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Integrating life cycle assessment and ecodesign to improve product effectiveness and environmental performance: A novel approach

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ABSTRACT

The sanitizing products market has grown significantly, accelerated by the Covid-19 pandemic, which increased both production and environmental impacts, highlighting the need for sustainable alternatives. However, "green products" are often perceived as less effective than conventional ones. This study introduces a novel approach integrating life cycle assessment (LCA) with ecodesign to optimize both environmental performance and product effectiveness. The approach was validated through a case study of a large Brazilian chemical industry producing sanitizers. A degreaser floor cleaner was selected for cradle-to-grave assessment, considering raw materials, manufacturing, transport, use, and end-of-life stages. While previous research has focused on LCA and ecodesign separately, this work combines the two to address these dual objectives. Environmental performance was evaluated using a single indicator encompassing and weighing five impact categories: Primary Energy Demand, Water Consumption, Global Warming Potential, Ozone Formation Potential, and Eutrophication. Ecodesign principles guided the redesign of the cleaning product, and its effectiveness was assessed through use tests, for the proposal of 8 improvement scenarios. After redesigning with three optimization strategies (formula, dilution rate, and use method), the solutions led up to 72 % environmental impact reduction. Five of the scenarios also improved product effectiveness, i.e. cleansing. A matrix integrating both environmental and effectiveness scores was developed to select the optimal solutions. This approach could be extended to other industries to support decision-makers in the stages of product development, manufacturing, use and end-of-life, by simultaneously enhancing sustainability and effectiveness.

1. Introduction

The global market for household sanitizing products has grown substantially since COVID-19 pandemic (World Health Organization, 2020), projected to be worth more than US$ 270 billion in 2024 and soaring towards USD 380 billion by 2032 (Fortune Business Insights, 2023). The necessity of sanitizers capable of minimizing health risks amplifies the production capacity of the category, thereby increasing the environmental impacts stemming from its practices (Chirani et al., 2021; Subpiramaniyam, 2021), advocating for a fundamental shift in how the sector operates. In this context, ecodesign emerges as a corporate solution applied to the development of processes or products, with the goal of enhancing their efficiency from an environmental perspective (Munaro et al., 2021). Ecodesign approaches lead to significant benefits when coupled with environmental impact assessment tools such as life cycle assessment (LCA), a tool that supports decision-making processes for environmental management, such as e.g. ISO 14044 standard (ISO-International Organization for Standardization, 2006). Additionally, it supports the selection of environmental indicators for diverse evaluations in project assessments and the strategic planning of products and/or processes (de Moraes et al., 2021).

Even though methodologies around LCA have been extensively explored in the consumer goods field, there are some limitations when conjugating other key factors for holistic approaches. While previous research has explored the use of LCA primarily focusing on the packaging industry (e.g., Pellengahr et al., 2023), discussion over

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understanding the complete life cycle of consumer goods (including their chemical formulations, raw materials, usage phase, and end-of-life) is far from mature, calling for the development of multifaceted methods that can be applied to a range of products.

Research suggests that integrated LCA and ecodesign methodologies in a cohesive approach are still lacking within the context of sanitizing products (Mahmood et al., 2020; Nogueira et al., 2019). However, exploring approaches that combine LCA and ecodesign may lead to additional challenges. Studies may rely on secondary data (Saouter et al., 2002) or even overlook the end-of-life impacts on products (de Lapuente Díaz de Otazu et al., 2022). Therefore, it is necessary to support industrial decision-makers in a thorough understanding of the optimization opportunities at hand. Furthermore, for an effective applicability in industry, tools should translate the environmental impacts identified through complex and systematic methods like LCA into easily understandable indicators, for both technical teams within the production chain and end-users. Additionally, new approaches should integrate the important balance between a product's environmental impact and its quality and efficiency standards.

By examining the case of a commercial sanitizer, this research aims at providing contribution to this research stream by proposing a novel approach that integrates both methodologies (LCA and ecodesign) into a single framework. In doing so, it also analyses the improvement scenarios according to several environmental impacts focused on reduced energy and natural resources consumption (i.e. Primary Energy Demand and Water Consumption), as well as diminished impact generation (i.e. Global Warming Potential, Ozone Formation for Terrestrial Ecosystems and Eutrophication). Furthermore, the approach aims at highlighting the optimal product designs in a similar overall optimization approach as Alejandre et al. (2022) and Nakic (2018). However, the current paper innovates in the proposed optimization by aiming at both superior environmental performance and optimal product functionality, expressed in terms of product quality and cleansing effectiveness.

The remainder of the study is structured as follows: Section 2 presents a comprehensive literature background about the technical aspects of sanitizing products, as much as the main approaches addressed in this paper: LCA and ecodesign. Also, it scavenges recent publications in the field exposing positive aspects and gaps. Section 3 presents the novel integrated approach and outlines the industrial case study selected for application. Section 4 provides an overview of the study results, also establishing correlations between the obtained data. Additionally, it applies ecodesign to the product, verifies the proposed alternative designs, and engages in detailed discussions regarding the outcomes. Section 5 discusses the proposed approach in light of extant literature and sketches suggestions for future research. Finally, Section 6 presents the study conclusions.

2. Literature review

LCA has been deemed as an essential tool to associate the quantification of product environmental impacts with sustainable production strategies (Silva and Kulay, 2019), thus contributing to sustainability improvement within industrial operations. As a critical catalyzer for LCA, ecodesign was initially crafted as a collective of measures applied at product development, aiming at reducing the environmental impact of products from the conception stage until the end-of-life in a holistic approach (van Weenen, 1995). However, while this interaction is timely and promising, recent literature on consumer goods abounds with LCA and ecodesign studies with a predominant focus on the packaging industry, varying within food packaging (Bi et al., 2018; Gallego-Schmid et al., 2018), pharmaceutical and cosmetic packaging (Bassani et al., 2022; Ren et al., 2022), biodegradable packaging (Chengcheng, 2022), packaging raw materials and polymers (Rebolledo-Leiva et al., 2023; Schwarz et al., 2023; Sifuentes-Nieves et al., 2023).

Though those investigations provided invaluable insights into packaging components, there is a deficiency in studying the complete life cycle of products, with a holistic examination of their chemical formulations, raw materials, use phase, up to end-of-life. Some authors used LCA for assessing ecodesign solutions in a case study for the production of titanium powder, using information extracted from patents as primary data (Spreafico et al., 2023). However, there is uncertainty associated with the subjectivity of the data collection since not all patents are equally reliable. In a case study of clay roof tiles, Kamalakkannan and Kulatunga (2021) used a parametric LCA model to assist designers in optimizing solutions of more efficient opportunities, integrating ecodesign, LCA and some Industry 4.0 technologies. Even so, the analysis presented some limitations in terms of reliability, as data was leveraged from existing products to support the unavailability of relevant information at the design stage. By looking at the food industry, scholars (Del Borghi et al., 2018) investigated the ecodesign-LCA relation for the environmental assessment of legume production, including its packaging containers. While the study increased its reliability for the whole life cycle thanks to a collection of primary data directly from the producers, its proposed alternative solutions were limited to only one impact category, Global Warming Potential (GWP).

With a growing importance of *sanitizing products* (specifically household and industrial cleaners) in the global consumer market due to the Covid-19 pandemic, previous research raised concerns about its associated environmental impacts (Daverey and Dutta, 2021). Even posing as a crucial segment, there is a lack of studies that redesign products, processes, or services related to the use of sanitizers by applying a structured (ecodesign) and systemic/quantitative (LCA) approach. Rungyuttapakorn and Wongwatcharapaiboon (2020) executed ecodesign for dishwashing detergents through a questionnaire-based approach conducted in focus groups with consumers. Yet, their study did not consider LCA as a quantitative tool to support the product development stages. Mahmood et al. (2020) assessed the environmental impacts of the extensive usage of hand sanitizers implemented to mitigate the transmission of the Covid-19 epidemic. However, the authors relied on a literature review of selected raw materials used in sanitizers, with neither offering an actual diagnostic of the associated environmental impacts, nor a proposal of potential alternative solutions. Nogueira et al. (2019) successfully explored a case study on raw materials for detergent production by adopting a 'cradle-to-gate' approach which explored some bio-based solutions, such as Brazilian palm kernel oil. Nevertheless, the analysis missed to include the redesign of solutions under the combined spotlight of LCA and ecodesign. Finally, other authors tried to environmentally evaluate detergents in a case study focused on the industrial production of granular laundry sanitizers (Saouter et al., 2002). However, they presented limitations in the life cycle inventory, requiring intensive use of secondary data extracted from literature, without relying on primary data collection from a real case study. Additionally, the study was limited to an assessment of current products, neither proposing new formulations nor employing ecodesign as a structured approach for the elaboration of solutions. De Lapuente Díaz de Otazu et al. (2022) recently explored this area by attempting to apply a 'cradle-to-grave' LCA analysis of an enzymatic cleaner. The environmental impacts were grouped into three phases: upstream (production and transportation of raw materials and packaging components), core (transportation of raw materials and packaging within the manufacturer, manufacturing, quality control and storage), and downstream (distribution, use and end-of-life), followed by the proposal of five improvement scenarios with the use of ecodesign. However, a reliable holistic evaluation was missing, limiting to an assessment of environmental impact by using primary data, not presenting energy or material inventory, with the inevitable risk of jeopardizing the model applicability in other contexts. Additionally, the study did not consider the impacts generated at the product end-of-life, such as the detergent potential deleterious effect as an effluent.

Building on these limitations, an additional research gap emerges: to the best of the authors' knowledge, previous studies have neither empirically quantified the cleaning effectiveness of the proposed improvement scenarios nor simultaneously evaluated the main product function alongside improvements in environmental performance.

As research shows, the shift to more sustainable products is conditioned upon not compromising their primary functionality (Kamal-Abyaneh, 2016). For this reason, integrating product effectiveness and environmental performance in a unique approach would not just represent a valuable contribution to the research, but also provide a tangible competitive advantage for corporations in the consumer goods industry by offering the opportunity to market more effective and sustainable products.

Given the extant research gap, the present study aims to integrate LCA and ecodesign by developing an integrated approach to product life cycle redesign for reduced environmental impacts without negatively impacting their original functions and quality standards, including meeting legal and regulatory requirements. Thus, a novel approach for impact quantification is introduced, creating a unique indicator correlating environmental performance with product effectiveness, serving as a resource for industrial decision-makers. Finally, the study extends the academic discussion by providing an empirical assessment of production and product use, offering a comprehensive proposal for sustainable consumption, and proposing scenarios with impact beyond end-users, thus involving the whole supply chain. This approach is validated by an empirical case study conducted within a multi-national Brazilian company that manufactures a floor cleaner (degreaser), representing this category (*sanitizers*) comprehensively. The study adds value to current research by offering scenarios based on a real industrial application encompassing the design, formulation, manufacturing, use, and post-use of the referred product.

3. Methods

3.1. A novel LCA-Ecodesign integrated approach

The novel approach, which integrates ecodesign and LCA, is focused on assessing products in both environmental performance and product effectiveness. For the environmental performance, a set of impact categories is defined, and a unified index is calculated to categorize the improvements of the baseline product and the improvement scenarios. Regarding product effectiveness, the benchmark (baseline) product's function is measured, and the proposed redesign aims at improving the capability of the product to perform its core purpose. Therefore, final propositions and conclusions are created considering potential improvements in both areas. The structure of the approach follows the four stages (see Fig. 1): 1) Product and system definition; 2) Environmental assessment; 3) Product redesign; 4) Calculation of global environmental index.

3.1.1. Product and system definition

The initial step of the approach involves identifying a relevant product that presents opportunities for redesign to improve both environmental performance and product effectiveness. It is essential to consult the manufacturer's technical staff regarding options in their portfolio that are sensitive to the use of ecodesign and LCA while also enabling the implementation of a systematic approach as described below. After considering these guidelines and applying decision-making criteria, the manufacturer may elaborate a preliminary list of products. Products that are strategically important to the producer should be the main emphasis of this initial proposal, especially those aligning with ecodesign and LCA principles. To support this process, the following six attributes might be considered:

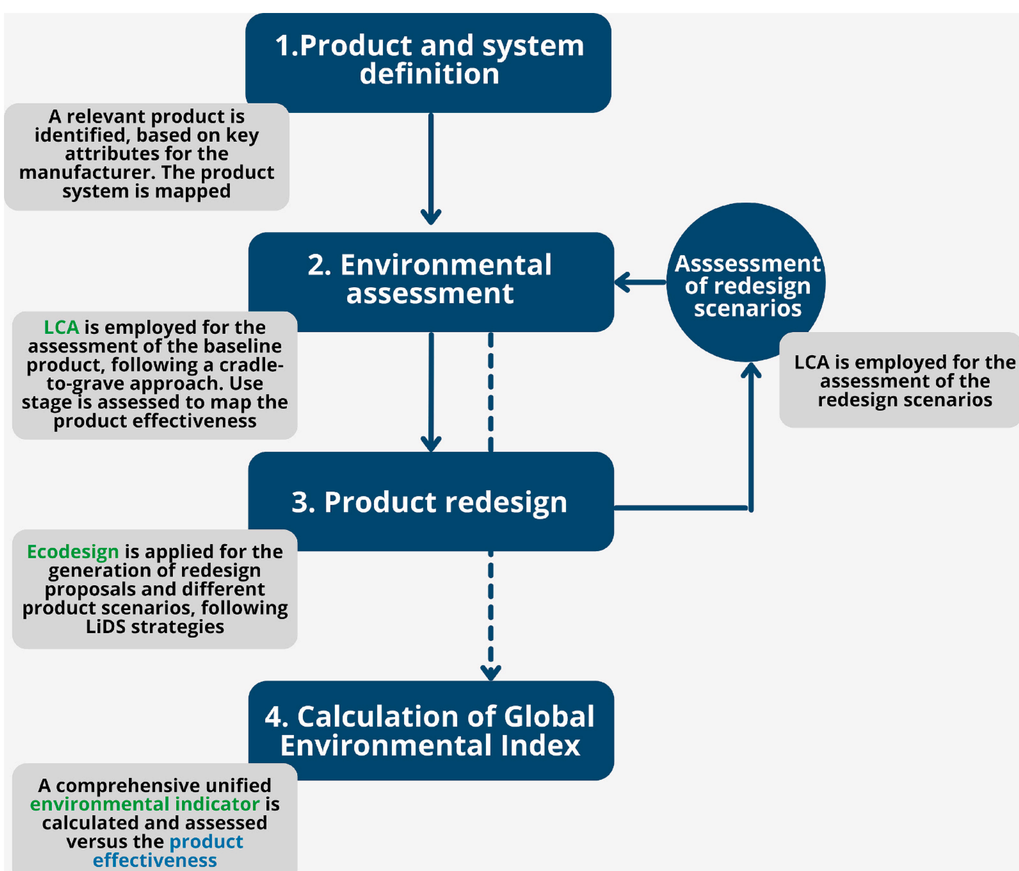

Fig. 1. LCA-ecodesign integrated approach for environmental and effectiveness assessment.

1. Product Attractiveness for the Business: Assess the product's congruence with existing business objectives, such as profitability, market trends, or adherence to corporate sustainability plans.
2. Market Representation: Choose products with substantial market share or elevated demand, guaranteeing that the redesign outcomes are influential for customers and stakeholders.
3. Sales Expectations: Prioritize products with anticipated growth or consistent demand in future markets, as their redesign may yield longer-term benefits.
4. Potential for Use: Consider products with extensive applicability, where enhanced environmental performance and effectiveness will generate greater user benefits.
5. Maturity Level: Focus on products that have not reached saturation in terms of innovation, as they are more susceptible to meaningful redesign interventions.
6. Flexibility/Susceptibility to Process Interventions: Assess products where modifications to the design, materials, or production processes are feasible without substantial disruption or excessive costs.

For instance, some of these attributes may not exert an entirely objective or quantitative influence on the decision-making process, as they may depend on confidential strategic factors determined by the manufacturer; however, such criteria remain grounded in the six attributes previously delineated. The shortlist withstands the initial scrutiny and requires further screening based on: (i) availability of process data, (ii) ease of access to suppliers, and (iii) openness to conducting estimation trials for variables in post-production stages. After this stage, products are selected, and the system (control volume) is defined, allowing the replication of the same structure across each variant, ensuring consistent conditions and hypotheses. It is important to ensure that consistent system boundaries, functional units, and assumptions are applied across all product variants to allow for comparative analysis and optimization. The system definition must align with the goals of the LCA study and the intended scope of ecodesign interventions.

3.1.2. Environmental assessment

The subsequent phase is focused on calculating the environmental footprints of the products, based on consolidated tools that add quantitative and structured aspects to the approach. LCA is the critical element of this stage, employed in a systemic manner (ISO-International Organization for Standardization, 2006) with differentiation from conventional methods by associating the quantification of impacts with the effectiveness of the selected product. To facilitate adoption of the method, the following parameters and decisions are standardized by adopters of the approach when conducting the environmental diagnostic:

1. Reference flow (RF) and functional unit (FU) determination: the FU represents the functional unit of analysis, which quantifies the product performance and allows for comparisons. Data treated in the analysis consist of defining a coherent reference flow (RF) and the criteria for treating situations of multifunctionality, following the approach from Rosa (2019).
2. Data sources and quality: the LCA holistic scope covers key life cycle stages of a product, i.e. raw materials production and transportation, product manufacturing, transportation, use and end-of-life. The execution of use tests, as recommended by the manufacturer, can corroborate empirical data to the approach and presents two main functions: on the one hand, to quantify environmental impacts specifically associated with this phase; and on the other hand, to generate data for the quantification of product effectiveness, i.e. one of the decision-making criteria to choose best alternative between the improvement scenarios.
3. Key Performance Indicators (KPIs): environmental impact categories are pre-defined (e.g., Global Warming Potential, Acidification, Eutrophication, Water Consumption, Human Toxicity), as much as effectiveness indicators of the product (which will be determined depending on product's function) must be assessed simultaneously with environmental impacts to enable a holistic evaluation.
4. End-of-life modeling: if applicable to the chosen product, the end-of-life evaluation is built by taking inspiration from theoretical models related to wastewater treatment plants (WWTP) based on technical premises (Sears et al., 2006; Tchobanoglous et al., 2003; Von Sperling, 2016). Such models are designed to project consumptions and emissions that would occur during the sewage disinfection process. Although the treatment plant is a conceptual model (with associated uncertainties), this design avoids situations of multi-functionality that naturally occur in WWTPs, given the diversity of types of contaminants treated there. The efficacy of WWTP treatment is assessed by the variation in Biochemical Oxygen Demand (BOD) values between the inlet and outlet, with BOD serving as an indirect measure of the organic matter present in the effluent (Cammarota, 2011). The model is then developed as a specific module of the LCA software to be used, so that relevant contributions from the effluents are also incorporated in the overall environmental assessment to increase the reliability of the novel approach. Furthermore, developing an exclusive model disregards synergistic and deleterious effects resulting from interactions between contaminants within the treatment itself, thus reflecting more precisely the consumptions and emissions related to this specific product use.
5. Software and Modeling: the use of LCA software (e.g., SimaPro, OpenLCA, GaBi) with customized modules for product-specific impacts ensures consistency.

3.1.3. Product redesign

This third stage involves an application of ecodesign for the redesign of the studied products. Among the available approaches in literature, the LiDS-wheel i.e., Life cycle Design Strategies (also known as Eco-wheel diagram), appears quite suitable. The LiDS-wheel is a tool specifically designed for product design, initially developed by Brezet and van Hemel (1997) but widely employed in identifying opportunities for improving their environmental performances (Van Doorsselaer, 2022). By leveraging on its results, practitioners (or product designers) can select the most suitable strategy for redesigning a product among 8 options. Taking inspiration from the traditional LiDS concept, due to the technical limitations of the model created, this research adapted some of the strategies, developed and validated a new approach with 6 strategies (Table 1). While most of the strategies have been adopted, it was not possible to change either the

Table 1
Strategies of ecodesign employed in this research (Adapted from Brezet and van Hemel, 1997).

LiDS Strategy	Strategy adopted	Example
New concept development	No	–
Low-impact raw materials	Yes	Cleaner raw materials Less energy consumption during use stage
Reduction of materials usage	Yes	Reduction in weight Reduction in transportation volume
Optimization of production	Yes	Fewer/cleaner production of consumables
Optimization of distribution	Yes	Improvement of energy efficiency in logistics
Reduction of impact during the use stage	Yes	Reduction of energy consumption Less/cleaner consumables
Optimization of initial product life	No	–
Optimization of system end-of-life	Yes	Clean discharge

product concept or the optimization of the initial product life.

3.1.4. Calculation of global environmental index

A comprehensive environmental diagnosis is then employed to assess trends resulting from the integration of various environmental impact categories evaluated in this LCA study. Based on that, for each of the impact categories under consideration, a Normalized Environmental Index for each product $\left(NEI_i^{(x)}\right)$ is created. The value of $\left(NEI_i^{(x)}\right)$ is estimated as described in the equation (Eq. (1)). For purposes of clarification, henceforth the product to be studied and eventually improved is referred to as "product baseline (PB)" and the proposed variations of this will be called "product (x)", with "x" representing the names of possible scenarios.

$$NEI_i^{(x)} = \left(\frac{EnvP_i^{(x)}}{EnvP_i^{(PB)}}\right) \quad (1)$$

where:

$NEI_i^{(x)}$: Normalized Environmental Index for product (x) for impact category (i);

$EnvP_i^{(x)}$: Environmental Performance of product (x) for impact category (i), representing the performance of the proposed scenarios;

$EnvP_i^{(PB)}$: Environmental Performance of the product baseline for impact category (i)

Through this approach, the values of $NEI_i^{(x)}$ are estimated for all impact categories (i_1 to i_n) of the product in question. Since PB represents the benchmark and the reference condition, by definition all $NEI_i^{(PB)}$ are equal to 1.

As these indicators are pure numbers, the values of $\left(NEI_i^{(x)}\right)$ for the product baseline and all formulations derived from its redesign can be summed. This operation establishes unique and total indices for PB, and each scenario created from redesign actions implemented in its life cycle. These indicators are then referred to as Global Environmental Indices $\left(GEI^{(x)}\right)$ (Eq. (2)).

$$GEI^{(x)} = \left[\left(\frac{EnvP_{i1}^{(x)}}{EnvP_{i1}^{(PB)}}\right) + \left(\frac{EnvP_{i2}^{(x)}}{EnvP_{i2}^{(PB)}}\right) + \left(\frac{EnvP_{i3}^{(x)}}{EnvP_{i3}^{(PB)}}\right) + \ldots + \left(\frac{EnvP_{in}^{(x)}}{EnvP_{in}^{(PB)}}\right)\right] \quad (2)$$

Furthermore, partial and overall indicators are developed to quantify trends of positive variation (improvement) or negative variation (deterioration) imposed by redesign actions on the analyzed cleaning product system. These indices are designated, respectively, as the environmental delta of product x $\left(\Delta_i^{(x)}\right)$ for each analyzed category (i) and the global delta of product x algebraically described by equations (Eq. (3)) and (Eq. (4)):

$$\Delta_i^{(x)} = 1 - \left(\frac{EnvP_i^{(x)}}{EnvP_i^{(PB)}}\right) \quad (3)$$

where:

$\Delta_i^{(x)}$: Environmental Delta of product (x) for impact category (i);

$EnvP_i^{(x)}$: Environmental Performance of product (x) for impact category (i);

$EnvP_i^{(PB)}$: Environmental Performance of product baseline for impact category (i);

$$\Delta^{(x)} = 1 - \left(\frac{GEI^{(x)}}{GEI^{(PB)}}\right) \quad (4)$$

where:

$\Delta^{(x)}$: Global Delta of Product x;

$GEI^{(x)}$: Global Environmental Index of product (x);

$GEI^{(PB)}$: Global Environmental Index of product baseline.

Consequently, the Global Environmental Indices of the baseline and the respective improvement scenarios are plotted against a product effectiveness indicator to graphically find the geometrical space of the optimal solution (i.e. the solution presenting the highest product effectiveness and lowest GEI).

3.2. Application of the proposed approach through case study

3.2.1. Product and system definition

The proposed integrated approach described in Fig. 1 has been tested within a Brazilian manufacturing company operating in the production of industrial sanitizers. After a consultation with the manufacturer's technical team, the product was selected following the approach described in Section 3.1.1. The identified product, referred to as *product baseline* (PB) is a degreaser designed to remove heavy dirt from institutional environments (companies, hospitals, and commercial establishments). Both the original product system and those constituted of the proposed solutions followed a typical structural pattern regarding their constituent elements. Fig. 2 illustrates this arrangement through a block diagram.

3.2.2. Environmental assessment

Environmental assessments are generated for PB through the application of the LCA technique using SimaPro® software with an attributional focus and a 'cradle-to-grave' scope. Following the guidelines established by the NBR ISO 14044 standard (ABNT, 2009), it is necessary to define the functional unit (FU) and the reference flow (RF) for each assessment. In this specific case, the adopted FU is to reduce to acceptable limits of hygiene and well-being, the degree of dirt in a specific laboratory floor of 90 m^2, through the application of a sanitizing solution. The RF is determined by the amount of sanitizer required to fulfil the defined FU, as detailed in Table 2.

The primary data received from the manufacturer includes the following: (i) technical aspects of the manufacturing process used, (ii) composition of PB in terms of the percentage of raw materials, (iii) energy consumption, (iv) distance from the factory to suppliers, and (v) instructions for using the product. These data are used to specify the consumption and emissions resulting from the formulation of PB, the transportation of its constituents, and the application of the sanitizer for its intended functions, corresponding to the use stage of the life cycle.

As a source of secondary data, the Ecoinvent® database is used to quantify environmental loads related to the raw materials and inputs used in the product (Appendix A). Regarding the geographical coverage, the information integrated into the databases originates from North and South America and European countries. However, with the application of harmonization procedures, the models represent the current technological developments in Brazil. Multifunctionality situations are addressed through the allocation procedure, always based on physical criteria of mass or energy.

The *life cycle impact assessment (LCIA)* addresses two areas: i) resource consumption and ii) emissions and waste generation. The first encompasses two aspects: energy and water. Depletion of energy resources is investigated through Primary Energy Demand (PED) using the Cumulative Energy Demand (CED) method v. 1.09 (Frischknecht et al., 2007). The CED method subdivides primary energy sources into renewable (Biomass, RB; Wind solar, geothermal renewable, RWSG; and Water, RW) and non-renewable (Fossil, NRF; Nuclear, NRN; and Biomass, NRB). Water Depletion/Water Consumption (WC) is estimated using the Water Use model proposed by Huijbregts et al. (2016). However, the approach quantifies water consumption from different sources without considering local water availability, thus not fully corresponding to an estimate of Water Footprint.

The second area of analysis investigates efforts on three *impact*

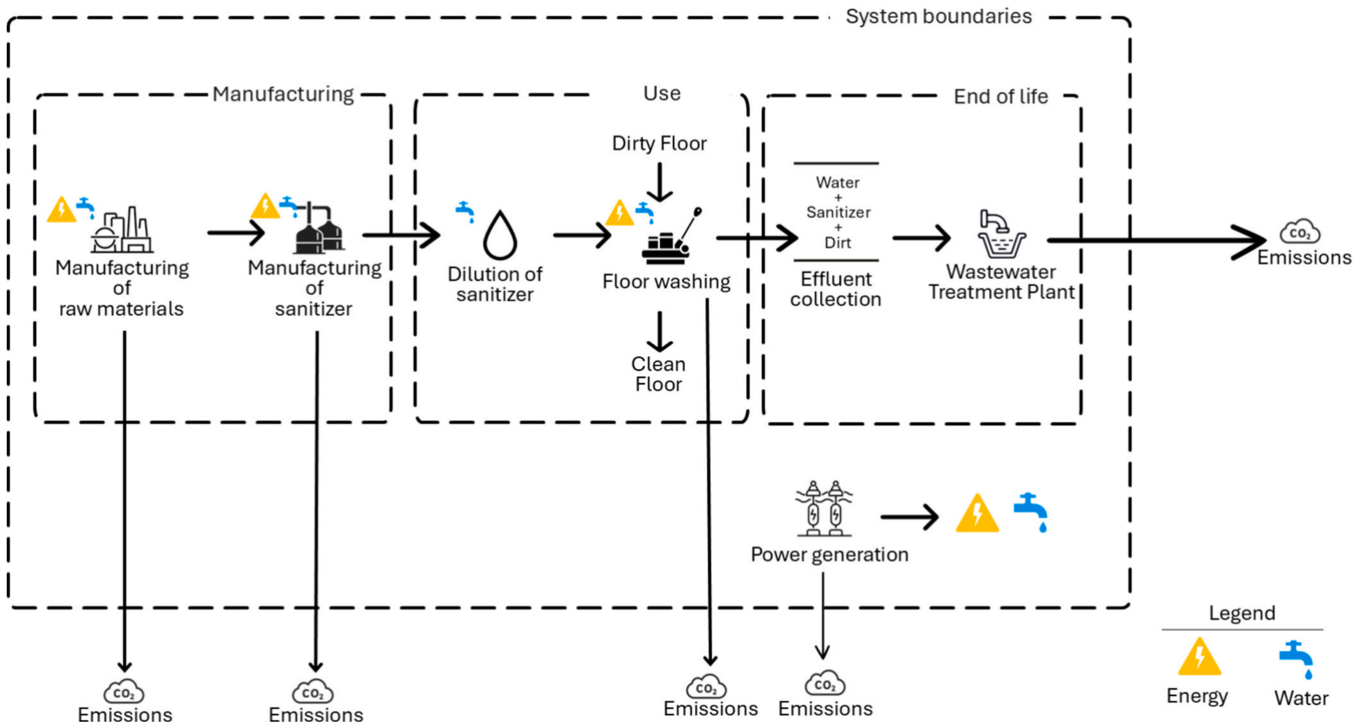

Fig. 2. Diagram of the evaluated system containing the boundaries (control volume).

Table 2
Quantity of product employed in the use test.

Laboratory and area	Volume of concentrate (sanitizer) in mL	Volume of solvent (water) in L	Volume of effluent solution (water + sanitizer + dirt) in L	Dilution rates (vol/vol)
LAREX (90 m^2)	625	11.9	12.5	1:20

categories: Global Warming Potential (GWP), Ozone Formation Potential (POFP), and Eutrophication (EP). GWP impacts are determined using the method proposed by the Intergovernmental Panel on Climate Change (IPCC 2013), based on Greenhouse Gas (GHG) emissions (Hauschild et al., 2013). The method proposed by Huijbregts et al. (2016) is chosen for POFP, generating midpoint indicators harmonized with the indicators adopted for the other impact categories under analysis (Huijbregts et al., 2016). Finally, for the EP category, the CML-IA baseline 3.06 is adopted, a robust LCIA method developed and improved by the Center of Environmental Science (CML) of Leiden University in The Netherlands (CML, 2016).

The selection of the five specified impact categories – Primary Energy Demand (PED), Water Consumption (WC), Global Warming Potential (GWP), Photochemical Ozone Formation Potential (POFP), and Eutrophication Potential (EP) – is determined by their relevance in assessing the environmental impact of sanitizers, as highlighted in existing LCA literature. Previous studies, such as those by de Moura and da Silva (2024) and Villota-Paz et al. (2023) emphasized categories like energy demand, water use, and eutrophication in the context of cleaning products but often lacked a comprehensive inclusion of ozone formation or global warming potentials. While de Moura and da Silva focused primarily on acidification and eutrophication impacts, neglecting broader emissions-related categories, Villota-Paz et al. addressed eutrophication, land use and climate change but omitted a detailed assessment of ozone formation potential. The present paper aims at addressing both issues, offering a more holistic evaluation of sanitizers environmental profiles by integrating all five categories, which were widely recognized as essential metrics in the LCA of such products (de Lapuente Díaz de Otazu et al., 2022). Additionally, it expands the selection of impacts made by de Lapuente Díaz de Otazu et al., since it includes the energy consumption impact, associated to the manufacturing and use stages of the life cycle. This comprehensive selection ensures robust applicability and comparability of results, firmly rooted in established LCA methodologies.

The life cycle inventory (LCI) of electricity generation (Grid BR) is tailored from the database to reflect Brazilian conditions (Appendix B). The natural gas (NG) consumed by Grid BR—as well as that used for thermal energy supply in the units integrated within each product system—is modelled to represent typical Brazilian conditions. This model encompasses offshore extraction stages in the country and onshore extraction in Bolivia, contributing to a proportion of [61:39] $_{vol/vol}$ to the Country's NG supply. It also includes operations for crude gas refining and the transportation of the final product to consumer centers. The LCI is adapted for Brazilian conditions based on previous literature (Sakamoto, 2019).

In Brazil, land transport occurs mainly by road. In this case, the LCI of diesel consumed for these movements is developed considering procedural and technological requirements practiced in the country. The transportation model (Appendix C) also considers trucks with a tare weight ranging from 3.5 to 7.5 tons as the vehicles used. Their consumption and emission factors are extracted from the Handbook Emission Factors for Road Transport (HBEFA) (Notter et al., 2019).

Regarding the *use* stage, the preparation of the sanitizing solution is conducted to replicate the recommended usage by the manufacturer. The dilution rate in water is [1:20] $_{vol/vol}$, and the quantities of solution used in the cleaning cycles depend on the areas where each product is applied. The area chosen for the product usage tests is a laboratory located at the University of São Paulo, Brazil. Product baseline, a heavy-duty degreaser, is employed to clean the floor of a recycling and waste treatment workshop, the Laboratory of Recycling, Waste Treatment, and Extraction (LAREX), with a high level of dirt in an area $S_A = 90\ m^2$. The floor has a waxed epoxy resin coating and is not painted. The initial dirt assessment is done by measuring adenosine triphosphate (ATP) on the floor, as per the manufacturer's recommended protocol (Hygiena, 2019).

Additional details about the sanitizing solution under investigation, with proportions and dilution rates, are reported by Table 2.

For the *end-of-life*, the cleaning of the areas is followed by the collection of effluents composed of dirt residues and excess sanitizing agents. Subsequently, the floor has been dried, and new ATP tests are conducted to assess the degree of dirt reduction. The washing waters undergo laboratory analyses to identify levels of BOD and Chemical Oxygen Demand (COD) (AWWA; APHA; WEF, 2017), aiming to assist in the subsequent step, encompassing the design of a hypothetical WWTP specifically tailored to manage these effluents.

3.2.3. Product redesign

The redesign follows the approach described by LiDS wheel (as mentioned in Section 3.1.3). By applying the adopted strategies (Low-impact raw materials, reduction of materials usage, optimization of production, optimization of distribution, reduction of impact during the use stage, optimization of system end-of-life) the manufacturer's technical team is involved in brainstorming sessions for the elaboration of redesign proposals that would further lead to new product scenarios. This includes actions implemented throughout the production, use, and/or final disposal, using a methodology comprehensive to all life cycle stages (Van Doorsselaer, 2022). Firstly, choosing lower-impact ingredients is a crucial decision for providing a better environmental profile of cleaning products, as verified by Farias et al. (2021). Secondly, the elevated energy consumption during use requires changes towards less-intensive cleaning appliances (Alejandre et al., 2022), or the use of manual techniques. Finally, the quantity of detergent used in the cleaning activity has a crucial impact on results for the life cycle profile (Giagnorio et al., 2017).

The development of proposals for the redesign of the life cycles of PB generates various scenarios for the cleaning product. Each alternative is then appropriately specified, followed by the creation of individualized environmental models, with the subsequent development of new chemical formulas and new environmental assessments (as described in Section 3.2.2) with the application of those cleaners on the laboratory floor. This allowed the creation of environmental assessments for the tested variants, using the methodology described earlier. The comparison between these design options allows the validity of the implemented actions. A detailed discussion of the redesign options can be found in Section 4.3.

3.2.4. Calculation of global environmental index

The calculation of the GEI is executed by comparing the environmental performance within the 5 impact categories (PED, WC, GWP, POFP, EP). As anticipated, Global Environmental Index for PB is equal to 5 by definition (see Section 3.1.4).

Subsequently, the effectiveness of the products is measured with respect to their dirt-removal performance, measured by the amount of BOD removed during use tests. This exercise is performed for the product baseline and all the improvement scenarios. Finally, both attributes (GEI and effectiveness) are crossed to choose the optimal solution for the sanitizer.

4. Results

4.1. Product and system definition

Establishing system assumptions and premises, which form the basis of the methodological framework outlined in Section 3.1.1, is the main goal of the first set of results. After the implementation of the proposed methodology, a thorough evaluation of the manufacturer's product portfolio has been conducted, with potential products for redesign further identified. The selection process, guided by the predefined attributes, results in a shortlist of products that demonstrate strategic alignment with ecodesign and LCA principles. These goods exhibit high market representation, consistent sales expectations, and sufficient flexibility for design and process interventions. Unfortunately, for confidentiality reasons, details over sales shares and other market figures for the considered products cannot be disclosed. Further meetings with the supplier have focused on screening based on process data availability, supplier accessibility. Such activities are essential to refine the selection, ensuring that only products with adequate data support and practical implementation potential are effectively considered. The final selection enables the definition of a consistent system boundary previously described (Section 3.2.1), guaranteeing comparability across product variants.

4.2. Environmental assessment

The baseline product is assessed through LCA across five categories. A summary of the results is presented in Table 3, constituted by the values of the measured impacts. Additionally, the table highlights the main sources of impacts within PB and the life cycle stage in which they are generated.

The majority of PED impact (14.5 MJ/RF) can be allocated to heat consumption stemming from the combustion of 0.069 m^3 of natural gas (NG), obtained from a low-efficiency process (61 % yield), due to offshore losses at the Brazilian coast (Maciel, 2018). In the synthesis of alkylbenzene, the PED concentration occurs due to the production of paraffin (4.01 MJ/RF), accounting for 86 % of the total impacts associated with this sulphated aromatic. The majority of WC impacts comes from the water added to the system from two sources: (i) in the preparation of the cleaning solution, for which the dilution rate solute (sanitizer concentrate): solvent (water) is [1:20] $_{vol/vol}$; and (ii) directly from the formulation of product baseline where water represents over 70 % $_{w/w}$. The GWP impacts are mainly (~95 %) from emissions of fossil-origin CO_2 ($CO_{2,f}$), land-use change ($CO_{2,LT}$), and fossil methane ($CH_{4,f}$) associated to the manufacturing of direct and indirect assets in the formulation of product baseline, with the most impacting source being the synthesis of ethylene (Barbosa et al., 2007), the precursor of those assets

Table 3
Environmental impact profile for the cleaning of the recycling workshop (LAREX), product baseline (PB).

Impact category	Unit (/RF)	Value	Main sources of impact (% of total)	Stage of life cycle
PED	MJ	14.5	Natural gas – energy source for the manufacturing of raw materials and final product (31 %)	Raw materials and Manufacturing
			Formulation ingredients: linear alkylbenzene sulfonate (32 %)	Raw materials
			Electric floor polisher (minor)	Use
WC	L	25.0	Product dilution (51 %)	Use
			Formulation ingredients: water, EDTA, and sodium metasilicate	Raw materials and Manufacturing
GWP	g $CO_{2\,eq}$	437	Formulation ingredients: sodium metasilicate, ethylene glycol, amine oxide, linear alkyl benzenesulfonate, C11 alcohol ethoxylate (AE11), and EDTA (95 %)	Raw materials
POFP	g $NO_{x\,eq}$	0.81	Synthesis of ethylene, raw material for the formulation ingredients: ethoxylated alcohol and ethylene glycol (12 %)	Raw materials
EP	g $PO_4^{3-}{}_{eq}$	0.75	Activated sludge from the WWTP	End-of-life

described in Table 3. Similarly to what occurs with GWP, the system's POFP impacts can be attributed to the synthesis of ethylene, with other contributions coming from the activated sludge system (4.0 %). This contribution is due to NO_x emissions that drive ozone formation (Grosjean and Grosjean, 1998), stemming from the oscillation between aerobic and anaerobic extremes in the digestion of organic matter by microorganisms in the activated sludge (TOMEI et al., 2016). Likewise, the largest share of impacts in terms of EP is attributed to the effluent treatment system. This is due to the assumption that the excess sludge would be incinerated, and the sterile material disposed of in a landfill. The impacts of this activity in terms of EP originate from leaching the remaining phosphates of rejected products. This study estimates the impact in the form of EP to be 1.27 g $PO_4{}^{3-}{}_{eq}$ for every 1.0 g of incinerated sludge.

4.3. Product redesign

Based on the strategies described in Section 3.2.3, the system involving product baseline has the following redesign proposals (RP) identified for its improvement:

- RP1: Replacement of sodium metasilicate with sodium hydroxide + sodium carbonate, as well as the substitution of EDTA with Nabion® 26, a builder, blend of sodium silicate and sodium carbonate (Seqens, 2023), followed by a revision of the quantities composing the formulation;
- RP2: Proposal for a new use methodology for the sanitizer, switching from floor cleaning with an electric polishing machine to manual action cleaning, aiming to reduce the energy demand of the system;
- RP3: Adjustments to the product dilution ratios were made to reduce the overall impact associated with product use. This action suggests that the cleaning level in the workshop (LAREX) be reduced in favor of a lower environmental impact throughout the entire life cycle under study.

Despite the actions characterizing the redesign of each arrangement, water remains as the solvent ingredient, being rebalanced to accommodate the quantity variations between the original and derived formulations. Thus, Fig. 3 synthesizes the eight improvement scenarios (C1 to C8) derived from the aforementioned RP combinations. The formula referred to as "Reformulated" comprises RP1. The diagram also includes the original conditions of the arrangement (product baseline).

4.4. Calculation of global environmental index

The same life cycle assessment (LCA) methodology, from cradle-to-grave, used for the baseline product is applied to all proposed improvement scenarios, including analyses of the use phase, BOD measurements, and WWTP modeling. Thus, the verification of the environmental effectiveness is assessed with the calculation of the Global Environmental Index (GEI) and the compiled diagnosis presented in Fig. 4. The scope definitions and assumptions used up to this point are maintained to elaborate the solutions. Details of the values for the specific impact categories are reported in Table 4.

An analysis of the impact results indicates that a clear trend is observed across all scenarios: as the optimization proposals progress from C1 to C8, there is a consistent reduction in PED, WC, GWP, POFP, EP, and GEI, indicating enhanced environmental performance. Notably, C8 achieves the lowest values across all categories, and this suggests that it represents the most sustainable option among those evaluated. However, intermediate scenarios such as C5 exhibit trade-offs, with higher EP and POFP values compared to others, highlighting the complexity of optimizing multiple environmental impacts simultaneously. While this overall trend analysis provides valuable insights into the general environmental performance of the alternatives, it is equally important to

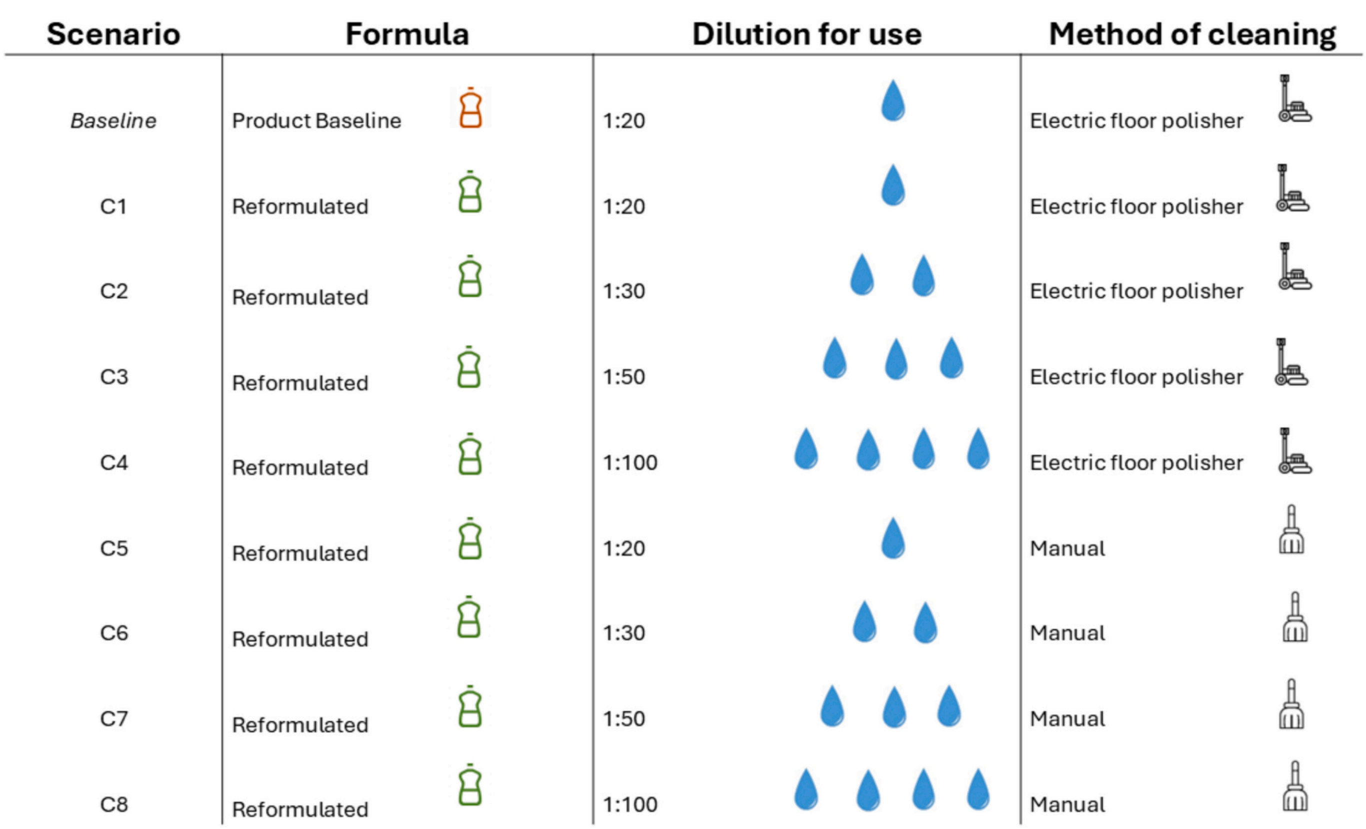

Fig. 3. Proposed improvement scenarios for the redesign of the cleaning system using PB. The term 'Reformulated' indicates the replacement of sodium metasilicate with NaOH + Na_2CO_3 and the exchange of EDTA with Nabion® 26 (a blend of Na_2SiO_3 + Na_2CO_3).

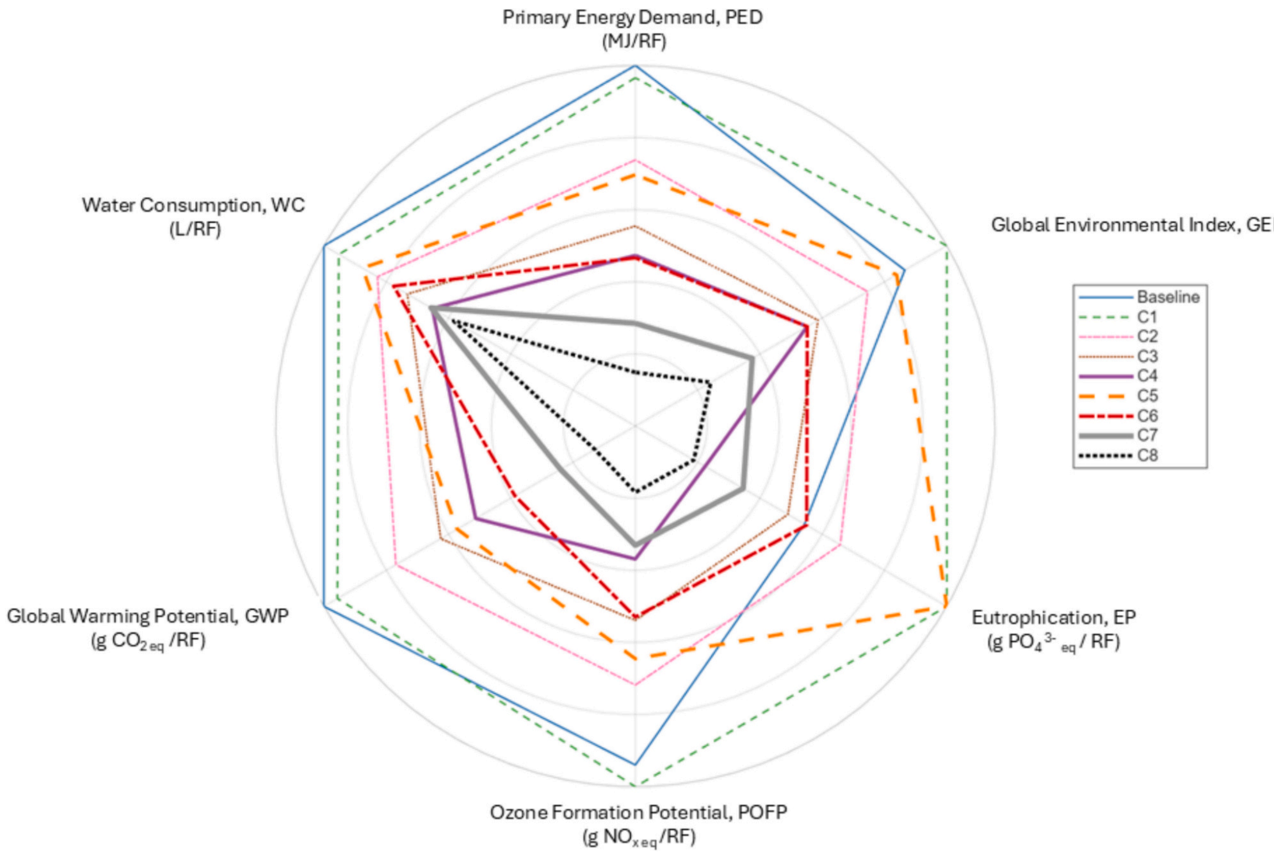

Fig. 4. Analysis of product baseline alternative redesign options (Product Baseline versus eight alternative designs).

Table 4
Results of the analysis comparing the product baseline and 8 alternative redesign options according to: Primary Energy Demand (PED), Water Consumption (WC), Global Warming Potential (GWP), Ozone Formation Potential (POFP), Eutrophication (EP), and Global Environmental Index (GEI).

Scenario	PED [MJ/RF]	WC [L/RF]	GWP [$gCO_{2\ eq}$/RF]	POFP [g $NO_{x\ eq}$/RF]	EP [g PO_4^{3-} eq / RF]	GEI
Baseline (PB)	14.5	25.0	437	0.813	0.75	5.00
C1	14	23.8	418	0.865	1.38	5.78
C2	10.7	20.7	336	0.621	0.908	4.31
C3	8.04	18.3	273	0.466	0.676	3.39
C4	6.05	16.3	224	0.319	0.394	2.50
C5	10.1	21.9	250	0.705	1.38	4.85
C6	6.76	19.1	169	0.458	0.759	3.19
C7	4.13	16.4	105	0.286	0.478	2.17
C8	2.16	14.6	56.7	0.159	0.259	1.40

assess each impact category separately in detail.

After analyzing the results described in PED, all the scenarios present some improvements, except for C1. In that case, where the product redesign presents the same dilution and cleaning method of the baseline product (with only the formulation to vary), impacts can be considered overall similar to PB. The results seem to suggest that the reformulation alone cannot substantially reduce the energy demand, when a significant contribution in terms of PED for cleaners is attributable to the use of non-renewable energy sources in the manufacturing phase (de Lapuente Díaz de Otazu et al., 2022), which has not been changed due to limitations from the manufacturer's suppliers. On the other hand, better energy profiles can be observed in scenarios (such as C7 and C8) that used manual cleaning (versus the baseline with high PED using the electric floor polisher) and significantly reduced the amount of cleaner.

For WC, the results are presented in Fig. 5 from the best to the worst profile, with their respective impact reduction percentages:

A crucial factor for the preponderance of C8 and C4 over the other scenarios is the presence of a high dilution rate which, although penalizing in terms of increasing water consumption in product preparation (use stage), is beneficial due to the lower amount of cleaner used.

In terms of GWP, all proposals prove themselves effective, with two notable points. First, the significant result of C8 (with 87 % of improvement versus the baseline) is due to the dilution changes (80 % less sanitizer concentrate) and removal of metasilicate from the formula. Sodium silicates and metasilicates historically carry significant environmental impacts to detergents (Fawer et al., 1999), most specifically with their contribution to GWP (Tang et al., 2021). Secondly, the similarity between the impact profiles of C5 and C3 shows a compensation between the use of electric polisher (negatively contributing to GWP in C3, with 34.8 % of the impacts coming from the electricity consumption of the equipment) and the dilution (the decrease in dilution impacts C5 negatively).

In terms of POFP, a change in the trend is observed as all proposed scenarios have better profile than the original condition, except for C1. Thus, C1 (865 mg NO_x eq/FR and a 6.0 % deterioration) has a larger impact than PB (813 mg $NO_{x\ eq}$/FR). Ozone formation is strongly influenced by ethylene (Nam et al., 2006), which is the precursor of the ingredients ethoxylated alcohol and ethylene glycol, present in PB. These ingredients are not replaced in the reformulation proposals for the baseline product due to technical factors involving formulation stability. Therefore, the modifications that could improve the overall environmental performance of fulfilling the function in terms of POFP would occur in two spheres: (i) increasing dilution, and (ii) adjusting the mode of use. Regarding the increase of dilution, the improvement is confirmed by the behavior observed in the C1 to C4 group, where dilution is increased (from 1:20 to 1:100), resulting in a decrease in impacts in g

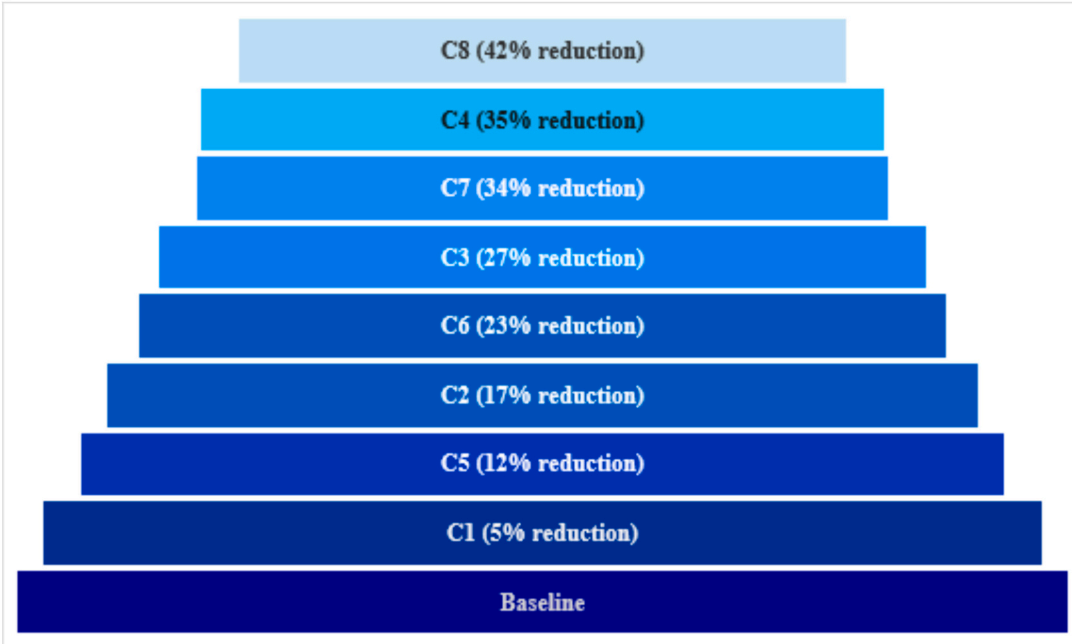

Fig. 5. Analysis of different scenarios with WC reduction percentages.

$NO_{x\ eq}$/FR, even with electric floor polisher usage. For the improvement scenarios with best POFP profile, C7 and C8, both aspects (i) and (ii) are combined, contributing to 65 % and 80 % reductions, respectively.

The diagnosis of the optimization scenarios for PB concerning eutrophication (EP) presents the most discrepant profile compared to the four previous categories, with two considerations deserving attention: (i) C1 and C5 present 84 % deterioration due to higher concentrations of cleaners; and (ii) only four scenarios propose a practical improvement in the EP profile (C3, C4, C7, C8), due to higher dilution (1:50 and 1:100), reducing BOD concentration, and requiring a less demanding WWTP. The effluent treatment model employed in this study considers secondary treatment via activated sludge, a key contributor to eutrophication (Mamathoni and Harding, 2021).

Therefore, it is observed that the best environmental scenario (based on its GEI) is C8, with 72 % optimization, contrasting with C1 in the position of the worst environmental performance, with a deterioration of 15 % when compared to PB. As a holistic approach to verifying both the environmental profile and the product effectiveness, a graphical representation is created in Fig. 6. The chart displays the dependence between the removed BOD and Global Environmental Index, allowing the determination of the best scenario in environmental terms (lower GEI) correlated with the highest product effectiveness, measured by the product efficiency of cleaning (highest BOD). Therefore, for the cluster with the best overall environmental impact (the set C8, C4, and C7), scenario C8 would be chosen as the most efficient in terms of environmental impacts. For the cluster with best efficiency (C1 and C5), the choice of optimal solution should be made after a critical analysis about the deleterious effect of their high environmental impacts, respectively $GEI^{(C1)} = 5.78$ and $GEI^{(C5)} = 4.85$.

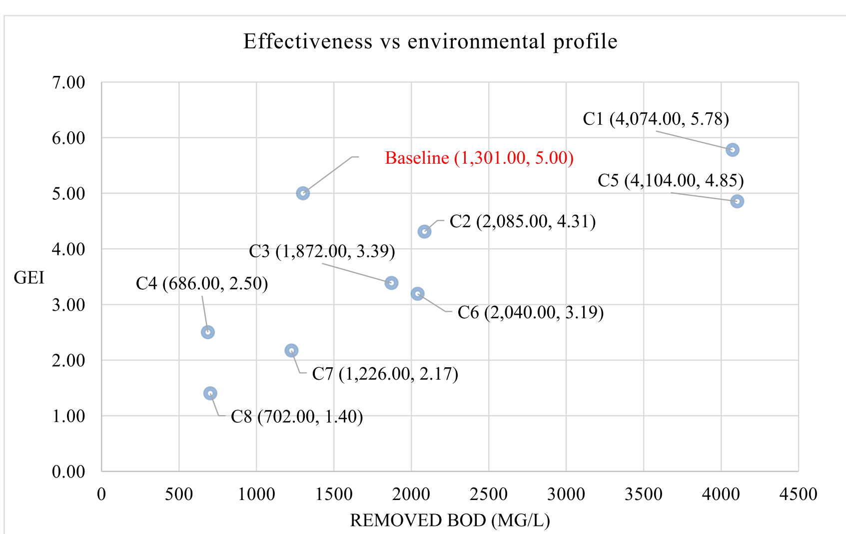

Fig. 6. Effectiveness-Environmental representation of product baseline and its product design alternatives, with removed BOD [mg/L] and GEI. Baseline point is reported in red.

5. Discussion

This study proposes a novel approach characterized by the LCA-ecodesign integration, with another integration that goes beyond the methodologies for environmental assessment: the connection between environmental performance and product effectiveness as a technical resource for manufacturers.

The research is positioned in the literature stream which develops frameworks and tools to integrate ecodesign decision-making for sustainable product development (Romli et al., 2015) to support sustainability transitions across various manufacturing sectors trying to reduce their environmental footprint (e.g., food and beverage: Garcia-Garcia et al. (2021) and textile industries: Fonseca et al. (2023)).

The proposed approach, differently from earlier studies (see e.g. Alejandre et al., 2022), aims at including relevant product performance (such as cleansing effectiveness) as a key parameter for the analysis and the establishment of the main scenarios for comparison with respect to the baseline. Thanks to this, the analysis of the potential alternatives (baseline and following) allows to keep a focus towards the main product purpose, i.e. degreaser floor cleaner, which is essential in product design, along with relevant environmental performances. Indeed, the proposed approach complements other studies where ecodesign principles were incorporated in e.g. product packaging (as done by González-García et al. (2011)) and, more recently, Civancik-Uslu et al. (2019).

As it can be easily observed, the approach proposed here is tailored for single products in the chemical industry, substantially differentiating from e.g. commodities for the building sector, as investigated by previous research (González-García et al., 2012; Ipsen et al., 2024). Recently, Pomponi et al. (2022) also explored a relationship between environmental impact and effectiveness. However, the authors used such a relationship as a benchmark to maintain the same efficacy as the original products, only towards improving the product environmental performance. Rather, the current study simultaneously assesses the improvement scenarios considering both the product effectiveness and environmental performance (Fig. 6). It can be argued that the proposed approach here presents some similarities to modalities of applications to TRIZ (as known as Theory of Inventive Problem Solving) strategies associated to material substitution in ecodesign (Spreafico, 2022). However, the proposed approach corroborates the analyses with a LCA perspective, thus fully encompassing the implications of a material substitution strategy throughout the product life cycle.

For this reason, the approach herein proposed can find effective application to manufacturing contexts, complementing and further extending other academic and corporate approaches for the selection of more sustainable products (L'Haridon et al., 2023), which as previously noted do not specifically remark product effectiveness as a key ecodesign variable. Scholars (Mengistu et al., 2024) have recently analyzed the state-of-the-art literature on sustainable product design, listing the main factors related to the environmental perspective, such as optimal resource usage, minimization of waste and efficient end-of-life management. However, scarce attention was offered to the application of product efficiency as a decision-making criterion in the elaboration of improvement scenarios. Therefore, it is important to clarify that the sole application of the environmental factor in this study would incur changes in the design structure and would lead to a limited approach with no intrinsic innovation.

This study successfully used primary data supplied by the manufacturer to obtain environmental assessments of products. However, limitations may arise in the model that could lead to potential future research avenues. The selection of the cradle-to-grave product system was intended to ensure sufficient scale and material for redesign, thereby encompassing post-production aspects and enhancing the comprehensiveness of the analysis. However, it is acknowledged that the same methodological approach could have been applied within a cradle-to-gate or cradle-to-cradle framework, offering a different analytical perspective. The absence of these alternative approaches in the present study should not be regarded as a limitation per se, rather as an opportunity for future research, further expanding the study's reproducibility and applicability. Regarding life cycle inventory, some of the raw materials were not found in original databases, having their inventories adapted, and the entire disclosure of ingredients was not possible due to confidentiality constraints imposed by the manufacturer. The modeling of the WWTP was based on a theoretical secondary treatment model of an activated sludge plant focused exclusively on treating this sanitizer, which may not carry realistic interferences of other streams. Additional opportunities were identified in both the effectiveness and the environmental assessments. As a measurement of the product effectiveness, the model analyzed solely the nature of the effluent, considering the amount of BOD removed. This was conjugated with the GEI for the final choice of the optimal solution, which culminated in a two-axis analysis (GEI vs removed BOD, Fig. 6). However, other effectiveness indicators, such as the ATP measurement before and after the floor cleaning, could be employed as an additional effectiveness variable to enhance the reliability of the model. From an environmental analysis perspective, the five impact categories had the same weight for the final indicator, GEI. To increase the granularity of the model, specific weights could be associated to the categories, depending on the product characteristics (e.g. electric appliances with higher weight associated to energy demand). Furthermore, the current selection of impact categories could be broadened to include additional categories addressing the scarcity of fossil and mineral resources. This expansion is particularly relevant for products containing surfactants, as highlighted by de Moura and da Silva (2024) in their life cycle assessment of dishwashing detergents. These adjustments would open opportunities for an expansion of the current two-dimensional model towards a multi-criteria decision-making approach.

6. Conclusions

This study proposes a novel integrated approach to optimize products by simultaneously evaluating environmental performance and product effectiveness, validated using a commercial cleaning product (degreaser) through five environmental impact categories: PED, WC, GWP, POFP, and EP. Eight optimization scenarios are analyzed, with reformulation emerging as a key factor, achieving better results than the baseline in 35 out of 40 measurements. Most scenarios show a significant inverse relationship between dilution and impact, with up to a 72 % reduction in impacts (scenario C8). The product cleaning efficacy is also assessed. A graphical representation is developed to integrate environmental assessments with cleansing effectiveness, aiding strategic decision-making based on numerical results.

The contributions of the present to the academic discussion in this area are three-fold. Firstly, by proposing quantification approaches consolidating solid methods (LCA and ecodesign) that bring impact reduction in product development, it exemplifies the concept of sustainable production. Moreover, evaluating a holistic life cycle that considers impacts not only in manufacturing but also during use and end-of-life is beneficial to the idea of sustainable consumption. Finally, the proposed approach offers the opportunity to conjugate the best environmental performance with the ideal product effectiveness.

CRediT authorship contribution statement

Filipe Mattos Batista de Moraes: Writing – review & editing, Writing – original draft, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luiz Kulay:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Andrea Trianni:** Writing – review & editing, Validation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Inventory of evaluated product

PRODUCT	QUANTITY	UNIT
Product baseline	100	kg
Inputs		
EDTA, ethylenediaminetetraacetic acid, transportation/RER U**	1.32	kg
Ethoxylated alcohol (AE11) BR| ethoxylated alcohol (AE11) transportation, palm oil | APOS, U*	3.00	kg
Sodium metasilicate pentahydrate, 58 %, powder, at transportation/RER U*	8.00	kg
Corante 205 BR| transportation*	2.00	g
Ethylene glycol monoethyl ether BR| production | transportation APOS, U*	5.00	kg
Amine oxide {RER}| amine oxide production | transportation APOS, U*	0.63	kg
Tap water BR| tap water production, conventional treatment | transportation APOS, U*	78.648	kg
Alkylbenzene sulfonate, linear, petrochemical, at transportation/RER U*	3.40	kg
Electricity, medium voltage, production BR, at grid/BR U*	1.30	kWh

Appendix B. Electrical grid considered

Source: (EPE, 2019)

SOURCE	QUANTITY	UNIT
Electricity, production mix BR/BR U*	1.00	kWh
Brazilian Electrical Matrix (Grid BR)		
Electricity, hard coal, at power plant/UCTE U	0.037	kWh
Electricity, at cogeneration 200kWe diesel SCR, allocation exergy/CH U	0.019	kWh
Electricity, natural gas, at power plant/UCTE U	0.086	kWh
Electricity, hydropower, at reservoir power plant/BR U	0.672	kWh
Electricity, nuclear, at power plant/CH U	0.025	kWh
Electricity, at wind power plant/RER U	0.076	kWh
Electricity, bagasse, sugarcane, at fermentation plant/BR U	0.085	kWh

Appendix C. Example of transportation inventory (product baseline)

PRODUCT	QUANTITY	UNIT
Alkylbenzene sulfonate, linear, petrochemical, at transportation/RER U*	1.00	kg
Inputs		
Alkylbenzene sulfonate, linear, petrochemical, at plant/RER U*	1.00	kg
Transport, freight, lorry 3.5–7.5 metric ton, EURO4 {RER}| transport, freight, lorry 3.5–7.5 metric ton, EURO4 | APOS, U	0.129	tkm

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