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Ecodesign coupled with Life Cycle Assessment to reduce the environmental impacts of an industrial enzymatic cleaner

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ABSTRACT

The application of life cycle assessment (LCA) through ecodesign strategies enables making informed choices on the sustainability of products and services. Accordingly, in this work we quantify the environmental impacts associated with the life cycle of an enzymatic multipurpose cleaner to provide guidance on how producers and consumers can boost the implementation of more sustainable production and consumption patterns. LCA methodology with primary data is applied. To enable future comparison, 1 kg of detergent in its container is used as a functional unit, and cradle-to-grave system boundaries are set according to the reference *"detergents and cleaning products"* Product Category Rules (PCR). The environmental impacts are grouped into upstream, core and downstream life cycle phases, and seven impact categories are analyzed. Regarding the upstream stage, the degreaser 3-butoxy-2-propanol has the larger environmental load in 4 of 7 categories analyzed. During the core stage, electricity, natural gas and road transport of raw materials are the main contributors, while road transport has the largest share in 6 of the 7 downstream impact categories. Considering a cradle-to-grave boundary, a CO_2-eq footprint of 0.76 kg per kg of packaged detergent is obtained, where energy consumption and transportation are the main impact drivers. Five ecodesigned scenarios are proposed to lower the overall environmental footprint of the enzymatic cleaner, including the use of renewable energy, higher volume packaging, the use of recycled packaging, the use of renewable surfactants from vegetal origin instead of petrochemically derived ones and the change from road transport for distribution to railway transport are analyzed. Among the proposed new scenarios aimed lower the cradle-to-grave environmental impacts, enlarging packaging volume results the most effective choice, lowering the impacts by 8–38% (global warming reduction by 25%). On the contrary, the substitution of the petroleum-based surfactant by one based on palm kernel oil increases the impacts by 4–16%. Overall, using larger packaging and the adoption of railway transportation are the most effective measures to reduce the impacts. As the followed PCR does not take into account the impacts generated after the use phase, we encourage its extension to the complete life cycle so toxicity and biodegradability aspects can also be considered. Covering from the extraction of raw materials, to production, transport, use and end-of-life, this work may pave the path toward the adoption of responsible production and consumption patterns in the cleaning sector.

1. Introduction

Cleaning agents are present in practically all areas of our life as they are used from household activities to a wide variety of industries, such as chemical, pharmaceutical or petrochemical activities (Lucchetti et al., 2019; Vargas-Parra et al., 2019). Within the cleaning sector, detergents are, from an economic point of view,

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the most relevant product with a global investment of approximately 60 billion dollars per year (Giagnorio et al., 2017). The function of detergents is to wash, understood as the action of removing deposits (from textiles, metal surfaces or others) that are difficult to dissolve in water. As the washing effectiveness is influenced by the characteristics of the material to be cleaned and the composition of the detergent used, many different detergents are available as recently highlighted in the comparative work of (Rebello et al., 2020). Given the large amount of detergents used worldwide, cleaners could have serious environmental impacts if not properly designed. To fulfill their function, detergents are composed by a combination of agents, including stabilizers, colorants, fragrances, viscosity agents, foaming agents, solvents and surfactants (Farias et al., 2021), being the latter considered as the most relevant driver in terms of functionality and environmental sustainability. The surfactant plays a pivotal role as it increases the surface tension of the washing liquid, facilitating its penetration into the material to be cleaned and allowing the emulsion and subsequent suspension of the dirt (Bzdek et al., 2020). Is such the economical relevance of surfactants that their market is expected to reach an economic value of $44.9 billion by 2022 (Rebello et al., 2020).

The pressing threat of climate change and environmental pollution affecting both animal and human life associated with conventional manufacturing of detergents requires the implementation of responsible production and consumption patterns which have been long neglected for economic reasons. Recent works by Amjad and de Oliveira have focused on the relevance of the cleaner sector and how eco-responsible solutions can be implemented to transition towards sustainable production and consumption patterns (Amjad et al., 2021; de Oliveira et al., 2021). Indeed, surfactants are considered as one of the most critical contributors in detergent composition as they largely deplete and damage the micro- and macro-biota of the aquatic and terrestrial environment (Rebello et al., 2020). Nowadays, surfactants from different origin are used in detergent formulation. Surfactants from petrochemical origin involving complex chemical transformations from petroleum derivatives represent 44% of the total (e.g. linear alkyl sulfate), while oleochemical surfactants are obtained upon the chemical transformation of vegetable oils such as coconut and palm oil, and present 52% of the total market share (e.g. sodium dodecyl sulfate) (Rebello et al., 2020). Finally, bio-surfactants such as sophorolipid rely on plants such as corn, palm, coconut and olive, or microorganisms, and are scarcely used (4% of the total). Marchant and Banat concluded that in spite of the environmental benefits of adopting biosurfactants which are less harming to the environment yet robust enough for industrial use, the extraction and refining costs encourage industries to use petrochemical and oleochemical surfactants (Marchant and Banat, 2012). However, they also encompass lager climate change and ozone layer depletion contribution as a result of the chemical processes involved during their synthesis. In this regard, ethoxylated alcohol is one of the most versatile surfactants as it is biodegradable and can be synthesized through both petrochemical and oleochemical approaches (Saouter et al., 2006).

Schowanek et al. recently provided a summary of the environmental impacts of detergents or its components, including petrochemical- and oil-based laundry detergents, or plant-oil based biosurfactants (Schowanek et al., 2018),. The last two decades have witnessed an increasing relevance of green chemistry concepts applied into detergent manufacturing, with lower amounts of toxic or hazardous products and a greater presence of bio-tensioactives (Perfumo et al., 2018). The substitution of surfactants based on petrochemical resources by those of renewable origin can be considered a plausible strategy to enable the fabrication of cleaners with lower toxicity and improved degradability, thus resulting in an environmentally preferred solution (Rocha e Silva et al., 2020). As their cleaning capacity is similar to those of non-renewable origin in terms of working temperature and concentration, their use does not jeopardize detergent functionality (Klöpffer, 2000). However, contradictory results have been obtained when comparing petroleum-derived and bio-derived detergents. Shah et al. analyzed 18 impact categories summarizing the cradle-to-grave environmental performance of petrochemical and oleochemical surfactants and concluded that the palm oil surfactant performs better on 6 impact categories, while petrochemical performs better on 12 of them (Shah et al., 2016).

These results emphasize the need for comprehensive works evaluating the environmental impacts of petro-based and bio-based detergents. According to (Farias et al., 2021), green surfactants present a growing future market economy projection, also considering the recent events regarding the long-term global supply of fossil fuel-derived resources. Providing transparent, reliable and comparable data regarding the environmental impact of the detergents may help consumers to make a thorough choice to enable a more sustainable consumption. This would also help to reduce the greenhouse gas emissions of laundry washing activities, where detergent-related parameters such as the type and amount used can markedly affect the overall impacts, especially in countries with low-carbon electricity mix (Shahmohammadi et al., 2018). The environmental performance of detergents can be measured and disclosed using life cycle assessment (LCA) methodology, which represents a potential and versatile approach to quantify the environmental impacts of a product or a service through the life cycle (applied into fields as varied as batteries or valorisation of discarded organic waste) (Iturrondobeitia et al., 2021; Sillero et al., 2021). To enable an improved comparison, which is considered as one of the shortcomings of LCA, the analysis should be performed following a standardized procedure. In this context, the Environmental Product Declaration (EPD) is aimed at providing relevant and comparable information regarding the environmental performance of a product or service (see the work by Del Borghi et al., 2020 to get further insights on different communication approached through ecolabels). Although EPDs are considered a Type III Ecolabel, they do not need to fulfill minimum environmental requirements to be certified. Instead, EPDs are aimed to disseminate LCA results so its environmental performance can be clearly communicated. The study relies on specific so-called Product Category Rules (PCR) (disclosed in ISO 14025, ISO 21930 and EN 15804 standards), which defines the rules for a specific group/category of products/services (Del Borghi et al., 2020; Schau and Fet, 2008). As EPDs provide contrasted information on the environmental functionality, they are a useful tool to minimize their environmental loads through re-design strategies.

It is generally accepted that nearly the 80% of all product-related environmental impacts are determined during the design phase. Importantly, the implementation of LCA during the early design stages through the so-called eco-design strategies enables the iterative evaluation of how the environmental impacts of a given product could be reduced, either for those applied into business-to-consumer or business-to-business models (Kamalakkannan and Kulatunga, 2021; Polverini, 2021). The consideration of these new scenarios opens new possibilities for strategic decisions aimed to a sustainable development. In this context, we analyze the cradle-to-grave environmental impacts of an enzymatic multipurpose cleaner to study the critical environmental stages during its life cycle. Primary data is used to carry out the LCA, providing reliability to obtained results. The impacts have been classified into upstream, core and downstream lifecycle stages. The "Detergents and washing preparations" PCR was followed to perform the impact analysis. With a CO_2 footprint of 0.76 kg CO_2-eq per kg of packaged detergent, energy consumption and transportation are the main

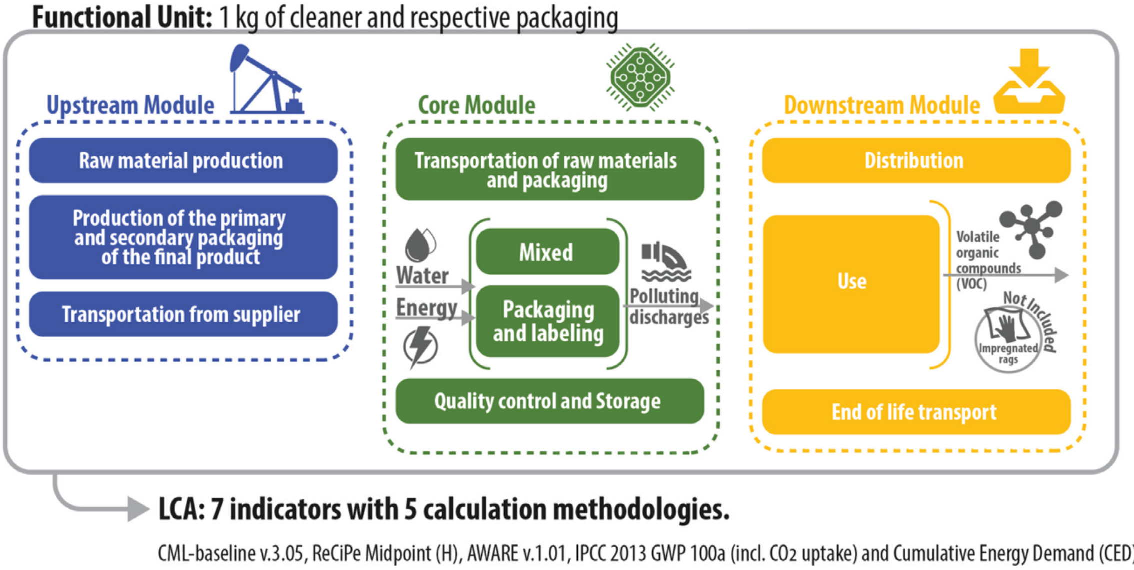

Fig. 1. LCA scope for the DD456 cleaner according to the "Detergents and washing preparations" PCR.

environmental impacts drivers during the life cycle of the enzymatic cleaner. As a novel contribution, five alternative scenarios are considered and their environmental impacts are quantified, serving as a guidance to redesign environmentally-friendlier products. Our results emphasize the need for extending the detergents and cleaning products PCR to the complete life cycle so toxicity and biodegradability aspects can also be considered. These results may facilitate the transition of production and consumption patterns associated to cleaner-related goods towards more sustainable practices.

2. Methods

2.1. LCA goal and scope

LCA is used to quantify the environmental impact of a product, process, or system throughout its life cycle. It is based on the collection and analysis of the inputs and outputs of the system to obtain results that show its potential environmental impacts. This enables ecodesign strategies to reduce the environmental impacts (Civancik-Uslu et al., 2019). LCA is divided into four stages as follows: objective and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation (ISO 14040:2006; ISO 14044:2006). LCA studies have been performed following the "Detergents and washing preparations" PCR (see **Table S1** in the Supporting Information) (Detergents and Washing Preparations, The International EPD System, 2011).

The main aim of this study is the evaluation of the environmental performance of the industrial enzymatic multipurpose cleaner (DD456) produced by A&B Laboratorios de Biotecnología S.A.U., and the optimization of its environmental performance through ecodesign principles. To enable an easier comparison with previously reported studies on the environmental impacts of cleaners and detergents, 1 kg of detergent in its container has been used as a functional unit (FU) (Rebello et al., 2020). The system boundaries are set according to the reference PCR, in which all attribution processes from "cradle-to-grave" are included using the principle of "limited loss of information in the final product". In this way, the life cycle has been divided into three different stages: *upstream*, *core* and *downstream*. Accordingly, Fig. 1 shows the scope of the study taking into account the "Detergents and washing preparations" PCR with a cradle-to-grave.

The production of auxiliary materials used during the upstream stage, such as rugs, and ordinary cleaning and maintenance operations during the core has not been included in the analysis. As the DD456 cleaner does not require specific storage or packaging conditions, these processes have been modelled based on energy consumption (*core*). The electrical consumption of the forklifts has been imputed by estimating the unproductive energy consumption.

LCA analyses were performed with OpenLCA software using Ecoinvent 3.7 Data set. In its section *"5.4.5 Environmental Performance"*, the reference PCR indicates that following impact categories need to be analyzed during the upstream, core and downstream stages: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), formation potential of tropospheric ozone (POCP), abiotic depletion potential – elements, abiotic potential – fossil fuels and water scarcity potential (see **Table S2** for further details). GWP impact category must be expressed cumulatively as tons of carbon dioxide equivalent and broken down according to the origin of the carbon dioxide: fossil, biogenic or related to land use or transformation. The disaggregation has been performed using the IPCC 2013 GWP 100a, that includes the CO_2 uptake. Furthermore, CML Baseline, ReCiPe Midpoint (H), AWARE and Cumulative Energy Demand (CED) calculation methodologies have been used to model the products.

2.2. Product specifications

An enzymatic all-purpose cleaner detergent is selected for the analysis (see **Figure S1**). Specifically, the DD456 industrial degreasing detergent aimed to clean large surfaces and all types of machinery components is selected. This detergent is suitable for daily cleaning of materials such as steel, plastic, glass, marble, ceramic or fabric and is characterized by its rapid action. The product already has the European Ecolabel Type I and has been awarded with the European Environmental Award. The DD456 has undergone through different ecodesign strategies to improve its environmental performance. Accordingly, it is based on enzymes and water (thus avoiding the need to toxic organic solvents) and does not bear any safety/hazard regarding Globally Harmonized System of Classification and Labelling of Chemicals (see **Table S3** for further details on the chemical composition). Importantly, the enzymes help to degrade oils and fats, enhancing the effectiveness

Table 1
Environmental impacts of the DD456 detergent according to the “Detergents and washing preparations” PCR.

.INDICATOR		UNIT	UPSTREAM	CORE	DOWNSTREAM	TOTAL
Global Warming Potential (GWP)	**Fossil**	$x10^{-2}$ kg CO_2-eq	31.19	6.39	19.85	**57.42**
	Bio		5.66	1.69	11.23	**18.58**
	Land Use		0.06	0.12	0.01	**0.19**
	TOTAL		**36.91**	**8.20**	**31.08**	**76.19**
Acidification Potential (AP)		$x10^{-4}$ kg SO_2-eq	13.00	2.40	6.10	**21.50**
Eutrophication Potential (EP)		$x10^{-4}$ kg $PO_4{}^{-3}$-eq	5.80	0.91	8.80	**15.51**
Photochemical Ozone Creation Potential (POCP)		$x10^{-5}$ kg C_2H_4-eq	12.00	1.56	4.76	**18.32**
Abiotic Depletion Potential - Elements (ADPe)		$x10^{-6}$ kg Sb-eq	7.63	2.77	5.20	**15.60**
Abiotic Depletion Potential - Fossil Fuels (ADPff)		MJ	7.86	3.05	2.81	**13.72**
Water scarcity footprint (WSF)		$x10^{-2}$ m^3-eq	42.22	9.65	1.67	**53.55**

of the product and reducing the amount of required surfactants (Philipp et al., 2021).

2.3. Product category rule (PCR) specifications

Product Category Rules (PRC) contains instructions on how the life cycle assessment of a specific product category needs to be performed. They provide further details in comparison with the ISO 14040 and ISO 14044. The functional unit, the system boundaries, the impact categories that should be analyzed and the accepted cut-off criteria are defined. Its main objective is that functionally similar products should be evaluated following a similar procedure. Following the baseline PCR, our analysis covers data on elemental flows to and from the product system that contribute to at least 99% of the stated environmental impacts (not including processes that are explicitly outside the system boundaries described in the PCR). The information used for the life cycle analysis of the DD456 detergent has been obtained from:

- Primary data provided by A&B Laboratorios de Biotecnología. This includes information related to the environmental aspects of the system, raw materials, energies, waste, emissions and discharges. This enables the full definition of the life cycle inventory regarding used chemical compounds in detergents, considered one of the main challenges faced by universities, environmental agencies and major manufacturers to design an accurate LCA.
- Secondary data from the Ecoinvent 3.7 database related to the life cycle impacts of the materials and energies of the process.

The year selected for the elaboration of the inventory was 2019, the most recent year representative of a normal activity. All the information shown in the inventory related to the consumption of raw materials and energy is real and traceable, as well as those related to production, waste management, waste and emissions in use of the product. The data on the transport of raw materials from suppliers to A&B Laboratorios de Biotecnología correspond to the distance at which the suppliers are located, and the means of road transport has been estimated according to:

- Distances equal to or greater than 500 km, truck with load capacity of 16–32 t.
- Distances less than 500 km and for last mile trips, 10 km, and truck with a load capacity of 3.5 to 7.5 t.

2.4. Comparison with environmental impacts of cleaners

The results have been compared to previously reported environmental impacts arising from detergents and cleaners. For the sake of comparison, only LCAs based on EPDs have been taken into account. In this sense, results have confronted against those reported by the Italian company È COSÌ, who produces and markets detergent and disinfectant products (Rebello et al., 2020). This helps to understand whether or not the industrial enzymatic multipurpose cleaner here analyzed is environmentally preferred over other commercially available options. The first EPD from È COSÌ was published in 2011, which has been later revised in 2020 (Rebello et al., 2020). The environmental impacts of 30 of their products based on the PCR for detergents and cleaning products is provided. The impact categories were calculated using IPCC 2013 for global warming potential based on 100 years impacts (including CO_2 uptake), CML-baseline v.3.05 for acidification potential, eutrophication potential, abiotic depletion potential (elements) and abiotic depletion potential (fossil fuels), ReCiPe v.1.01 Midpoint with Hierarchist (H) perspective for formation potential of tropospheric ozone, AWARE for water scarcity footprint and Cumulative Energy Demand (CED) for primary energy resources. Of the 30 products disclosed in the EPD of È COSÌ, Brixen and Proteo can be considered close to the cleaner here studied in terms of functionality (Rebello et al., 2020).

3. Results and discussion

3.1. Environmental impacts of the detergent

The cradle-to-grave environmental impacts of the DD456 detergent have been firstly evaluated according to the "Detergents and cleaning products" PCR. From the entire inventory, 93.9% could be modelled according to Ecoinvent 3.7 database, while 5.1% of the remaining compounds were modelled based on analogies. Therefore, our work takes into account 99% of the detergent (by weight), leaving aside from the analysis the water-soluble sodium gluconate and the green dye used in the detergent. This allows compliance with the reference PCR, which stipulates that 99% by weight of the components of the product analyzed must be included. Following the mandates of the reference PCR, the LCA of DD456 has been calculated by grouping the unit processes in the three lifecycle stages: *upstream, core* and *downstream*. Obtained results are summarized in Table 1. **Tables S4** to **S6** display further details on the environmental impacts for each lifecycle stage obtained according to the CML-IA Baseline (2016) method, where the processes with the highest contribution are red highlighted.

It is seen that the production of 3-butoxy-2-propanol and ethoxylated alcohol concentrate the most relevant environmental loads during the *upstream* phase. Throughout the *core* stage, energy consumption (comprising natural gas and electricity) and raw material transport are the most relevant drivers; while hazardous waste management is the process that contributes most to water scarcity due to the large amount of water required in this stage (by 48%). Those results are in line with the study reported by Giagnorio et al., who concluded that the primary energy demand and global warming potential play a key role of the application of renewable resources in the detergent production phase (study of the environmental impacts of detergents throughout their life cycle comparing petrochemicals and oleochemicals and using the ReCiPe, CED and IPCC 2007 methods) (Giagnorio et al., 2017). Prod-

Table 2
Cumulative Energy Demand (CED) impacts of the DD456 detergent.

PARAMETER	UNIT	UPSTREAM	CORE	DOWNSTREAM	TOTAL
Non-renewable, biomass	MJ	2.70E-04	2.46E-05	5.87E-05	**3.53E-04**
Renewable, water	MJ	1.60E-01	2.95E-01	2.12E-02	**4.76E-01**
Non renewable, fossil	MJ	7.83E+00	3.36E+00	2.98E+00	**1.42E+01**
Non-renewable, nuclear	MJ	9.27E-01	8.10E-02	6.22E-02	**1.07E+00**
Renewable, biomass	MJ	4.15E-01	1.14E-01	1.07E-02	**5.40E-01**
Renewable, wind, solar, geothermal	MJ	9.55E-02	7.80E-01	7.43E-03	**8.83E-01**

uct distribution by means of road transportation contributes most markedly to *downstream* impacts in 6 of the 7 categories, while plastic waste management is only relevant eutrophication category. To lower the environmental impact of the detergent, apart from the use of bio-based compounds, environmentally friendlier stabilizers, colorants, fragrances, viscosity agents, foaming agents, and solvents with lower toxicity and higher biodegradability may be also introduced during detergent formulation (Farias et al., 2021).

To provide a better understanding from the perspective of the energy footprint, the CED method has been applied as it represents the direct and indirect energy use throughout the life cycle (Huijbregts et al., 2006). The results in Table 2 show that a large fraction on non-renewable energy is used during the lifecycle of the detergent, mostly originating from fossil and nuclear plants. *Upstream* is the stage showing the largest CED, where raw material and packaging are produced. In the future, selecting alternative raw materials and packaging (either from different origin or material) should be pursued. For example, fabricating cleaning products within closed circuits for both biological and technical cycles using waste was as raw material could be an additional strategy to lower the environmental impacts in the *upstream* stage (Edser, 2014). Moreover, increasing the share of the renewable energy mix could serve to lessen the overall impacts of the detergent due to a reduction of pollution-related environmental impacts of electricity production, such as CO_2 emissions, freshwater ecotoxicity, eutrophication, and particulate-matter exposure (Hertwich et al., 2015).

3.2. Comparison with commercial detergents

Obtained environmental impacts have been compared with the EPD disclosed by the Italian company È COSÌ, a manufacturer aimed to provide professional and industrial detergents and disinfectants (Rebello et al., 2020). This manufacturer provides the results of the analysis of the 30 domestic cleaning, catering cleaning and laundry cleaning products. This information was selected because, to the best of our knowledge, no additional EPD showing the environmental impacts of detergents is publicly accessible. However, the product analyzed in this work, the DD456 cleaner, is an industrial degreasing detergent aimed to clean large surfaces and all types of machinery components, tools and parts. In this sense, it should be pointed out that the detergents aimed for the industrial field contain a higher additive concentration to ensure their function (in comparison with those designed for domestic use). Ideally a comparison should be carried out other industrial detergents, although the lack of information has pushed us towards Proteo and Brixen cleaners (see **Table S7** for further details). Proteo is the most closely related product regarding the functionality of the DD456 cleaner. With a pH value of 8.7, Brixen presents a milder character in comparison with Proteo, whereas Proteo has a pH of 11.5 (higher the pH values result in improved degreasing capacity but also larger environmental impacts). Based on these data, it can be concluded that Proteo's cleaning and degreasing capacity is much higher than Brixen and therefore closer to the cleaning power of the DD456, which is designed for industrial cleaning processes requiring more vigorous degreasing than domestic products Although the reference PCR defines the categories to be analyzed and the corresponding units, È COSÌ uses for its category "potential formation of tropospheric ozone" a "kg of NMVOC" (non-methane volatile organic compounds) indicator as opposed to the "kg of C_2H_4 eq" stated in the PCR. Therefore, even though NMVOC have been converted to C_2H_4 eq, the comparison in this category is considered not accurate.

The results are summarized in Fig. 2. Obtained impacts are in range with those of È COSÌ's products with the exception of the abiotic depletion category. As shown in **Table S8**, the electricity consumption and transportation of raw materials from the supplier to the DD456 manufacturer are responsible for the large abiotic depletion impact obtained (a 100% renewable electricity was used for the modeling; see **Table S9**). It should be noted that È COSÌ's EPD considers an electricity supply partly originating from the standard Italian electricity mix and partly from its own photovoltaic panels. A possible error in the quantities expressed for this category is considered possible given the low impact of electricity consumption and transportation.

Regarding the GWP category of Proteo and Brixen, striking results are observed in the section of biogenic CO_2-eq emissions, where the biotic carbon uptake is displayed as a negative value, generating differences with DD456. A possible cause of these negative values is that one or more of the components of È COSÌ products are considered a bio-product and this result in absorption greater than emission. However, further information than that discloses in their EPD would be needed to conclude that this is the main cause. A second option would be that part of the electrical energy consumed in the factory arises from photovoltaic sources, contributing to the biotic carbon uptake.

DD456 shows an improved environmental performance over Proteo, the most similar cleaner in terms of performance, with overall impact reductions between 10 and 83% (the same impact was obtained in the eutrophication category). On the contrary, higher environmental loads are generally observed when comparing with Brixen. It should be considered, that in our opinion, the biodegradability and toxicity of detergents remains poorly modeled in databases. For example, the impacts after use covering biodegradability and toxicity are not properly reflected, as the ethoxylated alcohol surfactant is one of the components that contribute largely to the overall impacts of the enzymatic multipurpose cleaner, in spite of its readily biodegradable character (Bragin et al., 2020). Therefore, possible environmental benefits from the DD456 detergent are not reflected in the EPD results provided in Fig. 2.

To shed further light on these results, the impact contribution according to the different lifecycles (*upstream, core* and *downstream*) is analyzed in Table 3. Overall, Brixen presents a lower environmental impact over Proteo, especially at the *core* (energy consumption and the transportation of raw materials from supplier to manufacturer are the main contributors) and *downstream* (product distribution, use of water and packaging) stages. The raw material transport from the supplier to the manufacturer and the subsequent distribution of the final product seem to be the processes that make the difference. The final management of detergent pack-

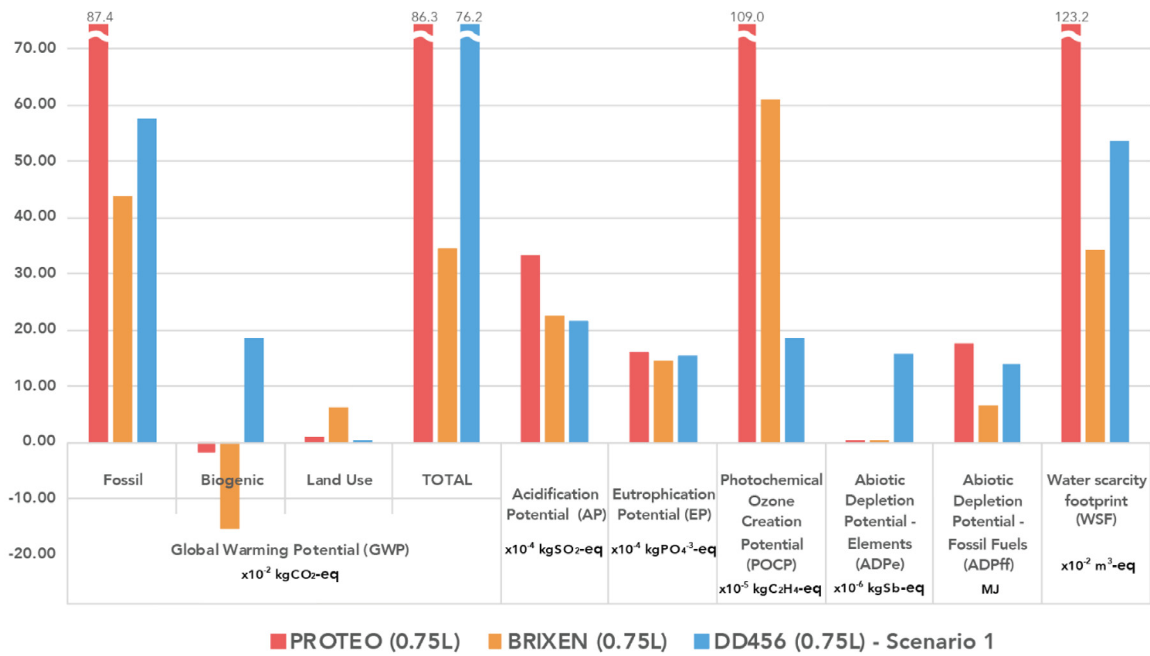

Fig. 2. Comparison of the environmental impacts of studied enzymatic cleaner with the corresponding EPD's to Proteo and Brixen products.

Table 3
Environmental impacts of Proteo and Brixen cleaners for *upstream, core* and *downstream*) lifecycles. POCP unit has been modified according to: non-methane volatile organic compounds (NMVOC) 1 kg = 0.416 ethylene-eq, Goedkoop (2000).

			PROTEO (0.75 L)				BRIXEN (0.75 L)			
INDICATOR		**UNIT**	**UPSTREAM**	**CORE**	**DOWNSTREAM**	**TOTAL**	**UPSTREAM**	**CORE**	**DOWNSTREAM**	**TOTAL**
Global Warming Potential (GWP)	**Fossil**	x10^{-2} kg CO_2-eq	72.00	5.60	9.80	**87.40**	33.00	5.00	5.60	**43.60**
	Bio		−3.50	0.21	1.40	**−1.89**	−17.00	0.21	1.40	**−15.39**
	Land Use		0.83	0.00	0.00	**0.83**	6.20	0.00	0.00	**6.20**
	TOTAL		**69.33**	**5.81**	**11.20**	**86.34**	**22.20**	**5.21**	**7.00**	**34.41**
Acidification Potential (AP)		x10^{-4} kg SO_2-eq	29.00	2.00	2.30	**33.30**	20.00	1.70	0.73	**22.43**
Eutrophication Potential (EP)		x10^{-4} kg $PO_4{}^{-3}$-eq	14.00	0.50	1.60	**16.10**	13.00	0.46	0.99	**14.45**
Photochemical Ozone Creation Potential (POCP)		x10^{-5} kg C_2H_4-eq	95.68	4.58	8.74	**108.99**	54.08	3.41	3.45	**60.94**
Abiotic Depletion Potential - Elements (ADPe)		x10^{-6} kg Sb-eq	0.11	0.00	0.00	**0.11**	0.19	0.00	0.00	**0.19**
Abiotic Depletion Potential - Fossil Fuels (ADPff)		MJ	16.00	0.80	0.66	**17.46**	5.40	0.71	0.23	**6.34**
Water scarcity footprint (WSF)		x10^{-2} m^3-eq	39.00	3.20	81.00	**123.20**	31.00	3.00	0.09	**34.09**

aging also needs to be considered in the *downstream* stage. A more detailed analysis could not be considered given the lack of additional information in the È COSÌ's EPD.

3.3. Five scenarios to lower the environmental footprint of the product

The environmental impacts and the hazard potential of the DD456 cleaner have been reduced following the ISO 14006 standard (Environmental management systems-Guidelines for incorporating ecodesign). The selection of biodegradable components with lower toxicity has been one of the most stringent design requirements so a product with no GHS hazard pictograms is achieved. For example, ethoxylated alcohol is used as a surfactant, which is known to be readily biodegradable. Fig. 3 summarizes the analyzed five new scenarios (with the standardized 1 kg of detergent as functional unit), which are briefly defined as:

- *Scenario 0*: Initialscenario: DD456 packaged in a 0.75 L bottle, marketed in a group of 8 in a cardboard box, with a power supply of the Spanish standard electricity mix. Calculations have been extrapolated to 1 kg of distributed detergent to final user, with the total weight of 1.12 kg including the packaging.
- *Scenario 1*: DD456 packaged in a 0.75 L bottle, marketed in a group of 8 in a cardboard box, with a renewable electric power supply. The current renewable source proportion of the Spanish electric market is used, with 6.8% of solar electricity, 26.4% of hydro-powered generation, 63.0% wind generated electricity and 3.9% of wood and biogas fueled renewable energy (Table S9). This is the current Scenario used by A&B Laboratorios de Biotecnología to produce the DD456 cleaner, since they already have a renewable energy supplier utility.
- *Scenario 2*: DD456 packagedin 10 L carafe, with a renewable electric power supply. This packaging represents an alternative option to the continuous purchase of the 0.75 L container, avoiding 0.055 kg of corrugated board box, and reducing by 32.4% the need of blow molding polymer. It allows refilling individual bottles with a sprayer at the customer's own location so the amount of polyethylene is reduced. The total weight of 1.12 kg (including the packaging) is lowered to 1.05 kg, reducing the impacts not only from upstream and core, but also from downstream section.
- *Scenario 3*: DD456 packaged in a 0.75 L bottle, marketed in a group of 8 in a cardboard box, with a renewable electric power supply. The packaging is obtained from recycled polyethylene. In the upstream section, an increase of 1.15% in the total weight of the packaging is observed (reaching 74.85 g), where 2.07%

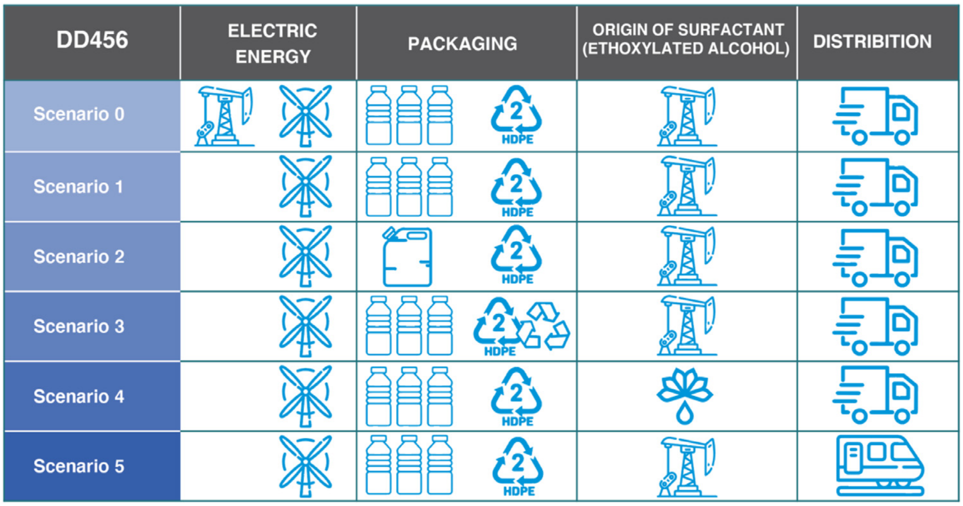

Fig. 3. Summary depicting proposed new five scenarios. As electric energy, standard Spanish mix with fossil and renewable resources (see details in Table S9) and a 100% renewable electric power supply are considered. Packaging considers a 0.75 L bottle made with virgin HDPE, a 10 L carafe made with virgin HDPE or a 0.75 L bottle made with recycled HDPE; surfactants from petrochemical or bio-based origin are considered; distribution considers truck or railway means.

belongs to non-recycled polyethylene, and the remaining to recycled HDPE.

- *Scenario 4*: DD456 packaged in 0.75 L bottles, marketed in a group of 8 in cardboard box, with a renewable electric power supply. Change in the surfactant; ethoxylated alcohol from petrochemical origin is replaced by one from oleochemical origin. Firstly, coconut oil (CO) and palm kernel oil (PKO) have been compared to the petrochemical oil (PC), and PKO has been chosen due to its environmental performance. PKO has been obtained from a non-organically produced palm fruit bunch, with respective herbicides (e.g. 0.14 g glyphosate per collected fruit kg), pesticides (e.g. 0.0018 g of pyrethroid-compound per collected fruit kg) and chemical fertilizers (e.g. 4.17 g of inorganic urea per collected fruit kg).
- *Scenario 5*: DD456 packaged in a 0.75 L bottle, marketed in a group of 8 in a cardboard box, with a renewable electric power supply. The distribution by truck is replaced byrailway(downstream), maintaining the average 1000 kms of distribution network. The previously modelled distribution, performed by a freight lorry of 16 to 32 t (Euro 5 technology), has been replaced by a 100% diesel-powered freight train. The entire transport life cycle of freight train in Europe-15 is represented, including the production and maintenance of the locomotive and the goods wagons, the construction of the railway track and the energy use, and operation emission of a freight train (Ecoinvent). The data of the energy use and operation emissions represent a 1000 Gt average goods train. Variation in the geography of different countries was modeled by Ecoinvent taking into account average performances in flat, hilly and mountain areas.

3.2.1. Scenario 1: renewable electric power supply

Here we analyze how transitioning from a standard energy mix to a mix based on 100% renewable energy affects the resulting environmental impacts of the DD456 cleaner. The standard energy mix has been modelled using 69% energy of fossil origin and 31% energy of renewable origin, while the renewable energy mix has been modelled by modifying the Ecoinvent electricity mix and converting it to 100% renewable. The results are depicted in Table 4 (see **Table S10** for the impacts classified into *upstream, core* and *downstream* lifecycle stages). 4 of the 7 categories decrease significantly after the implementation of renewable energy. Especially relevant are the 26, 19 and 12% reductions in the categories of acidification, tropospheric ozone formation and GWP, respectively. Those results are in line with previous reports underlining the relevance of energy mix during production phase (Rödger et al., 2021). According to primary data from the manufacturer, these improvements are materialized in an estimated cost increase of 0.011 €/kg as the cost for energy increased from the 0.12 €/kWh for the standard scenario to 0.16 €/kWh for the renewable mix.

3.2.2. Scenario 2: 10 L carafe

Using a larger packaging can be sought as a simple strategy to lower the environmental impacts as lower amounts of plastics will be required, reducing raw materials' embodied impact, manufacturing and non-degradable waste (Su et al., 2020). Table 5 summarizes the sensitivity analysis regarding the environmental impacts of the cleaner bottled in 0.75 and 10 L containers (see **Table S11** for the impacts classified into *upstream, core* and *downstream* lifecycle stages). Significant reduction in all of the studied impact categories are observed, with notable changes in eutrophication and GWP, with a 38 and 25% reduction, respectively. Importantly, a reduction of 0.19 kg CO_2-eq per kg could be achieved. Refill business models relying on reuse are environmentally preferred over recycling and they close the materials and energy loop into a more efficient approach (Kunamaneni et al., 2019). Additionally, this refill format could also open up new market possibilities given the fact that customers increasingly seek plastic waste reduction. Additionally, a 44% reduction on the packaging price could be obtained (specific values are not provided to ensure fair competence). Repurposing packaging for durability and reuse is recommended.

3.2.3. Scenario 3: recycled polyethylene packaging

In this case, we explore whether or not the use of recycled polyethylene could result in a reduction of the environmental impacts. The fabrication of the polyethylene containers has been modeled through blow molding, replacing the virgin polyethylene synthesis process by recycled polyethylene. Although recycling seeks to minimize waste generation and prevent the emissions associated with the extraction of virgin materials (Accorsi et al., 2020), as seen in Table 6, this approach barely changes the environmental impact of the product, encompassing reductions of 1% in GWP and 5% in tropospheric ozone formation potential (see **Table S12** for the impacts classified into *upstream, core* and *downstream* lifecycle stages). However, this strategy has a great poten-

Table 4
Environmental impacts arising from sensitivity analysis where the energy mix is changed from standard to renewable.

INDICATOR	UNIT	DD456 Scenario 0	DD456 Scenario 1	Reduction from 0 to 1
Global Warming Potential (GWP)	x10^{-2} kg CO_2-eq	86.50	76.19	**−12%**
Acidification Potential (AP)	x10^{-4} kg SO_2-eq	29.20	21.5	**−26%**
Eutrophication Potential (EP)	x10^{-4} kg $PO_4{}^{-3}$-eq	15.03	15.51	**3%**
Photochemical Ozone Creation Potential (POCP)	x10^{-5} kg C_2H_4-eq	22.60	18.32	**−19%**
Abiotic Depletion Potential - Elements (ADPe)	x10^{-6} kg Sb-eq	15.48	15.59	**1%**
Abiotic Depletion Potential - Fossil Fuels (ADPff)	MJ	14.95	13.72	**−8%**
Water scarcity footprint (WSF)	x10^{-2} m^3-eq	53.33	53.55	**0%**

Table 5
Environmental impacts arising from sensitivity analysis where the packaging size is changed from 0.75 to 10 L.

INDICATOR	UNIT	DD456 Scenario 1	DD456 Scenario 2	Reduction from 1 to 2
Global Warming Potential (GWP)	x10^{-2} kg CO_2-eq	76.19	57.27	**−25%**
Acidification Potential (AP)	x10^{-4} kg SO_2-eq	21.5	18.30	**−15%**
Eutrophication Potential (EP)	x10^{-4} kg $PO_4{}^{-3}$-eq	15.51	9.60	**−38%**
Photochemical Ozone Creation Potential (POCP)	x10^{-5} kg C_2H_4-eq	18.32	13.96	**−24%**
Abiotic Depletion Potential - Elements (ADPe)	x10^{-6} kg Sb-eq	15.59	14.00	**−10%**
Abiotic Depletion Potential - Fossil Fuels (ADPff)	MJ	13.72	12.63	**−8%**
Water scarcity footprint (WSF)	x10^{-2} m^3-eq	53.55	48.66	**−9%**

Table 6
Environmental impacts arising from sensitivity analysis where the packaging material is changed from virgin to recycled polyehylene.

INDICATOR	UNIT	DD456 Scenario 1	DD456 Scenario 3	Reduction from 1 to 3
Global Warming Potential (GWP)	x10^{-2} kg CO_2-eq	76.19	75.80	**−1%**
Acidification Potential (AP)	x10^{-4} kg SO_2-eq	21.5	21.40	**0%**
Eutrophication Potential (EP)	x10^{-4} kg $PO_4{}^{-3}$-eq	15.51	15.51	**0%**
Photochemical Ozone Creation Potential (POCP)	x10^{-5} kg C_2H_4-eq	18.32	17.32	**−5%**
Abiotic Depletion Potential - Elements (ADPe)	x10^{-6} kg Sb-eq	15.59	7.66	**−51%**
Abiotic Depletion Potential - Fossil Fuels (ADPff)	MJ	13.72	13.57	**−1%**
Water scarcity footprint (WSF)	x10^{-2} m^3-eq	53.55	53.30	**0%**

tial to bring economic benefits *via* improved brand positioning, as it allows continues to differentiate the company from its competitors through its commitment to environmental protection. Plastic recycling is also one of the cornerstones of Circular Economy as it allows turning waste into raw materials, keeping materials in use for longer times (Eriksen et al., 2019). Interestingly, polyethylene could be recycled (with no loss on its physic-mechanical properties) around 10 times in comparison with other common packaging materials such as polyethylene terephthalate (PET), which can only be recycled nearly 2–3 times (Schyns and Shaver, 2021).

3.2.4. Scenario 4: oleochemical surfactant

Biomass feedstocks offer a renewable source for their conversion into energy (Malicoet al., 2019), materials such as lignin (Lizundia et al., 2021), and chemicals (Ioannidou et al., 2020). *A priori*, biomass-derived materials represent a good strategy to significantly reduce the environmental impacts of a given product (Ladu and Morone, 2021). Accordingly, we analyzed the potential environmental benefits arising from the substitution of the surfactant, an ethoxylated alcohol from petrochemical origin, by one from oleochemical origin based on palm kernel oil. This would reduce the amount of extracted primary raw materials to produce the cleaner, which is considered one of the cornerstones of Circular Economy. The results in Table 7 show that environmental impacts are only reduced in the fossil fuel depletion category (7%), while they increase by 4–16% in 5 of the analyzed categories (see **Table S13** for the impacts classified into *upstream, core* and *downstream* lifecycle stages). Those results reflect that in spite of the currently a growing demand for bio-products partly originating from the generally perceived consumerś environmental benefits (Confente et al., 2020), renewable-based materials do not *per se* bring lower environmental impacts. Those results agree with Shah et al., who found that the LCA impacts of bio-based products are highly dependent on forest management, fertilizer use and operational practices (Shah et al., 2016). Although the presence of biosurfactants on the market is minimal, exploring their synthesis from agricultural and industrial waste and extending their prospective use could yield to environmentally friendlier industrial cleaners, one of the priorities within the European Green Deal.

To shed further light on these *a priori* counterintuitive results, the impacts arising from the raw material extraction and transformation of ethoxylated alcohol are compared (cradle-to-gate perspective) for both cases using a ReCiPe 2016 Midpoint analysis (palm kernel oil and coconut oil-based ethoxylated alcohol is modeled according to Ecoinvent 3.7 database). Table 8 summarizes obtained comparative results, where the lowest impact for each category remains highlighted. It is seen that the oleochemical synthesis route from coconut oil has the larger impacts in most of the analyzed categories. Such large impacts could arise from the localized coconut oil production, as a large fraction originates from tropical island nations (Meijaard et al., 2020). In this sense, coconut oil production represents a serious biodiversity threat, being deforestation one of the main drivers. When palm kernel oil is used as a raw material, the impacts could be lowered in 8 categories (in comparison with petrochemical synthesis). However, the marked large impacts on GWP and terrestrial ecotoxicity attributable to oleochemical synthesis based on palm oil remain particularly striking.

When modeling the 4th scenario with vegetal-based oil ethoxylated alcohol, several chemical compounds have been identified. Authors consider that further analysis with organic crop production would notoriously reduce the impact of the oleochemical cleaner. The estimated impact reduction will be driven by avoiding the compounds currently present in the modelled alcohol such as herbicides (metsulfuron-methyl, glyphosate, parquat and 2,4-dichlorophenoxyacetic acid) and pesticides (pyrethroid-

Table 7
Environmental impacts arising from sensitivity analysis where the petroleum-based surfactant has been replaced by one from oleochemical origin (palm kernel oil).

INDICATOR	UNIT	DD456 Scenario 1	DD456 Scenario 4	Reduction from 1 to 4
Global Warming Potential (GWP)	x10^{-2} kg CO_2-eq	76.19	79.09	**4%**
Acidification Potential (AP)	x10^{-4} kg SO_2-eq	21.5	21.60	**0%**
Eutrophication Potential (EP)	x10^{-4} kg $PO_4{}^{-3}$-eq	15.51	17.11	**10%**
Photochemical Ozone Creation Potential (POCP)	x10^{-5} kg C_2H_4-eq	18.32	21.32	**16%**
Abiotic Depletion Potential - Elements (ADPe)	x10^{-6} kg Sb-eq	15.59	9.49	**−39%**
Abiotic Depletion Potential - Fossil Fuels (ADPff)	MJ	13.72	12.72	**−7%**
Water scarcity footprint (WSF)	x10^{-2} m^3-eq	53.55	55.65	**4%**

Table 8
Environmental impacts arising from surfactants obtained through 3 different processes, petrochemical, coconut oil and palm kernel oil, using 1 kg of ethoxylated alcohol as functional unit.

INDICATOR	UNIT	Petrochemical (PC)	Coconut Oil (CO)	Palm Kernel Oil (PKO)	Reduction from PC to CO	Reduction from PC to PKO
Fine particulate matter formation	x10^{-3} kg PM2.5-eq	22.90	3.91	2.80	−83%	−88%
Fossil resource scarcity	x10^{-1} kg oil-eq	14.50	10.34	9.35	−29%	−36%
Freshwater ecotoxicity	x10^{-2} kg 1,4-DCB	10.06	22.51	9.82	124%	−2%
Freshwater eutrophication	x10^{-4} kg P-eq	5.40	7.80	5.50	44%	2%
Global warming	kgCO_2-eq	2.19	2.61	2.86	19%	31%
Human carcinogenic toxicity	x10^{-2} kg 1,4-DCB	12.93	2.17	1.24	−83%	−90%
Human non-carcinogenic toxicity	kg 1,4-DCB	1.25	2.72	1.11	117%	−12%
Ionizing radiation	x10^{-1} kBq Co-60-eq	1.75	1.85	1.75	5%	0%
Land use	x10^{-2} m^2a crop-eq	3.57	230.09	85.37	6342%	2290%
Marine ecotoxicity	x10^{-3} kg 1,4-DCB	1.29	2.08	1.24	61%	−4%
Marine eutrophication	x10^{-5} kg N-eq	3.68	403.00	195.00	10,862%	5204%
Mineral resource scarcity	x10^{-3} kg Cu-eq	8.53	15.11	11.56	77%	36%
Ozone formation, Human health	x10^{-3} kg NO_x-eq	5.23	6.43	4.76	23%	−9%
Ozone formation, Terrestrial ecosystems	x10^{-3} kg NO_x-eq	6.02	7.23	5.41	20%	−10%
Stratospheric ozone depletion	x10^{-7} kg CFC11-eq	3.48	61.86	46.94	1680%	1250%
Terrestrial acidification	x10^{-3} kg SO_2-eq	6.30	12.33	7.41	96%	18%
Terrestrial ecotoxicity	kg 1,4-DCB	1.78	3.26	2.62	84%	48%
Water consumption	x10^{-2} m^3	3.27	31.18	4.39	855%	34%

compound, carbofuran). Furthermore, instead of using chemical fertilizers, such as currently used ones (inorganic urea, potassium chloride, ammonium nitrate, potassium sulfate, inorganic phosphorus, inorganic nitrogen and ammonium sulfate), organic compost and manure would reduce the environmental affections. Environmental impact improvements in palm oil production from certified cultivation obtaining a 35% reduced GHG emissions compared to conventional crop can be obtained. Additionally, management strategies are being developed in oil palm crops to lower the above-mentioned pesticide usage. It has also been identified that with a sustainable crop production of coconut and palm kernel oil the fatty alcohols from fossil origin used in the detergent could be replaced by those of biological origin with lower GWP (Schowanek et al., 2018). Finally, biorefinery approaches aimed at the conversion of abundant agricultural residues into high added-value products (such as surfactants) may provide environmentally favourable options over the approaches relying plant sources specifically aimed at oil production (Sillero et al., 2021).

3.2.5. Scenario 5: distribution by railway

Here the substitution of the initial scenario considering a 100% road distribution by a railway transport is analyzed. To do so, 100% road transport is replaced by a 100% diesel-fueled railway transport in the downstream stage. As shown in Table 9**,** notable reductions are achieved, where abiotic depletion and GWP are reduced by 29% and 16%, respectively (see **Table S14** for the impacts classified into *upstream, core* and *downstream* lifecycle stages). Those results are in line with the European Environment Agency Report No 19/2020 on “Transport and environmental report 2020, Train or plane?”, which underlines the generally preferred rail travel over plane or petrol/diesel-powered cars (although the results can change depending on several conditions) (European Environment Agency, 2020).

Finally, Fig. 4 summarizes the environmental impacts of the 6 scenarios considered here, where *scenario 1* considers the initial case analyzed in Section 3.1. Notable reductions are obtained when the detergent is packaged into a 10 L carafe (*scenario 2*), avoiding the continuous purchase of smaller 0.75 L bottle through a refilling alternative. The use of recycled polyethylene (*scenario 3*) slightly reduces the environmental impacts, while adopting surfactants based on renewable resources (*scenario 4*) increases the environmental pressures in 5 of the analyzed impacts. Finally, railway transportation is preferred as it lowers the impacts on all the categories, especially in the GWP.

This research brings light as it shows how the specific actions that are behind the modeled ecodesigned scenarios can contribute to reduce the total environmental impact of the final product. Fig. 5 shows the reductions over Scenario 1 (Tables S15–17). It should be stated that the current use of PKO is modeled with a non-organic production, thus, organically produced one could significantly improve the performance:

Table 9
Environmental impacts arising from sensitivity analysis where a 100% diesel-fueled railway transport is used during the *downstream* stage.

INDICATOR	UNIT	DD456 Scenario 1	DD456 Scenario 5	Reduction from 1 to 5
Global Warming Potential (GWP)	x10^{-2} kg CO_2-eq	76.19	63.93	**−16%**
Acidification Potential (AP)	x10^{-4} kg SO_2-eq	21.5	20.50	**−5%**
Eutrophication Potential (EP)	x10^{-4} kg $PO_4{}^{-3}$-eq	15.51	15.41	**−1%**
Photochemical Ozone Creation Potential (POCP)	x10^{-5} kg C_2H_4-eq	18.32	17.30	**−6%**
Abiotic Depletion Potential - Elements (ADPe)	x10^{-6} kg Sb-eq	15.59	0.82	**−95%**
Abiotic Depletion Potential - Fossil Fuels (ADPff)	MJ	13.72	11.76	**−14%**
Water scarcity footprint (WSF)	x10^{-2} m^3-eq	53.55	51.89	**−3%**

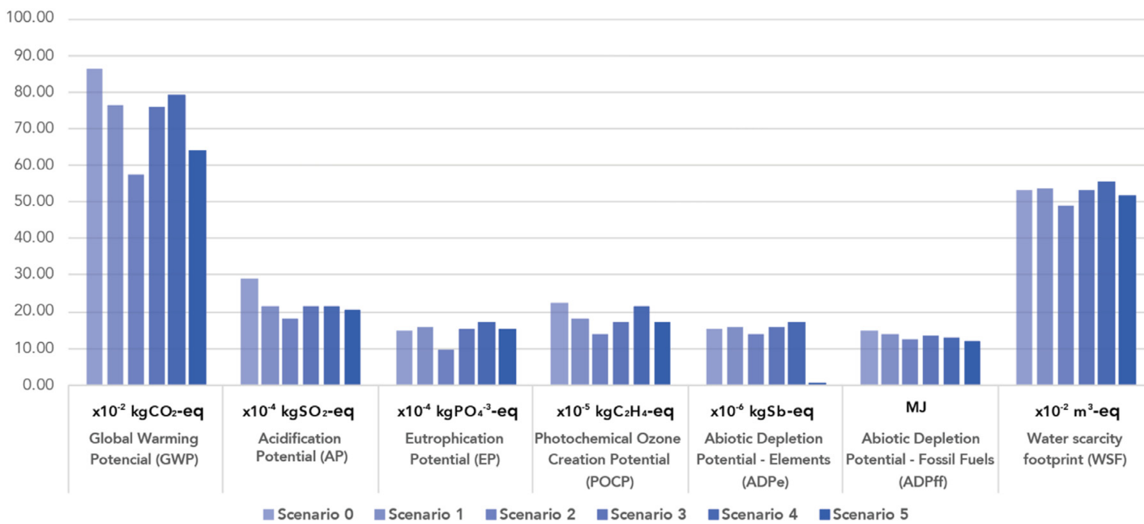

Fig 4. Comparison of the environmental impacts regarding 6 possible scenarios (Scenario 1 is the currently used scenario to produce DD456).

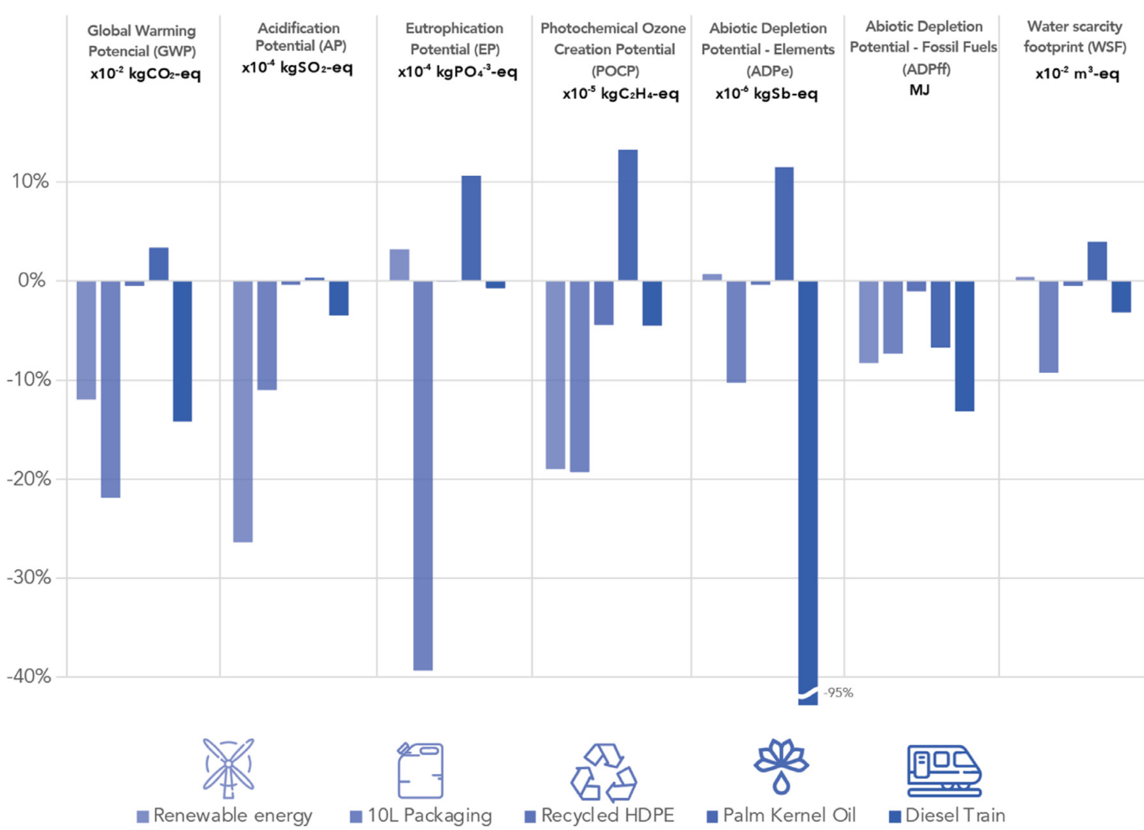

Fig 5. Comparison of the environmental improvements of the actions behind the designed 5 scenarios.

- **GWP impact:** The adoption of larger distribution packaging systems reduces GWP by 22%. Shifting from road transport to railway-transport reduces GWP by 14%, and the integration of renewable energies can reduce this impact by 12%.
- **AP impact reduction:** renewable energies lower this impact by 26%, followed by the increase of packaging size by 11%.
- **EP impact:** The increase of packaging size reduces by 39% and the adoption of PKO reduces by 11%.
- **POCP impact:** Renewable energy and packaging changes both can achieve reduction of 19%, while PKO could improve the impacts by 13%.
- **ADPe impact:** Train based distribution reduces ADPe by 95%, while the packaging size increases this impact by 10%. PKO integration could potentially increase the current impacts.
- **ADPff impact:** Integration of train transport reduces impacts by 13%, followed by renewable energy which lower ADPff by 8%.
- **WSF impact:** The use of a larger packaging lowers WSF by 9%, while the PKO use increases WSF by 4%.

4. Conclusions

Here we quantify the environmental cradle-to-grave impacts of an industrial enzymatic multipurpose cleaner following an Environmental Product Declaration. Product category rules within the "detergents and cleaning products" section were applied. During the *upstream* stage, the degreaser 3-butoxy-2-propanol represents the larger environmental load, being the largest contributor in 4 of 7 categories. In this stage, the ethoxylated alcohol surfactant highly contributes to the abiotic depletion category (42.2%), while the production of PE containers contributes by 33.9% to the eutrophication category. Regarding the *core* stage, electricity, natural gas and road transport of raw materials are the main contributors. Finally, during the *downstream* stage, road transport has the largest share in 6 environmental impact categories analyzed. With a total 0.76 kg CO_2-eq per kg of packaged detergent, the enzymatic cleaner generates similar CO_2 emissions in comparison with previously reported multipurpose cleaners. Following ecodesign principles, 5 scenarios are proposed to reduce the environmental impacts and open new possibilities for strategic decisions aimed to sustainable production and consumption patterns in the cleaning sector. Those include using renewable energy (12% reduction on CO_2 emission), increasing packaging volume from 0.75 L to 10 L (25% reduction on CO_2 emission), using recycled polyethylene for packaging (no differences), the substitution of petroleum-based ethoxylated alcohol by an oleochemical ethoxylated alcohol (no differences) and the distribution of the product by railway (16% reduction on CO_2 emission).

This research encourages detergent industries to reduce the current impacts of commercial detergents. In this sense, Fig. 5 has been specifically designed to support strategic reduction of impacts based on contrasted numeric results. Importantly, this study considers primary data for the environmental impact assessment, but the exact material and energy input inventory cannot be provided due to its sensitive character. The lack of complete life cycle inventory makes future comparisons challenging. However, this information is available from the corresponding author upon reasonable request. In addition, the followed "detergents and cleaning products" PCR does not take into account the impacts generated after the use phase, where toxicity and biodegradability aspects play a pivotal role. As a result, incomplete analyses are obtained, especially considering the impact of detergents on terrestrial and marine environments. In addition, specific cleaner products prioritize the need for formulations bearing reduced toxicity and improved biodegradability, which is translated into larger CO_2 footprints due to longer transport of raw materials, but can be manifested in reduced impacts in other impact categories such as terrestrial/marine ecotoxicity, terrestrial acidification, marine/freshwater eutrophication or fossil resource scarcity. Therefore, a future research work worthy of investigation may be the extension of the PCR to the complete life cycle so comprehensive analyses on the full cradle to grave environmental impacts of detergents and cleaning products can be performed.

Data availability

Original datasets that describes the inventory of performed LCA of the current study are not publicly available to ensure fair competence. The data that support the findings of this study are available from A&B Laboratorios de Biotecnología S.A.U. but restrictions apply to the availability of these data.

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.

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