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Lowering the environmental impact of dishwashing and laundry in Europe: a LCA perspective

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Abstract: This study presents findings from three Life Cycle Assessment (LCA) studies conducted in European markets, conformant with ISO 14040/44 standards, to evaluate the environmental footprints of automatic dishwashing (ADW), hand dishwashing (HDW), and laundry detergents. The primary objectives were to identify key impact areas and compare current consumer practices with more sustainable product usage. Across all product categories, the in-use phase has the largest environmental impact, with global warming potential (a proxy for carbon footprint) averaging 77 % for ADW detergents, 93 % for HDW detergents and 61 % for laundry detergents. This impact is strongly associated with the energy required to heat water, which is influenced by each country's energy mix i.e., fossil fuels, renewable sources, or nuclear power. Sustainable usage practices, such as reducing wash temperatures and employing energy-efficient cycles in both dishwashing and laundry, present significant potential for lowering the environmental impact of these common household tasks. Future scenarios for laundry products indicate that, despite the projected greening of the electricity grid by 2025 and 2030, the in-use phase will remain the primary driver of environmental impact. The findings underscore the need for a holistic approach to assessing environmental impacts, with emphasis placed on reducing the in-use phase via the promotion of sustainable consumer behaviors through education and innovation.

Keywords: life cycle assessment; sustainable cleaning; in-use; environmental impact; consumer habits

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1 Introduction

Dishwashing and laundry care products are essential for maintaining hygiene and cleanliness; however, they significantly contribute to the environmental footprint of EU household goods.[1] Out of the total Greenhouse Gas (GHG) emissions by activity, households account for 18.3 %,[2] and 13.9 % of those emission are due to larger appliances and lighting.[3] Given their importance and frequent use, it is crucial to holistically assess the environmental footprints of dish and laundry detergents and identify key hotspots. The most common method for achieving this is through life cycle assessments (LCAs). LCAs facilitate the design of products with smaller environmental footprints from a systems perspective by identifying improvement strategies, such as selecting raw materials with lower environmental impacts, making formulation changes, optimizing sourcing and packaging strategies, and reducing direct impacts related to the in-use phase of products (e.g., minimizing energy and water consumption), without burden shifting.[4]

LCAs have long been used by companies to evaluate the environmental impact of dishwashing and laundry products. Pioneering work in this area was conducted by Saouter and van Hoof in 2002,[5] who introduced the first LCA database tailored specifically for laundry applications. This database facilitated the first measurements of energy and resource use from a system-wide, functional unit perspective. Subsequently, this methodology was used to compare different forms of laundry detergents.[6] These foundational studies indicated that the in-use phase contributed the most significant impact, accounting for between 70 % and 80 % of most environmental indicators, mainly due to the energy required to heat water.

The first study to include dishwashing products was performed by Golsteijn et al. in 2015.[7] This study included manual hand dishwashing (HDW) detergents, powder and tablet laundry detergents. Again, the in-use phase was identified as the primary contributor to environmental impact, representing 86–98 % of the impact of HDW detergents across all indicators, (except for natural land transformation and agricultural land occupation which were driven by ingredient sourcing) and 46–95 % of the impact of laundry detergents.[7] A more nuanced evaluation of laundry practices was conducted in 2018 by Shahmohammadi et al. in 2018,[8] marking the first inclusion of product usage and consumer washing habits. This study assessed four laundry detergent product formats and four wash temperature settings across 23 European countries. Notable inter-country variations in life cycle GHG emissions were observed, with differences attributed to country electricity grid mixes. In countries reliant on fossil-based electricity systems, consumer choices regarding washing machine usage emerged as the principal source of variability in GHG emissions. Conversely, in countries with a predominantly low-carbon electricity mix, the variability in life cycle GHG emissions was primarily determined by parameters associated with laundry products.[8]

The increasing complexity of these studies over time is unmistakable, largely facilitated by advancements in LCA modelling and enhanced accuracy in data related to individual ingredients in product formulations. These improvements, along with significant changes in product forms, formulations, and packaging over the past seven years, underscore the necessity for a comprehensive re-evaluation of dishwashing and laundry detergents. Notably, soluble forms in standardized unit doses have largely replaced powder and tablet forms in the premium sector of laundry products. Furthermore, the absence of published LCA studies specifically addressing automatic dishwashing (ADW) highlights a critical gap in the existing literature.

This paper presents insights from three ISO14040/44-conformant LCA studies of products recently available on the market. These studies utilize updated models, achieving 99.9 % ingredient coverage with minimal reliance on proxy data, and are informed by a deep understanding of consumer habits in key markets. We aim to analyze the contribution of each life cycle stage to the overall environmental impact of ADW, HDW, and laundry products while exploring how consumer choices and behaviors influence these outcomes. For instance, the ADW study investigates energy savings through optimized ingredient use to enable lower energy cycles. The HDW analysis quantifies potential reductions in environmental impact by lowering water temperatures across various washing habits. Finally, the laundry detergent study projects the importance of reducing wash temperatures in future scenarios (2025–2030), as urban energy grids are expected to decrease their LCA footprints across Europe.

2 Materials and methods

Life Cycle Assessment (LCA) is a standardized method used to analyse the inputs and outputs of a product system to evaluate its potential environmental impact.[9] The standard steps in an LCA include: (1) defining the scope of the study; (2) conducting a life cycle inventory, (3) assessing the impact, and (4) interpreting the results. The methods section is organized as per this order.

2.1 Defining the scope of the study

This study presents the results of three different LCA studies covering automatic dishwashing detergents (ADW), manual dishwashing detergents (HDW), and laundry detergents. Each assessment has been reviewed by independent third-party reviewers to ensure conformance with ISO 14040:2006[9] and ISO 14044:2006.[10]

2.1.1 Geographical boundaries

The assessments span the following European countries: Austria (AT), Belgium (BE), Czech Republic (CZ), Germany (DE), Spain (ES), Finland (FI), France (FR), Great Britain (GB), Greece (GR), Hungary (HU), Italy (IT), The Netherlands (NL), Poland (PL), Portugal (PT) and Sweden (SE). Turkey (TR) and Israel (IL) were also included in the ADW study (Table 1). The selected countries represent those where Procter & Gamble (P&G) operates and thus, where primary data is available. LCAs were developed for each country individually. Aggregated results are based on a weighted average by sales volume and % share and are referred to as “EMEA-14,” “EU-10,” and “EU27 + GB” for ADW, HDW, and laundry, respectively.

2.1.2 Functional unit and reference flow

A functional unit is defined as the quantified performance of a product system for use as a reference unit.[9,10] This facilitates the determination of reference flows for the system being studied. The definitions of both for each product category are provided in Table 2.

Table 1: Overview of the countries included (X) for the studied product categories.

Country code	ADW	HDW	Laundry
AT	X		
BE	X	X	
CZ	X		
DE		X	X
ES	X	X	X
FI		X	
FR	X		X
GB	X	X	X
GR	X	X	
HU	X		
IL	X		
IT	X		X
NL	X	X	
PL	X	X	
PT		X	
SE	X	X	
TR	X		
Aggregated	EMEA-14	EU-10	EU27 + GB

Table 2: Functional unit and reference flow for the studied product categories.

Product category	Functional unit	Reference flow
ADW	Cleaning a full load of soiled dishes in one cycle of automatic dishwashing according to IKW configuration of type and number of dishes, soil composition and dishwasher model.[11]	One dishwasher pod (17–18 g)
HDW	One hand dishwash of 24 pieces of tableware containing eight pieces of cutlery, six glasses/mugs, six plates, and four pots/pans.[12]	Average amount of product used for one hand dishwash (3.6 g).[12]
Laundry	One average home laundry wash, consisting of normally soiled dry fabric, with the recommended dosage for a 4.5 kg load in a 6 kg capacity machine wash at 75 % loading capacity.[13]	One soluble unit dose (SUD), defined as 24.24 g for EU27 + GB, FR, IT, ES, GB, and 25.56 g for DE.

2.1.3 System boundaries

All LCAs reported in this study were conducted as cradle-to-grave assessments, thus life stages include: formula ingredients production, packaging materials production and processing, transport of materials from suppliers to P&G plants, manufacturing at the plant, transport from P&G plants to consumer homes, the use phase, end-of-life of detergent formula, and end-of-life of packaging. Figure 1 presents a representative diagram of the product categories studied. Detailed system boundaries for each product category are defined in the Supplementary Material (Figures 1–3 and Table 1).

2.2 Conducting a life cycle inventory

2.2.1 Data sourcing

Whenever possible, primary (i.e., company-specific) data was used. Primary data for ADW and HDW products is from 2021. Primary data for laundry studies is from 2020. In cases where primary data was unavailable, secondary data (SD) was obtained and averaged from third-party life cycle inventory (LCI) databases. Figure 1 provides a representative overview of the systems modelled. Secondary data was mainly sourced from Ecoinvent v3.8[14] and Industry Data 2.0.[15] A complete overview of data sources is provided in the Supplementary Material (Table 1).

2.2.2 Scenario modelling for ADW

We compared the environmental impact of an improved product formula optimized for performance in short cycles under conditions representative of an average short cycle with that of the base product formula assessed under average conditions for auto/normal cycles (Table 3) in each of the countries in scope of assessment (Table 1) and for the aggregated weighted average. Data for the in-use phase were defined by a habits and practices (H&P) study of auto dishwasher cycle usage and brand penetration. Austria, Czech Republic, and Hungary were not included. The wash cycle parameters of temperature, energy, water, and duration for these missing countries in the EMEA14 model is the mean of those parameters per cycle type across the 10 of the 11 countries in the H&P study (excluding Russia). The average water and energy consumption per type of dishwashing cycle come from the assessment of 133 dishwasher manuals across 27 brands. Manuals consulted were for new machines to those 10 years old, with most of them being 5 years old. The average is weighted based on the machine penetration in each country.

Similar average conditions were also found by Tewes et al. in 2023[16] by comparing the consumption data reported of 164 dishwashers in 11 countries, short cycles have been lauded as an economical and convenient alternative to the more time-consuming 'eco' programmes,[16] which is a significant barrier to consumer adoption.[17] This advantage is particularly pronounced when short cycles are paired with

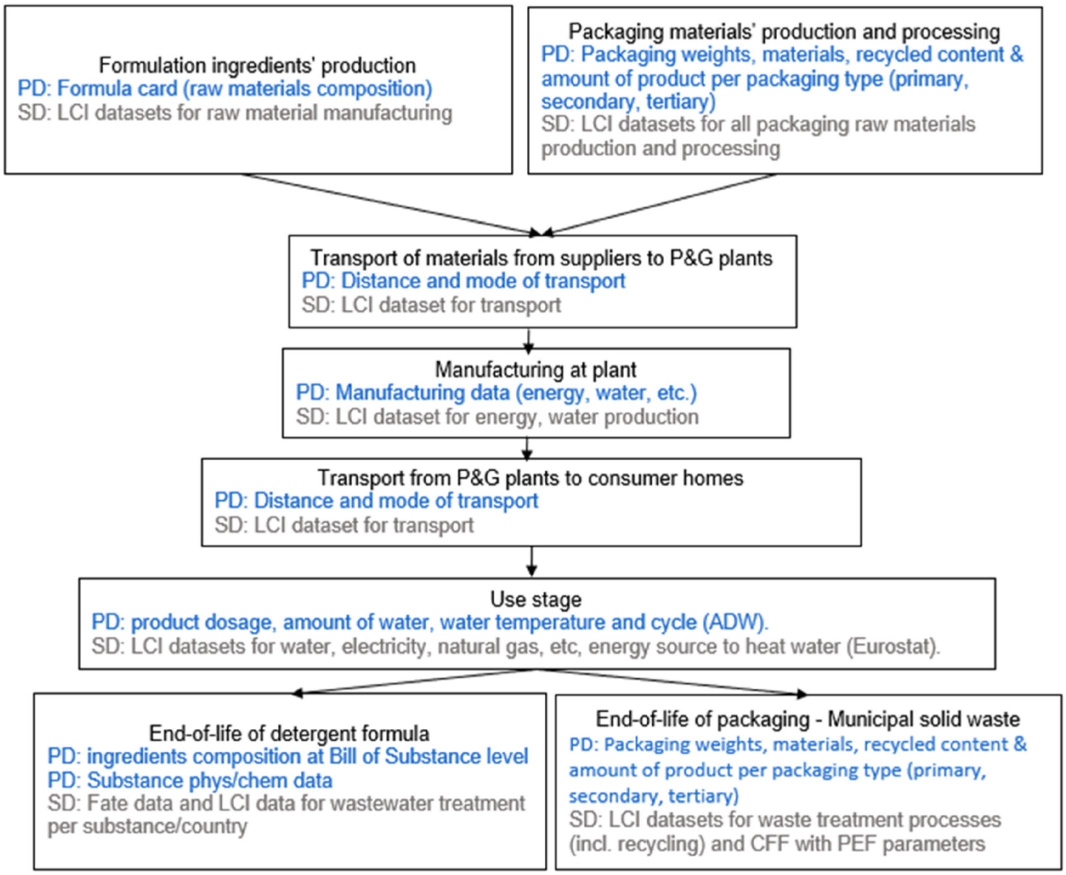

Figure 1: System boundaries for the studied product categories. PD denotes primary data, while SD indicates secondary data, representing averaged data from third-party life cycle inventory (LCI) databases.

Table 3: Average (± standard deviation) duration, water, and energy consumption of short cycles and auto/normal cycles compared in this study. Eco-cycles are included for additional perspective.

Cycle	Time (min)	Water (L)	Energy (kWh)
Short	31.0 ± 0.52	10.4 ± 0.19	0.7 ± 0.02
Auto/normal	120.8 ± 2.68	13.6 ± 0.37	1.2 ± 0.04
Eco	204.1 ± 6.31	10.9 ± 0.27	0.9 ± 0.01

high-performing detergents.[18] Recent research indicates that a high-performance commercially available detergent can achieve cleaning results nearly as effective as those obtained in 'eco' cycles;[19] it was this insight that provided the impetus for developing the improved product formula tested in this study.

2.2.3 Scenario modelling for HDW

We examined the environmental impacts of various washing methods, product formulas, dosages, and temperatures across the EU-10 countries. The washing techniques analysed included: (1) direct application open tap (product applied on the sponge with the tap opened constantly during washing and rinsing); (2) direct application closed tap (product applied on the sponge with the tap only opened for rinsing) and (3) full sink (product applied on a sink filled with water used for washing and tap opened again for rinsing). These reflect the most recent H&P data, derived from recent consumer tests and surveys that were considered valid and fair to measure the consumption of water, product and energy throughout the in-use phase. Product formulas reflected the most recent and innovative product available in each market in 2022. Product dosage was assessed at both regular and double amounts. Washing temperature was modelled based on the current temperatures used in each country, which range from 33 °C to 45 °C, as well as a target temperature of 23 °C. This target was chosen based on the results of a survey of 88 consumers, which identified 23 °C (mean ± standard deviation: 23 °C ± 4.75) as the minimum comfortable water temperature for immersing hands in the sink or under the tap.

2.2.4 Scenario modelling for laundry

We investigated the environmental impact of washing laundry at two temperatures: 40 °C and 30 °C using the product formulation that had the highest sales in each country in 2022 (i.e., the % of volume of SUDs sold with respect to the P&G portfolio). These temperatures were chosen to reflect the current average wash temperature in Europe (42.6 °C according to A.I.S.E., i.e., International Association for Soaps, Detergents and Maintenance Products) and a target temperature promoted by several campaigns, including P&G's 'Turn to 30°' and A.I.S.E.'s 'I Prefer 30' campaigns. The environmental impact of washing at these two temperatures was compared across three different years: 2020, 2025, and 2030. This comparison aims to evaluate how the increasing share of renewable energy in the electricity grid will impact the environmental footprint of laundry washing.

2.3 Assessing the impact

The impact assessment phase of an LCA evaluates the significance of potential environmental impacts. Various Life Cycle Impact Assessment (LCIA) methods are available to analyze different topics. This study focuses on relevant indicators identified using the ReCiPe 2016 method (Hierarchist (H) characterization set at endpoint level and global normalization factors), following the approach described in Van Hoof et al., 2013.[20] After identifying the relevant indicators, the results are calculated using state-of-the-art impact assessment methods specific to each indicator (Table 4). It is important to note that, in the global warming category, biogenic CO_2 is included in the assessment. While the primary focus for result interpretation is on the carbon footprint as a key impact category, other indicators are also analysed to identify potential trade-offs and prevent burden-shifting.

2.4 Interpreting the results

2.4.1 Modelling choices and tools

The Circular Footprint Formula (CFF) from the Product Environmental Footprint (PEF) method[21] was used for modelling recycled content and packaging end-of-life. The CFF models packaging waste treatment (including recycling, incineration with energy recovery, and landfill disposal) and instances when recycled content is used in packaging. The formula allocates the benefits and burdens of recycling and virgin material production between the life cycle that sends the material for waste treatment and the life cycle that uses the recycled material. Please see the "Modelling approaches" section in the Supplementary Material for a detailed description. For modelling the end-of-life of the product down the drain, the Wastewater Treatment Life Cycle Inventory (WWT LCI) tool[26] was used. The WWT LCI tool specifically assesses the impacts of chemical substances going down the drain to sewers, wastewater treatment, and eventually the aquatic environment. This tool includes physical and chemical attributes specific to those substances, affecting their behaviour at typical municipal wastewater treatment plants in a country. Country-specific operations and infrastructure are also included in the model. All life cycle modelling was conducted using SimaPro software version 9.3.

2.4.2 Energy grid mix considerations

The energy grid mix of each country plays a significant role in determining the environmental impacts associated with the life cycle phases of the products, and thus merits consideration when interpreting the results. As such, country-specific overviews of the energy grid mix for electricity generation and residential water heating are provided in Supplementary Material (Tables 2–5).

Table 4: Impact categories selected for this study and the associated life cycle impact assessment (LCIA) methods used.

Impact category	Unit	Method	Reference
Global warming	kg CO_2 eq	IPCC GWP 2021 100a incl. biogenic CO_2	22
Fine particulate matter formation	kg $PM_{2.5}$ eq	ReCiPe 2016 midpoint (H) v1.06	23
Water scarcity	m^3	AWARE v1.04	24
Fossil resource scarcity	kg oil eq	ReCiPe 2016 midpoint (H) v1.06	23
Cumulative energy demand	MJ	Cumulative energy demand v1.11	25

3 Results

Graphs A to C in Figure 2 illustrate the relative contribution of each life cycle phase to the products carbon footprint for each country. Graphs D to F display the relative contributions of each life cycle phase for various environmental impact indicators, based on the weighted average across the countries studied. These represent the current state-of-the-art. The effects of consumer choices and behaviors, explored in the scenario modelling and illustrated in Figure 3, will be addressed after. For clarity, the results will be discussed by product category.

3.1 Quantifying the environmental impact of household tasks

3.1.1 Automatic dishwashing (ADW) detergents

The in-use phase is the largest contributor to the carbon footprint of ADW detergents in all countries (Figure 2A). This impact mainly arises from the energy needed to heat the washing water. For most countries, the in-use phase accounts for 78–92 % of global warming, but in France and Sweden, it accounts for significantly less (50 %). The in-use phase has a particularly high impact in markets that rely more on fossil fuels for electricity generation (Supplementary Material, Table 3) and residential water heating (Supplementary Material, Table 4). In France and Sweden, where the energy grid is cleaner, the relative impact of the use phase is lower, but it remains the most significant life cycle stage. This highlights the importance of nuclear and renewable energy in reducing the global warming impact of ADW detergents. The weighted average across EMEA-14 indicates that the in-use phase contributes the most to all other environmental indicators: fine particulate matter, fossil resource scarcity, water scarcity, and cumulative energy demand (Figure 2D). This pattern applies for all countries except those with a lower-impact energy grid mix i.e., France and Sweden, where the product formulation stage has the highest contribution. This reinforces the significant role that a country's electricity mix plays in determining the environmental impact of ADW detergents.

3.1.2 Hand dishwashing (HDW) detergents

The in-use phase is the largest contributor to the carbon footprint of HDW detergents across all countries (Figure 2B), accounting for 83–95 % of the carbon footprint when

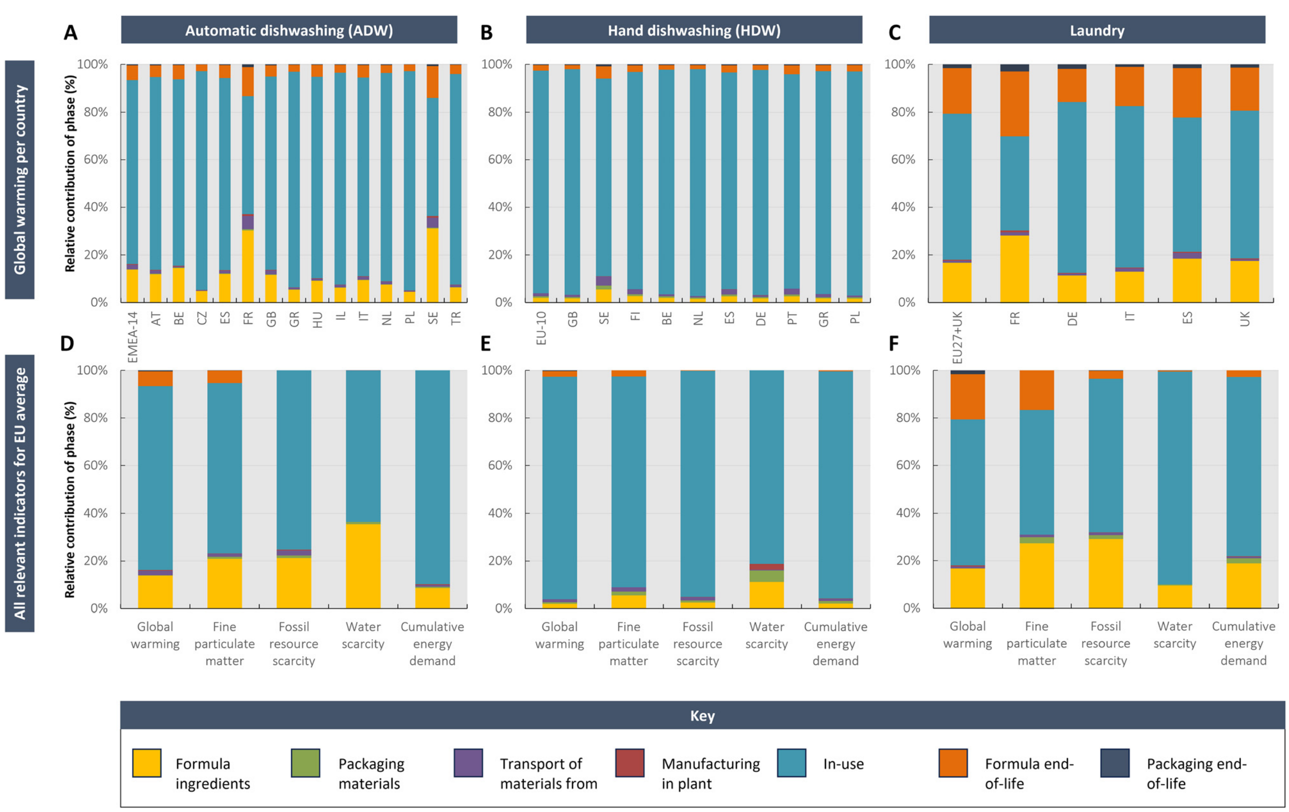

Figure 2: Relative contributions of each life cycle phase to carbon footprint impact by country (A–C) and environmental impact indicators (D, E; graphs show aggregated data) for automatic dishwashing (A, D), hand dishwashing (B, E), and laundry detergents.

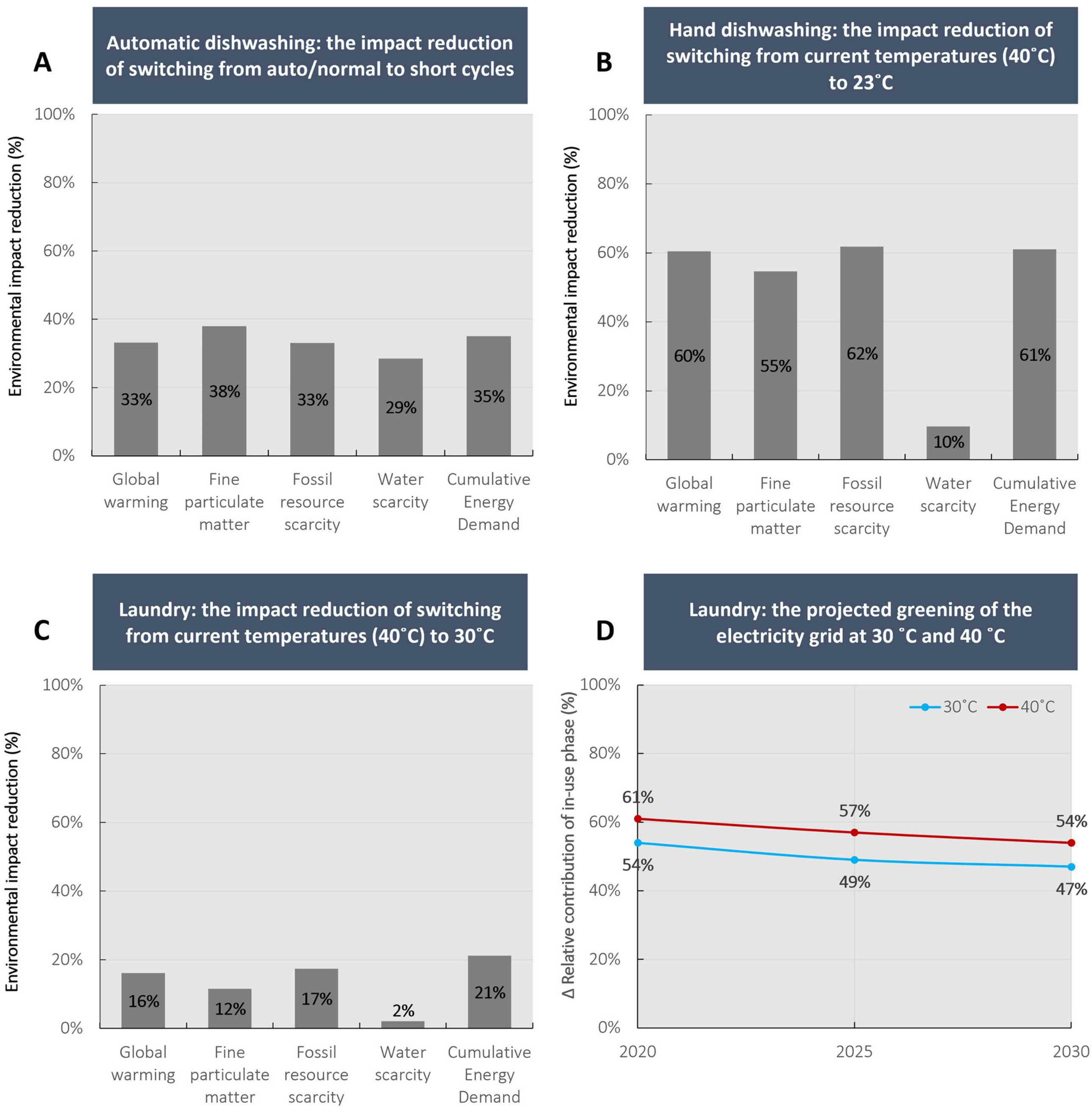

Figure 3: The environmental impact of consumer choices and behaviors. Results show the aggregated data of the countries in scope for: (A) automatic dishwashing (ADW): impact of switching from auto/normal cycles to short cycles; (B) hand dishwashing (HDW): impact of reducing current washing temperatures (40 °C) to 23 °C; (C) laundry: impact of lowering washing temperatures from current temperatures (40 °C) to 30 °C; and (D) projected effects of the greening of the electricity grid on the relative contribution of the in-use phase at 30 °C and 40 °C.

considering country-specific wash temperatures and habits. The primary factor driving this impact is the energy consumed to heat the water. Energy mix also influences the product's carbon footprint. The relative and absolute impact of the use stage is lowest in Sweden (Figure 2B), which has the highest share of renewable energy sources in its electricity mix (Supplementary Material, Table 2). The results for fine particulate matter, fossil resource scarcity, water use and cumulative energy demand mirror those observed for the carbon footprint i.e., the in-use phase has the highest relative contribution across EU-10 (Figure 2E). The contribution is most pronounced for fossil re-source scarcity and cumulative energy demand in those countries with a higher-impact energy mix. The results for water use were uncertain and hence no conclusions can be drawn for this impact category.

3.1.3 Laundry detergents

The in-use phase is the largest contributor to the carbon footprint of laundry at current wash temperatures of 40 °C, followed by formula ingredient production and formula end of life (Figure 2C). The in-use phase accounts for 40–72 % depending on the country. The impact of the in-use phase is highest in countries which are dominated by a high-carbon electricity grid mix. Germany, which has a high share of coal in its portfolio, exhibits the highest impact, followed by Italy, which has a high share of natural gas (Supplementary Material, Table 3). Like the results for carbon footprint, the in-use phase is the most significant life cycle stage for fine particulate matter, fossil resource scarcity, water scarcity, and cumulative energy demand when washing at 40 °C (Figure 2F).

3.2 Quantifying the environmental impact of consumer choices and behaviors

3.2.1 Switching consumers from auto/normal to short cycles

For all environmental indicators studied, the improved product formula in short cycles has a lower impact than that of the base product formula in auto/normal cycles (Figure 3A). The average carbon footprint reduction for this scenario across EMEA-14 is 33 % (Figure 3A). This reduction is mainly due to short cycles using ~42 % less energy per load than auto/normal cycles – 0.7 kWh versus 1.2 kWh. The carbon footprint of 1 kWh of electricity varies by country, making short cycles more beneficial in countries with a higher carbon-intensive grid mix. For instance, reductions equal 37 % in Poland and the Czech Republic, while France and Sweden see smaller reductions of 18 % and 22 %, respectively (Supplementary Material, Table 6). A sensitivity analysis confirmed the robustness of our results: the improved product formula in short cycles has a lower impact than the base product formula in auto/normal cycles in all cases as long as the short cycle consumes less electricity than the auto/normal cycle. The average reduction in fine particulate matter across EMEA-14 is 38 % (Figure 3A). While for fossil resource scarcity, the average reduction is 33 % (Figure 3A), with potential improvements ranging from 27 % in Belgium to 37 % in the Netherlands and Poland. The average reduction in water scarcity across EMEA-14 is 29 %, with reductions ranging from 5.5 % in the UK to 35.6 % in Italy. This is due to short cycles consuming less water on average (9.9–10.6 L per cycle) than auto/normal cycles (13.1 and 14.3 L per cycle). Finally, the average reduction for cumulative energy demand across EMEA-14 is 35 %, with potential improvements ranging from 33 % in Belgium to 38 % in the Czech Republic. These lower impacts are attributed to reduced extraction and less electricity generation needed for washing processes with lower energy demands.

3.2.2 Changing washing habits and using cooler water when hand dishwashing

The environmental impact of HDW is influenced by both washing habits and water temperature. The direct application open tap method has a carbon footprint that is more than double that of other techniques, such as direct application closed tap and full sink. While reducing washing temperatures from current levels (33 °C–45 °C) to 23 °C could lead to a 60 % reduction in the carbon footprint of HDW products across EU-10 countries (Figure 3B), primarily due to decreased energy demand for heating water. The carbon footprint associated with 1 kWh of energy varies by country, making the reduction from lower temperature washing more significant in countries with a higher carbon-intensive energy mix, such as the Netherlands, which rely heavily on natural gas for residential water heating (Supplementary Material, Tables 3 and 4). Sensitivity analyses were conducted by varying parameters such as product dosage, target washing temperature, and water volume. Even when the product dosage for washing at 23 °C is doubled, a significant carbon footprint reduction is still observed: 64 % with the recommended dosage and 60 % with the doubled dosage. Reductions are also seen when washing at temperatures above 23 °C but below current levels; for example, in the UK, washing at 23 °C results in a 64 % reduction, while washing at 27 °C yields a 49 % reduction. Furthermore, even in a hypothetical scenario where consumers use more water at lower temperatures, a reduced carbon footprint would still be achieved compared to washing at current temperatures. Reducing wash temperatures also yields significant environmental benefits, including a 55 % reduction in fine particulate organic matter, a 62 % reduction in fossil resource scarcity, a 10 % reduction in water scarcity and a 61 %

reduction in cumulative energy demand (Figure 3B). Collectively, these findings indicate that using HDW products at a lower washing temperature of 23 °C, combined with the direct application closed tap method, can substantially reduce environmental impacts by decreasing energy and water consumption.

3.2.3 Reducing wash temperature in laundry and the impact of the greening of the electricity grid

Washing at cooler temperatures has on average, a positive impact on all environmental indicators (Figure 3C). Considering the weighted average of the countries in scope shows that washing clothes at 30 °C rather than 40 °C reduces the carbon footprint of laundry detergents by 16 %, fine particulate matter by 12 %, fossil resource scarcity by 17 %, water scarcity by 2 %, and cumulative energy demand by 21 % (Figure 3C). Interestingly, the relative contribution of the in-use phase remains stable, despite the projected greening of the electricity grid between 2020 and 2030 (Figure 3D). Washing at 30 °C remains better than washing at 40 °C as is evidenced by the offset between the two lines over time (Figure 3D).

4 Discussion

This study emphasizes the critical role of the in-use phase in shaping the carbon footprint of automatic dishwashing (ADW), hand dishwashing (HDW) and laundry detergents. Specifically, the in-use phase contributes, on average, 77 % to the carbon footprint of ADW detergents in EMEA-14, 93 % to the carbon footprint of HDW detergents in Europe-10, and 61 % to the carbon footprint of laundry detergents in Europe27 + UK. The in-use phase also dominates fine particulate matter formation, fossil resource scarcity, water scarcity and cumulative energy demand. These findings are consistent with those of previous research[5–8] and can be explained by the energy required for heating water during use.[1]

The energy mix of a country is highly influential in determining the environmental impact of the in-use phase. A lower-impact electricity mix significantly reduces the absolute and relative impacts of this stage. Consequently, countries like France and Sweden, which have a higher share of nuclear and renewable energy, experience lower impacts from the in-use phase. In contrast, countries that rely heavily on fossil fuels face amplified negative effects. For laundry detergents, projections indicate that as the share of renewables in future electricity mixes increase, the contribution of the in-use phase will decrease; however, it will still be the largest contributor to the life cycle impacts. The transition offers substantial benefits, with potential reductions ranging from 12 to 62 % across all impact categories (except water use) across all product categories when low-impact energy sources are used.

Given the significant contribution of the in-use phase to overall life cycle impacts, altering consumer behaviour can be considered an effective strategy for reducing environmental effects. Our scenario modelling suggests that simple adjustments can yield substantial benefits. For example, switching from energy-intensive auto/normal cycles to short cycles in ADW can reduce carbon emissions by 33 %. Likewise, lowering HDW temperatures to 23 °C could lead to a 60 % reduction in carbon footprint across Europe, while reducing laundry temperatures from 40 °C to 30 °C can result in a 16 % reduction. Importantly, these adjustments do not induce any environmental trade-offs; rather, they offer cascading benefits, for example quick and cold cycles in laundry can reduce microfibre release.[27]

Of course, behavioural changes should never compromise on product performance, as lower consumer satisfaction can lead to the adoption of compensatory behaviours aimed at avoiding or compensating for perceived failures. These behaviours may include: (1) the use of alternative programmes or speed-modifying buttons;[28,29] (2) additional pre-treatment of dishes or clothes before placing them in the machine; and/or (3) increased dosing of detergent.[29] All these practices should be avoided as they can undermine the intended benefits of optimizing washing processes. Rather, it is crucial to develop solutions that align with modern consumer expectations for convenience and environmental responsibility.

Despite the rigorous methodologies employed in this study, several limitations warrant consideration:

– Survey data: the assessment of consumer habits partly relied on survey data, which may not capture the full spectrum of behaviours. Nevertheless, efforts were made to ensure a representative sample, enhancing the reliability of the findings, and reflecting key trends in consumer behaviour.
– Pre-treatment data: The exclusion of pre-treatment data for automatic dishwashing (ADW) presents a gap that future studies will address.
– Scenario Modelling for ADW: the average water and energy consumption per type of dishwashing cycle cis derived from the assessment of dishwasher manuals.

While this approach is valid, incorporating real energy and water consumption measurements in future studies would enhance the accuracy and applicability of the findings.
- Country-specific data: The use of country-specific habits limits the extrapolation of results to other regions. However, this approach allows for deeper insights within the specific contexts examined.
- Proxy data: A limited amount of proxy data was used for product formulations (10–20 % in the ADW study, 0.3 % in the HDW study and 2.4 % in the laundry study). This was guided by expert judgment and is not expected to impact the overall results.
- Manufacturing data: aggregated data were used for manufacturing sub-steps (e.g., inputs, assembly, filling). Given that manufacturing does not represent a major contributor to overall impact, the lack of granularity does not compromise the conclusions of the study.
- Transportation assumptions: assumptions regarding transportation distances were made for some downstream distribution legs. However, this is not a concern, as results indicate that the transportation phase is not a significant hotspot within the life cycle.
- Scope of the LCA: while the LCA captures key environmental impacts with a high degree of certainty, its scope could be enhanced by integrating additional methodologies to assess broader social and environmental impacts.

While these limitations are acknowledged, they do not detract from the overall validity of our findings. Rather, they offer valuable insights into the environmental impacts associated with the in-use phase of dishwashing and laundry products, laying a solid foundation for future research and practical applications.

5 Conclusions

The insights from these studies underscore the necessity for collaboration among policymakers, consumers, and industry stakeholders to reduce the environmental impact of dishwashing and laundry products. Collective actions can lead to substantial reductions in carbon emissions and other environmental impacts, where sustainable consumer behaviour remains the biggest opportunity. Recognizing the significance of the in-use phase reinforces the need to evaluate products across their entire life cycle. Furthermore, as results depend on consumer habits and regional practices, these studies should be regularly updated when new data is available.

Abbreviations

ADW	automatic dishwashing
AISE	international association for soaps, detergents and maintenance products
CFF	circular footprint formula
GHG	greenhouse gas
HDW	hand dishwashing
ISO	international organization for standardization
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
P&G	Procter & Gamble
PD	primary data
PEF	product environmental footprint
SD	secondary data
SUD	soluble unit dose
WWT	wastewater treatment

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