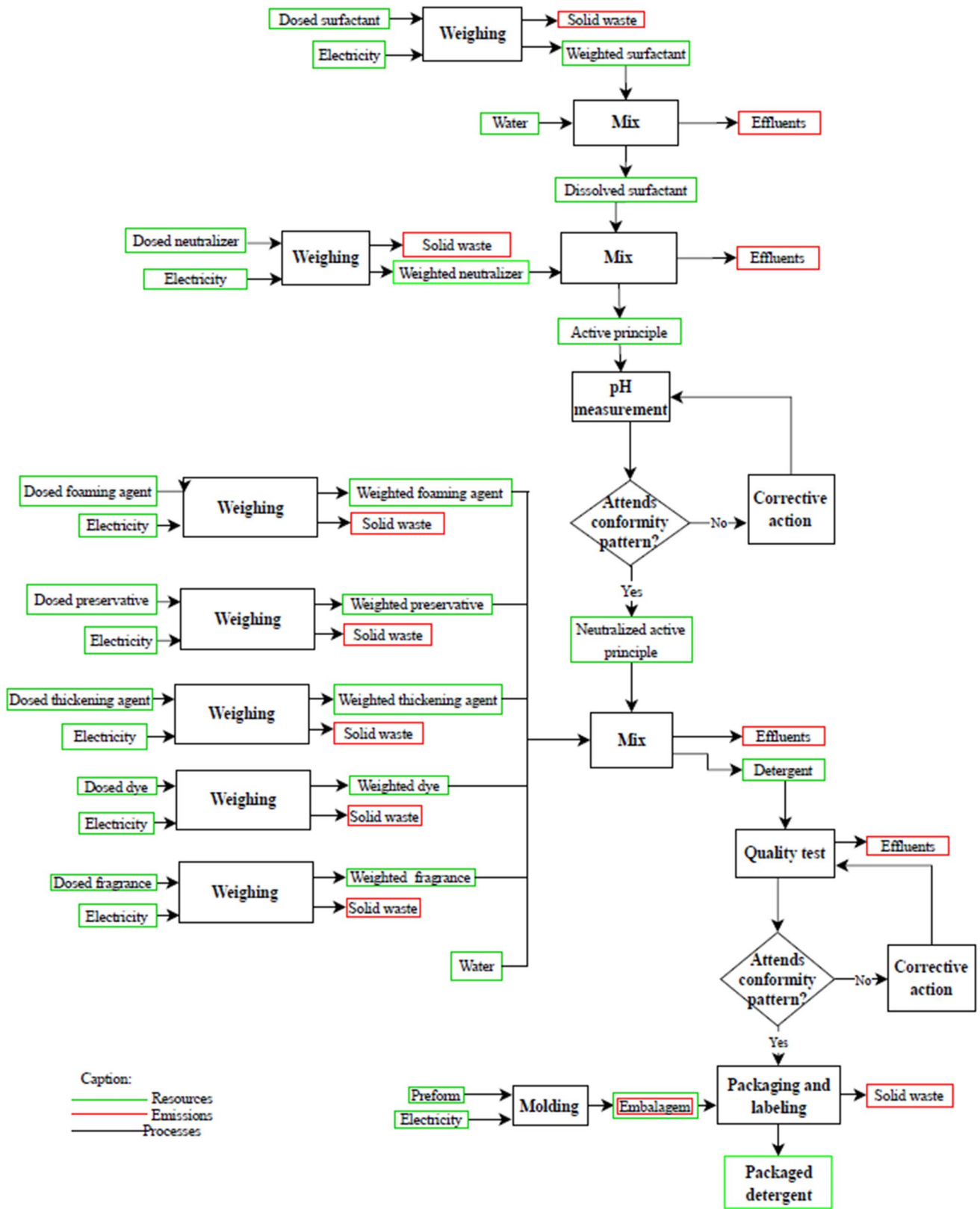


Fig. 3 Detergent production flowchart. Source Authors

Table 6 Detergents environmental profile by functional unit

Method	Impact category	Detergent A	Detergent B	Detergent C	Unity
ReCiPe (H) 2016	Terrestrial acidification	6.95E-03	6.27E-03	6.26E-03	kg SO ₂ eq
	Freshwater eutrophication	1.16E-03	1.11E-03	1.12E-03	Kg P eq
	Fossil resources scarcity	4.20E-01	3.49E-01	3.50E-01	Kg oil eq
	Mineral resources scarcity	1.66E-02	1.61E-02	1.61E-02	Kg Cu eq
CML (baseline)	Acidification	8.23E-03	7.47E-03	7.44E-03	kg SO ₂ eq
	Eutrophication	1.25E-02	1.20E-02	1.20E-02	Kg PO ₄ - eq
	Abiotic depletion (fossil resources)	1.79E+01	1.49E+01	1.50E+01	MJ
	Abiotic depletion (mineral resources)	2.39E-05	2.20E-05	2.17E-05	Kg Sb eq
AWARE	Water use	5.05E+00	4.71E+00	4.75E+00	m ³

Source Authors

With the Inventory data, the detergents life cycle was modeled using the OpenLCA software and the Ecoinvent database. The results are presented in Table 6, detailed by the chosen methods and each selected impact category, for products A, B and C.

Detergent A had the highest indicator in all of the assessed categories in the three LCIA methods. This makes it the least environmentally friendly product. Then, product B occupied the second position, with the greatest impacts in three categories of ReCiPe (Freshwater eutrophication, fossil resources scarcity and mineral resources scarcity), two categories of CML (Eutrophication and abiotic depletion (fossil resources)) and in the water use category of the AWARE method.

Detergent C had the lowest impacts in three categories of ReCiPe (Freshwater eutrophication, fossil resources scarcity and mineral resources scarcity), two of the CML method (Eutrophication and abiotic depletion (fossil resources)) and in the category of water consumption of the AWARE method.

The greatest impacts in all selected categories of the ReCiPe and CML method were caused by the water consumption processes (in the detergent production and the dishes rinsing) and the treatment of domestic sewage. A considerable amount of water is used when washing dishes (plates and cutlery). This is due to the rising to remove the detergent and the dirtiness from the dishes. An output of the rinsing process is the generation of sewage (formed by water, detergent and dirt) that must be treated before returning to the water bodies, according to the Resolution of the National Council for the Environment (CONAMA) n° 430/2011 (Brasil 2011).

The results indicate the use by the consumer stage as the most impactful among the life cycle stages covered in the scope of this research, for the selected categories. This corroborates to Van Lieshout et al. (2015), Golsteijn et al. (2015) and Saouter and Hoof (2022) studies. These authors indicated the use stage as the most impactful for different cleaning products assessed by them. It is noteworthy

that Golsteijn et al. (2015) and Saouter and Hoof (2022) research scope considered the water heating for washing, which is not used by Brazilian consumers.

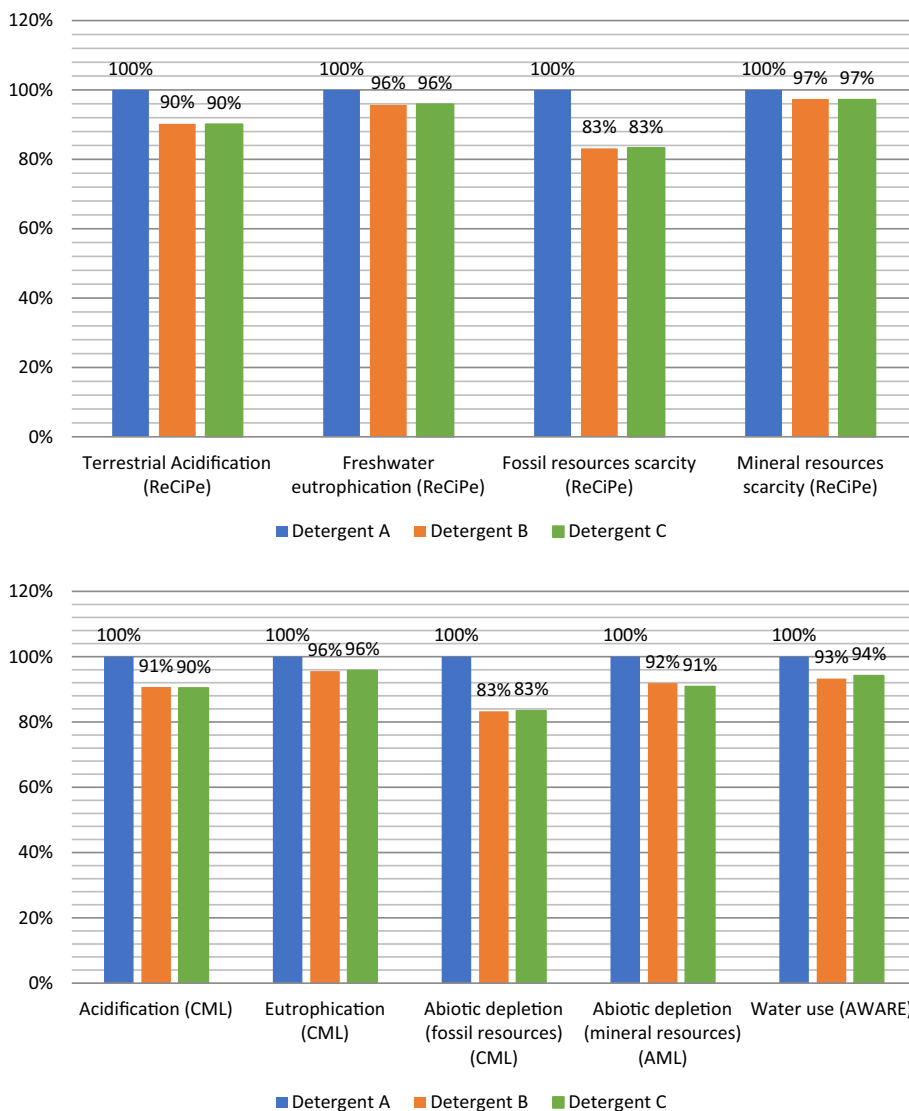
In the work by Van Lieshout et al. (2015), the water consumption caused 48% of the overall life cycle impact of the Method detergent and 42% for the Ecover. For Brazilian products, the water consumption and the domestic sewage treatment generated, between, 50 and 80% of the global impact of the life cycle stages of this research scope.

Golsteijn et al. (2015) identified that electricity (to heat water during manual dishwashing) was the most impactful process in the use stage. This caused 86–98% of product life cycle impacts. Despite the consumption of electricity to heat the water, the authors pointed out the water itself as the most impactful process for the terrestrial acidification (ReCiPe) and freshwater eutrophication (ReCiPe) categories.

In turn, Saouter and Hoof (2022) identified significant impacts in the category of acidification (CML) and eutrophication (CML) for detergents to wash clothes. For acidification, it was caused by the electricity consumption to heat the water in the washing machine in the use stage. For eutrophication (CML), it was from the disposal of chemical products in water bodies, which are not completely removed in sewage treatment plants. In addition to water consumption and domestic sewage treatment, additional data for the most impactful processes for the assessed products are given in Online Resource 1, by selected category.

The normalization was performed with the impact categories indicators for the assessed detergents. This procedure aims to indicate the results magnitude for the category's indicators referred to a reference information. This is considered an optional step for Eco-efficiency and LCA studies. Furthermore, it is useful to provide and communicate to the decision makers the relative importance of the environmental indicator's results (ABNT 2014). The authors admit that this procedure brings uncertainties to the study, such as the influence of outliers (values outside

Fig. 4 Environmental indicators normalization of detergents.
Source Authors



the normal frequency distribution) and the potential for division by zero (generating non-significant values) (Norris 2001).

The normalization calculation in this study was simple and internal. This is simple for dividing each category value indicator by a reference value, and internal because this reference value was chosen directly from the study in question. Thus, for each impact category, it was identified the highest indicator value between the three detergents and then represented in the graph as 100%. Subsequently, the other products with values indicator per category, lower than the reference value, were divided by the reference value to discover the representativeness percentage. Figure 4 shows the detergent’s normalized environmental profile. The normalized data were used in the Eco-efficiency quantification stage. It was used to relate the environmental and the product system value indicators in an Eco-efficiency matrix.

Product system value assessment

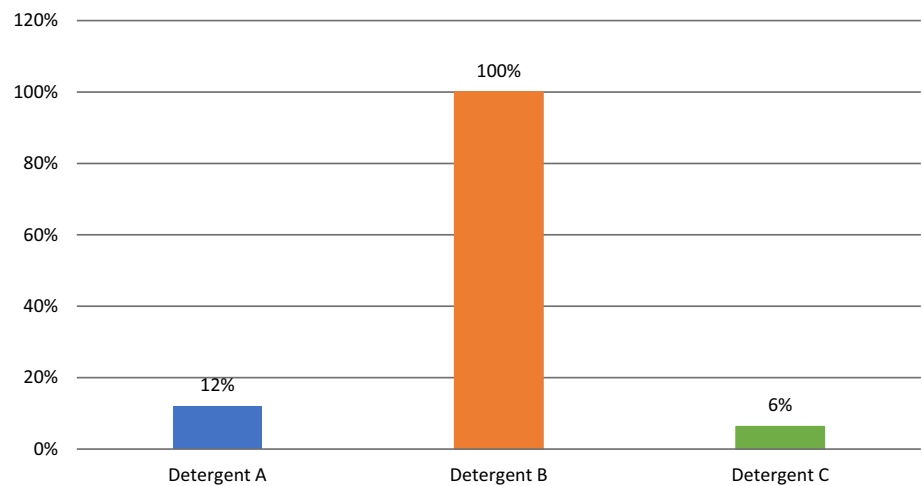
In this study, the detergent’s sale price, in Brazilian real, was chosen as the product system value indicator. This choice considered this indicator importance for producers and

Table 7 Detergents sale price in Brazilian Real per liter

Month	Detergent A	Detergent B	Detergent C
January	0.390	3.00	0.180
February	0.396	3.05	0.183
March	0.402	3.10	0.186
April	0.408	3.13	0.188
May	0.410	3.14	0.189
June	0.412	3.16	0.190
Mean	0.40	3.10	0.19

Source Authors

Fig. 5 Detergents product system value normalization. Source Authors



consumers. It also covered the main costs of the product's regarding this research's boundary system. The mean of the selling prices per liter, during the first semester of 2022, for the assessed detergents is shown in Table 7.

The product system value indicator was calculated for the reference flow of each product, based in the mean of the selling prices. For the assessed detergents, the price paid by the consumer is BRL 0.48, BRL 4.03 and BRL 0.25³ for the product quantities of the reference flow of 1.2 L of product A, 1.3 L of product B and 1.33 L for product C. It should be noted that the referred prices considered products A and C (concentrated format) after dilution, to avoid unfair comparisons with detergent B (ready-to-use format).

Figure 5 shows the normalized results of the product system value assessment. Normalization was necessary to relate the environmental impact categories and the product system value in the Eco-efficiency quantification.

Product B had the highest sales price indicator between the three detergents. This detergent is the only one sold in the ready-to-use format, which has a higher consumption of water in the production stage. In turn, product C had the lowest sales price indicator, due to the lack of transport between the production site and the retailer and its concentrated format. The water consumption in concentrated product is changed from the production stage to the dilution procedure (in the use stage). This reflects in production costs and in the selling prices, since the water tariff per cubic meter for industrial enterprises is, on average, twice the value for the final consumer in 2023, according to the Águas de Teresina concessionaire,⁴ which is responsible for the water collection, treatment and distribution in the city.

³ The commercial dollar exchange rate on May 1st, 2023 was R\$5.314. Thus, the product system value indicator in dollars was \$0.095 for product A, \$0.800 for product B, and \$0.050 for product C.

⁴ Concessionary website: <https://www.aguasdeteresina.com.br/legislacao-e-tarifas/>.

The referred sales prices represent the most important value for users and manufacturers in the context of this research, since they have a direct impact on the company's competitiveness and revenues and are one of the factors in customers' purchase decisions. In addition, changes in the inputs prices affect the final price of the product, especially in the light of higher BRL-dollar rates. Considering that most of the inputs are part of the petroleum production chain (such as surfactants, antibacterials and preservatives), the purchase price is influenced by foreign currency variations of the international market. Therefore, analyzing the sales prices is essential to establish the value of the product's environmental and economic impacts in the Eco-efficiency assessment.

Eco-efficiency quantification

The Eco-efficiency quantification is represented in the matrix shown in Fig. 6. In this matrix there are four quadrants, with the first representing lower environmental and product system value indicators, which is the most Eco-efficient alternative. Quadrant two represents the lowest environmental indicator and the highest product system value indicator, and quadrant three represents the highest environmental indicator and the lowest product system value indicator. In turn, quadrant four represents the least Eco-efficient alternative, with the highest environmental indicator and the product system value.

From the Eco-efficiency quantification, it was possible to identify that all products had significant impacts on the selected environmental categories. The close in the environmental indicator's values of the three detergents may be explained by the water consumption estimate for dishwashing and the similarities in the product's formula. Detergents A and C are ready-to-use and their product system value indicators were close (compared to product B). This may

Fig. 6 Detergents Eco-efficiency profile by impact category. Source Authors

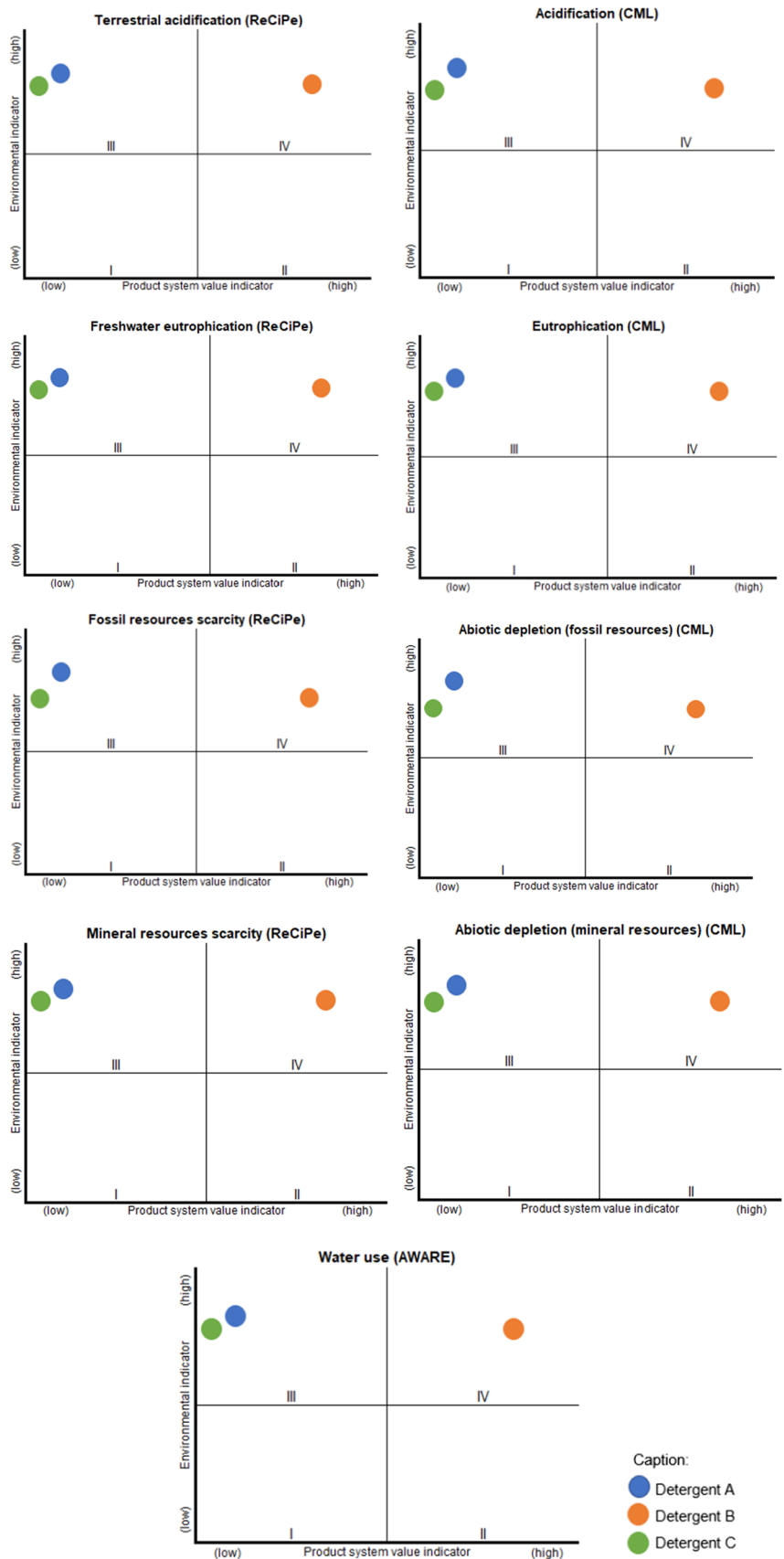


Table 8 Uncertainty analysis results of the detergent's study

Impact category	Detergent A		Detergent B		Detergent C	
	Mean	SD*	Mean	SD*	Mean	SD*
Terrestrial acidification (ReCiPe)	7.04E-03	5.95E-04	6.24E-03	5.77E-04	6.36E-03	6.01E-04
Freshwater eutrophication (ReCiPe)	1.18E-03	1.58E-04	1.12E-03	1.55E-04	1.13E-03	1.58E-04
Fossil resources scarcity (ReCiPe)	4.25E-01	3.14E-02	3.44E-01	2.50E-02	3.55E-01	2.66E-02
Mineral resources scarcity (ReCiPe)	1.68E-02	1.68E-03	1.62E-02	1.70E-03	1.64E-02	1.81E-03
Acidification (CML)	8.36E-03	7.21E-04	7.45E-03	7.11E-04	7.53E-03	7.28E-04
Eutrophication (CML)	1.28E-02	2.03E-03	1.21E-02	1.99E-03	1.21E-02	2.09E-03
Abiotic depletion (fossil resources) (CML)	1.82E+01	1.35E+00	1.47E+01	1.12E+00	1.51E+01	1.14E+00
Abiotic depletion (mineral resources) (CML)	2.42E-05	2.07E-06	2.18E-05	2.12E-06	2.19E-05	2.09E-06
Water use (AWARE)	4.97E+00	7.04E+00	4.20E+00	7.04E+00	3.98E+00	7.05E+00

Source Authors

*Standard deviation

have determined their positioning in quadrant three, of the Eco-efficiency matrix.

Detergent C was the most Eco-efficient product, considering all of the selected categories in this research. Its environmental performance was the lowest for the categories of terrestrial acidification (ReCiPe), acidification (CML), mineral resources scarcity (ReCiPe) and abiotic depletion (mineral resources) (CML). This better performance may be linked to the lack of a transport step between the factory and the retailer, which happens only in product C. It was influenced by the smaller quantity of active substances in its formula than product A and the greater quantity than product B. For the product value system, the lowest selling price of detergent C may be linked to the lack of a distribution stage, its ready-to-use format and its higher dilution factor (higher than detergents A and B).

Detergent B was the least Eco-efficient. Despite this, that product had the lowest environmental impact in the categories of freshwater eutrophication (ReCiPe), eutrophication (CML), fossil resources scarcity (ReCiPe), abiotic depletion (fossil resources) (CML) and water use (AWARE). This result may be associated to its lower quantity of active substances in the formula (approximately 10% less than detergent A). However, its lower Eco-efficiency was influenced by its higher selling price in BRL, resulting in the worst product system value indicator, and its ready-to-use format.

The sale price indicator of detergent A was lower than product B and higher than product C. Despite that, detergent A had the highest environmental impact indicators in all of the selected categories. Due to it, the referred product occupied quadrant three of the Eco-efficiency matrix for all impact categories. This was also a position close to product C. Their significant environmental impact is linked to a greater quantity of active substances in the formula and the presence of the EDTA (whose production had considerable repercussions on the environmental indicators). The

product system value assessment indicated the product A selling price as double of the product C, which may be due to the EDTA purchasing costs, the extraction of water from wells and a lower dilution proportion.

After the Eco-efficiency quantification, an uncertainty analysis was carried out. For this, the NBR ISO 14044:2014 describes a series of checks to test if the conclusions are adequately supported by the input data and the chosen procedures. It is considered that life cycle models have some uncertainty, either regarding the input data variation and the subjective choices, such as the functional unit, the defined scenarios and the allocations (Goedkoop et al. 2016).

The variation in input data can be calculated through statistical techniques, such as the Monte Carlo simulation, available in the OpenLCA software. That technique processes the data and establishes an uncertainty interval in the results. For this, the geometric standard deviation is estimated using the Pedigree matrix with a Lognormal distribution in the Ecoinvent database. Each inventory data is assessed for reliability, completeness, temporal correlation, geographic correlation and additional technological correlation (Goedkoop et al. 2016). In this paper, the simulation was performed with 1000 interaction and a 95% confidence interval. The mean and the standard deviation of the input data are the results of the uncertainty analysis, shown in Table 8.

Among all the selected categories in the ReCiPe and CML methods, the greatest uncertainty was in the abiotic depletion (fossil resources) (CML) category for the three products. For the ReCiPe method, the greatest uncertainty was in the fossil resources scarcity category. This greater uncertainty in that category may be due to the differences in their calculations. It was represented by different units of measurement (it is heating power in kilograms of oil equivalent for ReCiPe and the necessary energy to extract the resources in Mega joules for CML) and their global



scope (Mendes et al. 2015). The categories of acidification, eutrophication and fossil resources scarcity in the ReCiPe method had greater uncertainties than these same categories in the CML method. This can be linked to the ReCiPe method global scope, while CML has a regional scope.

Detergent A had the highest uncertainty in all categories of the three methods used in this research. This was caused by this product greater number of estimated input data (since company A did not give the product formula during the visits). In turn, the uncertainty values between detergents B and C were close. For all chosen impact categories of the ReCiPe and CML methods, detergent B uncertainties were greater than product C. For the water use category, in the AWARE method, the uncertainty was high for all of the three detergents, since the main input data (amount of water used to rinse the dishes) was estimated.

For product A, the surfactant, neutralizer, foaming agent, thickening agent and chelating agent reflected, in terms of reliability and completeness, in the Pedigree matrix. These data were estimated based on labels, patents and consultation with a chemist of the sector that may have contributed to the referred uncertainty. For detergents B and C, the surfactant, neutralizer, foaming agent and thickening agent caused a low score in the completeness item due to the collected data scope.

The Isothiazolinone, present in the three assessed detergents formula, was not available at the Ecoinvent database. Thus, its modeling was based on the patent of Jin et al. (2013), which reflected in the aspects of reliability, temporal correlation, geographic correlation and additional technological correlation grades. The visited companies did not provide primary data about their suppliers, so the transport between the raw material production site and the factories located in Teresina-PI was estimated based on the ABIQUIM information. The distance of transport between the retailer and the place of consumption was also estimated. These reflected in the reliability, completeness and geographic correlation grades, when filling out the Pedigree matrix.

A sensitivity analysis was performed for the three assessed products, in addition to the uncertainty analysis. For this, the data used in the modeling of the life cycle of detergents were analyzed regarding the choices related to the LCI data and the selected methods. This analysis is a way to compare each impact category indicators, with the default assumptions, methods and data of the goal and scope definition, with the results obtained changing the assumptions, methods or data (ABNT 2014). This procedure aims to indicate improvements in the indicators of environmental impact and the product system value, as a way to improve the detergents' Eco-efficiency profile. In this research context, improvement proposals were based only on the

environmental indicator, since the visited companies did not provide detailed information about their product's costs.

In this study, scenario one is the default (created with the collected data) and scenario two had a 15% reduction in the water consumption (with consequent reduction in emissions into water) in the consumer use stage of products A, B and C. In turn, a third scenario was created covering a 15% reduction in water consumption (considering a reduction in the emissions to the water) in the consumer use stage and the substitution of well water for tap water in the product A formula. It took into consideration that tap water is treated to have an adequate hardness for detergent production, which makes possible the exclusion of EDTA from the product A composition. For products B and C, the third scenario had a 15% reduction in the water consumption (and in the emissions into the water), in the use by consumer stage, and a surfactant replacement, from petrochemical sources (Alkylbenzene sulfonate, linear, petrochemical) to an oleochemical one (Fatty alcohol sulfate—from palm kernel oil).

Table 9 shows the results for scenarios 1, 2 and 3 for the assessed detergents by impact category. It should be noted that the oleochemical surfactant, proposed in scenario 3 for detergents B and C, is produced in Brazil and can be purchased by the visited companies in the national market.

According to the NBR ISO 14044: 2014, the comparison between two scenarios, in the sensitivity analysis, can be expressed in a percentage of variation. This represents the influence on the results, when a variation in the input data and the assumptions is done. The changes are considered significant to potential impact reduction greater than 10% (ABNT 2014). Table 10 shows the potential impact reduction by impact category of scenarios 1, 2 and 3 for detergents A, B and C.

In scenario two, a reduction in the water consumption and the emissions to the water were implemented, as these processes had the greatest environmental impacts for the assessed categories. For detergents B and C, all selected categories from the ReCiPe, CML and AWARE methods had a significant reduction potential, ranging from 10 to 14%. For product A, only the fossil resources scarcity (ReCiPe) and the abiotic depletion (fossil resources) (CML) categories did not get significant reduction potential (of 10% or more) in scenario two. This was due to the use of EDTA and the petrochemical surfactant.

In the scenario three, product A had a more significant potential reduction than scenario two, for all the assessed categories. The percentages varied between 14 and 20%, which was caused by the removal of EDTA from the detergent A formula. Products B and C, in scenario three, had significant potential impact reduction in almost all impact categories, except for the terrestrial acidification in ReCiPe method. Despite this, in some categories the potential reduction was less significant in scenario three than in scenario



Table 9 Results for scenarios 1, 2 and 3 of detergents A, B and C

Detergent	Impact category	Scenario 1	Scenario 2	Scenario 3	Unity
A	TA (ReCiPe)	6.6.95E−03	6.17E−03	5.78E−03	kg SO ₂ eq
	FE (ReCiPe)	1.1.16E−03	1.01E−03	9.74E−04	Kg P eq
	FRS (ReCiPe)	4.4.20E−01	3.86E−01	3.37E−01	Kg oil eq
	MRS (ReCiPe)	1.1.66E−02	1.43E−02	1.40E−02	Kg Cu eq
	AC (CML)	8.8.23E−03	7.32E−03	6.86E−03	kg SO ₂ eq
	EU (CML)	1.1.25E−02	1.08E−02	1.05E−02	Kg PO ₄ eq
	AD-FR (CML)	1.1.79E+01	1.65E+01	1.44E+01	MJ
	AD-MR (CML)	2.2.39E−05	2.11E−05	1.97E−05	Kg Sb eq
	WU (AWARE)	5.5.05E+00	4.39E+00	4.32E+00	m ³
B	TA (ReCiPe)	6.6.27E−03	5.50E−03	5.69E−03	kg SO ₂ eq
	FE (ReCiPe)	1.1.11E−03	9.58E−04	9.59E−04	Kg P eq
	FRS (ReCiPe)	3.3.49E−01	3.16E−01	2.62E−01	Kg oil eq
	MRS (ReCiPe)	1.1.61E−02	1.38E−02	1.39E−02	Kg Cu eq
	AC (CML)	7.7.47E−03	6.55E−03	6.68E−03	kg SO ₂ eq
	EU (CML)	1.1.20E−02	1.02E−02	1.06E−02	Kg PO ₄ eq
	AD-FR (CML)	1.1.49E+01	1.35E+01	1.12E+01	MJ
	AD-MR (CML)	2.2.20E−05	1.92E−05	1.94E−05	Kg Sb eq
	WU (AWARE)	4.4.71E+00	4.05E+00	4.13E+00	m ³
C	TA (ReCiPe)	6.6.26E−03	5.49E−03	5.71E−03	kg SO ₂ eq
	FE (ReCiPe)	1.1.12E−03	9.60E−04	9.60E−04	Kg P eq
	FRS (ReCiPe)	3.3.50E−01	3.16E−01	2.55E−01	Kg oil eq
	MRS (ReCiPe)	1.1.61E−02	1.38E−02	1.38E−02	Kg Cu eq
	AC (CML)	7.7.44E−03	6.53E−03	6.68E−03	kg SO ₂ eq
	EU (CML)	1.1.20E−02	1.03E−02	1.07E−02	Kg PO ₄ eq
	AD-FR (CML)	1.1.50E+01	1.35E+01	1.09E+01	MJ
	AD-MR (CML)	2.2.17E−05	1.89E−05	1.92E−05	Kg Sb eq
	WU (AWARE)	4.4.75E+00	4.09E+00	4.18E+00	m ³

Source Authors

TA Terrestrial Acidification, FE Freshwater Eutrophication, FRS Fossil Resource Scarcity, MRS Mineral Resource Scarcity, AC Acidification, EU Eutrophication, AD-FR Abiotic Depletion Fossil Resources, AD-MR Abiotic Depletion Mineral Resources, WU Water Use

two, such as the water use in the AWARE method. The main difference between scenarios two and three, for detergents B and C, was in the fossil resources scarcity (ReCiPe) and the abiotic depletion (fossil resources) (CML) categories, due to the use of oleochemical surfactant.

From an environmental perspective, the proposed product changes are the ideal one and they have the potential to improve the product's environmental performance. However, the Eco-efficiency profile of detergents also covers the economic bias, which can undergo significant variations when replacing the petrochemical surfactant to an oleochemical one and the EDTA removal from the formula. These costs variations were not calculated, because none of the visited companies provided data on production costs/sales price of their detergents.

Thereby, it was searched, on the internet, detergents available in the Brazilian market, with a similar formula to the assessed products in the scenarios two and three. This aimed at

support assumptions regarding the variation in the product system value indicator. The Bioz Green detergent has a surfactant derived from Palm Kernel oil and does not contain a chelating agent in its formula. Assuming that this product is manufactured in a different context from the local detergents (as different cities, producers, market positioning, suppliers and others), its sale price is higher (Price per liter of Bioz Green detergent BRL 22.34) (Bioz Green 2023). Thus, it is speculated that the proposed changes will increase the manufacturing costs of the assessed products. The suggestions implementation will depend on its feasibility for each company reality.

Discussion

The Eco-efficiency assessment of detergents identified that the use by consumer stage was the most impactful. It was due to the water consumption and the emissions into the

Table 10 Potential impact reduction in scenarios 1, 2 and 3 for detergents A, B and C

Detergent	Impact category	Potential impact reduction	
		Scenarios 1–2 (%)	Scenarios 1–3 (%)
A	TA (ReCiPe)	–11	–17
	FE (ReCiPe)	–13	–16
	FRS (ReCiPe)	–8	–20
	MRS (ReCiPe)	–14	–16
	AC (CML)	–11	–17
	EU (CML)	–14	–16
	AD-FR (CML)	–8	–20
	AD-MR (CML)	–12	–18
	WU (AWARE)	–13	–14
B	TA (ReCiPe)	–12	–9
	FE (ReCiPe)	–14	–14
	FRS (ReCiPe)	–10	–25
	MRS (ReCiPe)	–14	–14
	AC (CML)	–12	–10
	EU (CML)	–14	–11
	AD-FR (CML)	–10	–25
	AD-MR (CML)	–13	–12
	WU (AWARE)	–14	–12
C	TA (ReCiPe)	–12	–9
	FE (ReCiPe)	–14	–14
	FRS (ReCiPe)	–10	–27
	MRS (ReCiPe)	–14	–14
	AC (CML)	–12	–10
	EU (CML)	–14	–11
	AD-FR (CML)	–10	–27
	AD-MR (CML)	–13	–12
	WU (AWARE)	–14	–12

Source Authors

TA Terrestrial Acidification, FE Freshwater Eutrophication, FRS Fossil Resource Scarcity, MRS Mineral Resource Scarcity, AC Acidification, EU Eutrophication, AD-FR Abiotic Depletion Fossil Resources, AD-MR Abiotic Depletion Mineral Resources, WU Water Use

water (sewage) for rinsing the dishes. This finding is similar to the ones found by Van Lieshout et al. (2015), Golsteijn et al. (2015) and Saouter and Hoof (2022), in which the use stage had the highest environmental impact in the life cycle assessment for cleaning products. Although they have considered automatic dishwashing (with machine) in their studies and this study assessed detergents for manual dishwashing, the water consumption was a critical point in these product's life cycle.

The water consumption in the use stage was influenced by the consumer behavior during the washing of dishes. Thus, some actions can reduce this resource consumption and its

impacts. These actions may include the removal of food remains from dishes and cutlery before washing, turning off the tap while applying detergent to the utensils and the installation of hydraulic devices on the taps. The examples of the referred devices are the aerator, which can mix the air with water to reduce its flow and promote the sensation of greater water volume in the user, and the flow regulator, that prevents a greater flow of water than the pre-established one for the faucet. Van Lieshout et al. (2015) also stated that modern faucets, available in the American market, can generate 50–75% less water consumption than the older ones.

A reduction in the emissions into the water (domestic liquid effluents) is got by reducing the water consumption in manual dishwashing. These effluents disposal (treated or untreated) before discharge into rivers represents another critical point in the detergent use stage. It is due to the detergents formula that is composed of chemicals, like surfactants, rich in phosphorus and phosphate. The large presence of these nutrients in effluents, released into water bodies, can cause an accelerated increase in cyanobacterias that causes eutrophication. It is recognized as a pollution problem in water systems and reservoirs in different locations around the world (Quevedo and Paganini 2016).

The amount of water to dilute the concentrated products is another aspect to be considered in the detergent use stage. Consumer behavior will influence the amount of water consumed and the final product quality. If the manufacturer's recommendations are not followed and the consumer uses more water than recommended, there will be repercussions on the product's environmental impacts and even a reduction in its quality and performance. If the consumer uses less water than recommended by the manufacturer, it will generate a higher concentrated detergent than recommended. It may cause sensitivity reactions in the user's hands and, also, effluents with greater potential to cause eutrophication. Thereby, ready-to-use detergents are safer to the consumers, as they are in the ideal concentration and guarantee its operational performance.

In an ideal scenario, the consumer will properly follow the manufacturer's recommendations, which causes no substantial changes in the results in the water use category (AWARE). Thus, comparing the impacts generated by the use of water in the production stage (ready-to-use products) and in the consumer use stage (concentrated products) there were no consistent differences. It is noteworthy that the choice of ready-to-use or concentrated formats for cleaning products can influence the impacts of packaging and transport in other categories.

Effluents generated after the detergents use need to be treated before being disposed in water bodies, in accordance with the Brazilian legislation. They can change the rivers

conditions, such as pH, temperature and biochemical oxygen demand (Brasil 2011). However, in the researcher's context, there is low sewage coverage in the city of Teresina, whose total sewage service rate was only 38.79% in 2021 (Sistema Nacional de Informações sobre Saneamento—SNIS 2022). With this, the local sewage treatment plant may not be prepared to fully remove high concentrations of surfactants (from detergents) in effluents. It was common during the Covid-19 pandemic due to the high use of detergents.

Thus, the low coverage of sewage in Teresina with the widespread use of detergents and soaps, makes self-depuration of water bodies unfeasible (Uzma et al. 2018). This represents more polluted waters that may cause a scarcity scenario. In addition, the aquatic system can lose its sustainability capacity. It reflects on public health (Quevedo and Paganini 2018) as the substances used to treat drinking water react with toxic algae (dioxins producers) causing chemicals harmful to human health (United States Environmental Protection Agency—USEPA 2019).

To face this, the European Union established the control of phosphorus and phosphate content in detergents for washing clothes and dishes, through the Regulation n° 259/2012. This control aims to reduce the phosphates from detergents contribution to eutrophication risks and to reduce the cost of removing phosphates in wastewater treatment plants (Council of the European Union 2012). In Brazil, the legislation requires the biodegradability of only anionic surfactants. This excludes non-ionic, cationic and amphoteric surfactants and other chemicals of the formula, such as the neutralizer, the chelating agent, the preservative, the fragrance and the dye.

In addition, the use of EDTA in product A formula is necessary to reduce the water hardness and make it suitable for use in detergent. This substance is made from Ethylenediamine, Formaldehyde and a source of Cyanide, which considerably affects the categories related to the fossil resources scarcity/depletion. When released into rivers, it may cause change in pH that affects the aquatic ecosystems (Sinex 2004). The EDTA purchase and the long-distance transport costs make their use unfeasible. Thus, this substance use is linked to greater negative environmental impacts and higher production costs. Another option is to get tap water from the municipal supply system that is environmentally and economic viable, as seen in the proposed scenario.

For products B and C, scenario three proved to be environmentally better, as the petrochemical surfactant was replaced by the oleochemical one. This change led to a reduction in the product's negative environmental impacts, mainly in the fossil resources scarcity/depletion categories. However, it needs to be carefully assessed for its implementation. This is because oleochemical surfactants are heavily

dependent on management in Palm and Coco plantations, which is influenced by the use of fertilizers and the operational practices in the crops and factories. If the cleaning products increase the Palm kernel or Coco demand, they may encourage greater deforestation and monoculture agriculture. Thereby, companies need to check the associated costs and the supplier's environmental management practices, before replacing the surfactants of their cleaning products.

It should be noted that detergents and soaps cause negative impacts on the environment when not properly managed. They can contribute to the eutrophication, the scarcity of fossil resources, the possible accumulation in living organisms and the biodegradation resilience (Giagnorio et al. 2017). In the face of urgent issues, such as the effects on biodiversity, water and soil contamination and the environmental footprint of products, a demand for environmental studies was generated to identify viable improvements (Schowanek et al. 2018).

The detergents assessment indicated the critical points into these products life cycle, within the product system boundaries. This supports the decision-making process of local companies regarding the environmental impacts of the choices made in the products processes. The product system value aspects, as the raw materials costs and the sales prices formation, need to be deeper investigated as a way of ensuring the improvements in the Eco-efficiency profile of detergents. The proposed scenarios two and three are the ideal improvements for the products. These can reduce their indicators in the environmental impact categories, which can improve their Eco-efficiency profile. At the same time, companies can propose new feasible scenarios, according to their reality and the impacts in the product system value indicator.

Conclusion

The assessed detergents had considerable impacts on the selected categories for the chosen methods (ReCiPe, CML and AWARE) and on the product system value. It considered the product's specificities, such as their ready-to-use or concentrated format. A sensitivity analysis was carried out, in view of the life cycle critical points, which supported proposals for technically viable improvements. These proposals considered the potential impact reduction only on the environmental indicator, being necessary to deepen it to the product system value indicator. This happened due to the non-availability of detailed data on the sales price's composition from the visited companies.

The stage of use by the consumer was the most impactful in the life cycle of detergents, considering the product

system boundaries of this study. Among the three assessed products, detergent C was the most Eco-efficient, which is the most recommended from the Eco-efficiency point of view. Thus, the proposed scenarios indicated improvements in the use stage, such as the use of equipment to reduce the water consumption and good consumer practices during dishwashing. In addition, changes regarding the product's formula were proposed, as at this stage the company has decision-making power to modify its product. Thus, it is possible to make choices to balance a reduction in the product's negative environmental impacts and in the product system value with the product performance.

The Eco-efficiency assessment can support a business level decision as a way to contribute to the sustainable development. Taking into consideration that there are no similar studies in the national literature to this work, it has a scientific relevance. For future research, it is recommended the use of primary data regarding the raw materials production processes, as a way to improve the assessment accuracy and to contribute to the Brazilian National Bank of Life Cycle Inventories. In addition, it is recommended the inclusion of the packaging stage in the study boundaries, so their impacts cannot be disregarded in the companies' decision-making process.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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