Comparing the Environmental Footprints of Home-Care and Personal-Hygiene Products: The Relevance of Different Life-Cycle Phases

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An in-depth life-cycle assessment of nine home-care and personal-hygiene products was conducted to determine the ecological relevance of different life-cycle phases and compare the environmental profiles of products serving equal applications. Using detailed data from industry and consumer-behavior studies a broad range of environmental impacts were analyzed to identify the main drivers in each life-cycle stage and potentials for improving the environmental footprints. Although chemical production significantly adds to environmental burdens, substantial impacts are caused in the consumer-use phase. As such, this research provides recommendations for product development, supply chain management, product policies, and consumer use. To reduce environmental burdens products should, for instance, be produced in concentrated form, while consumers should apply correct product dosages and low water temperatures during product application.

Introduction

The life-cycle environmental impacts of consumer goods are increasingly discussed for sustainable product design, environmental consumer information, and product policy-making, indicating a very high demand for environmental data. Despite the increasing need for such information, and the existence of recognized tools for environmental decision support, such as life-cycle assessment (LCA), very few public LCA studies exist which, from a life-cycle perspective, investigate the ecological impacts of home-care and personal-hygiene products. Apart from an analysis of kitchen-cleaning agents (*1*), the surveys available entirely focus on laundry detergents and different product variants thereof (*2*−*5*). Thus, the environmental performance of other types of commonly used household-cleaning and personal-hygiene products remains unexplored. Existing LCA databases (e.g., (*6*)) contain life-cycle inventory (LCI) data relating to many frequently applied chemicals. However, production data on the products listed above and more specific chemical ingredients can be difficult to obtain, and rarely appear in public literature. Similarly, public data about consumer behavior and product-use patterns are difficult to find. The application of such consumer products also generally raises concerns about environmental burdens associated with extensive water use and packaging-waste generation. However, such aspects have not yet been systematically analyzed for a broad product portfolio.

The aim of this study is to (i) provide environmental data for unexplored home-care and personal-hygiene products, (ii) evaluate the ecological relevance of different life-cycles stages of products from various categories, (iii) compare the environmental footprints of products serving equal applications, and (iv) provide recommendations for different stakeholders along the products' life cycles. Product-specific LCI data were collected from producing industries and their environmental impacts were analyzed, focusing particularly on processes and factors influencing the environmental performance of each life-cycle phase. Based on our findings, potentials for reducing the environmental footprints are quantified and recommendations are elaborated for suppliers, producers, retailers, and consumers.

Methods

Products under Study. Nine products were investigated, encompassing household-cleaning agents (kitchen, window, and bathroom cleaners), detergents (liquid and powder detergents, detergent booster), soaps (liquid and bar soaps), and a toilet-care product. Product-blending formulas were provided by two producers (*7, 8*) (Supporting Information (SI) S2). Apart from the toilet-care product, the products' chemical compositions are largely comparable with those of similar products (e.g., (*3*)) and are thus representative within their product groups in the Western European markets.

Study Scope: System Boundaries and Functional Unit. Two product analyses with different scopes were performed for Western European conditions. The first cradle-to-gate analysis was based on 1 kg of final product. It covers raw-chemical production and supply, finished-product manufacturing (formulation), and packaging. It aims to assess the environmental relevance of raw-material usage and different processes within the production phase of each individual product. The second cradle-to-grave analysis investigates the entire product life cycles. Besides production, it includes sales and distribution of packaged products to wholesale and retailers, consumer use, and product end-of-life (waste disposal, recycling, and wastewater treatment). Here products are compared on the basis of their functions using the functional unit "one typical application" (Table 1). In addition to the foreground processes, the background system comprises auxiliaries and packaging fabrication, energy generation and supply, transport (among suppliers, to product manufacturers, and by consumers), infrastructure investments and waste-management activities (SI S1). Data on background processes for both the cradle-to-gate and cradle-to-grave analysis were taken from the ecoinvent database (*6*).

Cradle-to-Gate Inventory Analysis. Life-cycle inventories (LCI) for the consumer products and raw chemicals were established following the methodology of Frischknecht et al. (*9*). When available, LCI data for raw chemicals were retrieved from the ecoinvent database (*6*). Missing data were estimated using process information from technical handbooks and literature sources describing current production technologies. Due to lack of exact information, for most raw-chemical LCI data sets production inputs and outputs were estimated applying stoichiometric ratios and generic yields of 95%. Sufficient information allowed establishing exact production LCI models for lactic acid, alkyl polyglucosides, and propylene-glycol monobutylether. First-hand data for state-of-the-art finished-product manufacturing were collected from

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TABLE 1. Description of Functional Units, the Base Case, and Alternative Scenarios of the Cradle-to-Grave Analysis

product	cradle-to-grave functional unit (FU)	base case (1)	alternative use and end-of-life scenarios (2)-(9)
all products	one typical application	product quantity: reference flow home transport by car (6 km) waste incineration of product packaging (with energy recovery)	variation of influencing parameters
bar soap (a) and liquid soap (b)	one-time hand washing	product quantity[a]: (a) 0.35 g of bar soap (b) 2.3 g liquid soap water use[a]: (a) 0.91 L (b) 0.64 L warm water temperature: 38 °C light fuel-oil boiler[b] for warm-water supply	(2) overdosage: double amount of soap applied (3) excessive water use: double amount of warm water applied (4) decreased water temperature: 20 °C (5) refill product: four refillable packages every one original package (for (b) only) (7) electric boiler[c] for warm-water supply (8) home transport by bike (9) plastic recycling and landfilling of packaging waste (for (b) only)
powder detergent (a) and liquid detergent (b) and detergent booster (c) (as additive to remove stains)	washing one load of laundry (5 kg)	product quantity[d]: (a) 68 g of powder detergent (b) 120 g of liquid detergent (c) 36 g of powder detergent (low dosage) plus 70 g of detergent booster water temperature 40 °C; medium water hardness; medium degree of laundry soiling state-of-the-art washing-machine technology: water use 49 L, electricity consumption 0.53 kWh per washing cycle	(2) overdosage: double amount of detergent applied; for (c): only double amount of detergent booster with low dosage of powder detergent (4) elevated washing temperature: 60 °C (7) older washing-machine technology: water use 175 L, electricity consumption (at 40 °C water temperature) 1.28 kWh (8) home transport by bike
toilet-care product	one-time toilet flushing	product quantity[a]: 0.16 g of toilet care product water use: toilet-flushing volume 6 L	(5) refill product: 4 refillable packages every one original package (7) older toilet-flushing system: water use 9 L (8) home transport by bike
bath cleaner (a) and kitchen cleaner (b) and window cleaner (c)	(a) and (b) cleaning a small wash basin/ kitchen sink (area ~0.24 m^2) (c) cleaning a small window (area ~0.12 m^2)	product quantity[e]: 5 spraying cycles (approximately 4.7 g) (a) and (b) water temperature 40 °C, light fuel-oil boiler[b] for warm-water supply, water amount 0.55 L (c) auxiliaries: one sheet of paper towels	(2) overdosage: 4-fold amount of cleaner applied for (a), (b), and (c) (3) excessive water use: double amount of warm water applied for (a) and (b) (4) decreased water temperature: 20 °C for (a) and (b) (5) refill product: 4 refillable packages every one original package for (a) and (c) (6) variation of auxiliaries: four sheets of paper towels for (c) (7) electric boiler[c] for warm-water supply for (a) and (b) (8) home transport by bike (9) plastic recycling and landfilling of packaging waste (for (a) and (b))

[a] Consumer-behavior study from industry (*7*). [b] Efficiency: 100%. [c] Efficiency: 78%. [d] Dosage recommended by producer, provided on product package. [e] Laboratory tests.

industrial producers (*7, 8*). Product-formulation processes largely consist of mixing chemical ingredients with water. For powder and chunk products (e.g., powder detergent, bar soap), a subsequent drying process is included. Inventories for finished-product manufacturing consider raw chemical, energy, and packaging inputs, while solid wastes (except for packaging waste) and wastewater were neglected because of the insignificant amounts generated. In addition to primary packaging, secondary and tertiary packaging material required for product distribution was considered. Chemical ingredients contributing more than 1% of the total chemical-input mass on a weight basis, excluding water content, were considered in the consumer-product data sets. Chemicals representing a lower weight share (<1%) were neglected for reasons of simplification. Average Western European production conditions were assumed for all raw-material and finished-product manufacturing processes, while U.S. conditions were investigated using sensitivity analysis. For an overview of product compositions, descriptions of raw-chemical and finished-product fabrication and corresponding LCI data sets, LCI modeling approaches, and consumer-product packaging systems, see SI S2 and S3.

Cradle-to-Grave Inventory Analysis. In the cradle-to-grave study a scenario-analysis based scheme was applied to investigate different consumer behavior-patterns and choices, various household appliances, and waste-management options (Table 1). The base case of this analysis represents an average Western European situation and describes consumer use as one typical product application employing average product amounts. Variability in consumer practices was modeled in alternative scenarios by changing different use-related factors, including applied product quantity, temperature and amount of water used, use of refillable packaging and paper towels, as well as mobility choices. Data on average product dosage and application frequencies (e.g., laundry-washing frequency) were collected from the manufacturers' consumer-behavior studies (*7, 8*) and various bibliographic sources. Recommended application amounts were available only for detergents. Missing data on product use were gathered in laboratory tests (SI S4). Technical inputs and outputs during use encompass electricity, (warm) water, paper towels, packaging, and wastewater. In respect to household appliances, the operation of various washing-machine technologies and water-heating systems was modeled. The production of the technical equipments itself was disregarded because it was considered of minor relevance. Home transport from the supermarket was incorporated in the use phase as it is determined by consumer's mobility choices. Mobility studies and the Swiss consumer-price index were used to calculate an average shopping distance and test sensitivities.

For sales and distribution, truck and train transport from manufacturing sites to wholesale and retail stores were computed using data from producing industries and a retailer (*7, 10*). For product storage only energy use was taken into account, occupied storage areas are disregarded. For the product end-of-life phase, LCI data were calculated for wastewater treatment and disposal of primary, secondary, and tertiary packaging material. State-of-the-art treatment of wastewater generated during consumer use and containing the products' chemical ingredients was modeled applying an inventory tool that computes the environmental interventions based on both purified wastewater volume and chemical composition. Combustion of packaging material in municipal-waste incineration plants with energy recovery was chosen as a base case. System expansion was applied to account for recovered heat and electricity using light fuel-oil boilers for heat supply and the European electricity-supply mix as reference systems. Open-loop recycling of plastic packaging and landfilling of all product packaging was investigated as alternative waste-management scenarios. Details on end-of-life modeling and sales and distribution data are given in SI S4.

Life-Cycle Impact Assessment. Following LCA standards (*11*), the products' carbon footprints were calculated using IPCC global-warming potential (GWP) with a 100-year time frame (*12*). To explore the consumer products' direct and indirect energy performance, we derived the fossil cumulative-energy demand (CED_{fossil}) according to Frischknecht et al. (*13*). CED_{fossil} was separated into fossil-feedstock related primary energy, and CED associated with energy generating processes including transport. The overall environmental footprint was assessed with the Eco-indicator 99 (EI99) methodology (hierarchist perspective) which depicts a manifold facet of ecological impacts and returns an aggregated single-score result (*14*). Ecotoxicity-characterization factors for chemical product ingredients were calculated with the USEtox model (*15*) and converted to EI99 damage factors denoting ecosystem-quality impairments. Additionally, the IMPACT2002+ method (*16*), which also evaluates a broad impact portfolio, was applied in the cradle-to-grave analysis to compare with the EI99 results of selected products (for LCIA methods see SI S5).

Relevance Analysis. As freshwater use plays an important role in the consumer products' life cycles the ecological damages induced by freshwater consumption in a water-scarce region were assessed by the method of Pfister et al. (*17*) using watershed-differentiated characterization factors. Note that not the entire amount of water used was evaluated, but rather the freshwater quantity effectively consumed. Because inventory data on freshwater consumption are generally very scarce (*18*), a screening analysis was conducted and freshwater consumption quantified for powder detergent, liquid soap, and window cleaner as examples of high, medium, and low life-cycle freshwater consumption, respectively (SI S6).

Further, we investigated the overall environmental relevance of the annual per-capita product use. We compared the global-warming impacts of the yearly application of all nine consumer products with the overall life-cycle climate-change impacts caused by all products and services serving the final consumption in the European Union. Data were retrieved from the EIPRO study (Environmental Impact of Products) which quantifies environmental damages of final consumption per EURO value in EU25 (*19*) (SI S6).

Results

Product Comparisons Based on Cradle-to-Gate Analysis. All nine home-care and personal-hygiene products were analyzed on the basis of 1 kg of finished product packaged in selling units. Note that this analysis is intended to evaluate the environmental impacts of different subprocesses of the individual products' cradle-to-gate system (Figure 1) (for quantitative records see SI S7.1).

The primary energy required for the entire production chain varies greatly among, and partly within, the product groups investigated (Figure 1a). The CED_{fossil} values range from 11 MJ-equ./kg to 66 MJ-equ./kg of finished product, with the lowest and highest results caused by the bar soap and the toilet-care product, respectively. Comparing the Western European production case with U.S. production settings results in slight increases of 3−14% in cradle-to-gate primary-energy requirements, with the bar soap showing the highest sensitivity (Figure 1a).

Within their product groups, different types of soaps and detergents show substantial differences in their energy footprint: powder detergents (detergent powder and booster) and liquid soap have 1.5−4.6 times higher CED_{fossil} values than their product counterparts, i.e., liquid detergent and bar soap. Depending on the product type, the largest CED_{fossil}

(a) Energy footprint CED_{fossil} [MJ equivalents/kg finished product] (Infrastructure expenditures and transports are incorporated in the results of each production stage.)									
Production stage	Bar soap	Liquid soap	Powder detergent	Liquid detergent	Detergent booster	WC care product	Bath cleaner	Kitchen cleaner	Window cleaner
Raw chemical production and supply	6.0	30.0	27.1	8.6	17.5	17.1	2.0	3.7	4.6
Fossil feedstock	2.0	25.8	22.1	5.7	12.9	9.9	0.5	3.0	4.2
Energy related	4.0	4.2	5.0	2.9	4.6	7.2	1.5	0.7	0.4
Packaging production and supply	1.0	19.4	1.2	4.2	1.5	47.2	10.3	10.6	10.6
Fossil feedstock	0.6	16.6	1.1	4.1	0.8	40.1	8.4	8.7	8.7
Energy related	0.4	2.8	0.1	0.1	0.6	7.1	1.9	1.9	1.9
Finished product manufacturing	4.0	1.0	3.3	1.2	2.2	1.2	0.9	1.1	1
Fossil feedstock	0.9	0.4	0.3	0.4	0.3	0.4	0.2	0.3	0.3
Energy related	3.1	0.6	3.0	0.8	1.9	0.8	0.7	0.8	0.7
Total cradle-to-gate CED_{fossil} based on European production conditions	**11.0**	**50.4**	**31.6**	**14.0**	**21.2**	**65.5**	**13.2**	**15.4**	**16.2**
Sensitivity analysis Total cradle-to-gate CED_{fossil} based on US production conditions	12.4	52.0	33.0	14.7	22.3	68.2	14.1	16.1	17.0
Changes in CED_{fossil}	+14%	+3%	+4%	+5%	+5%	+4%	+6%	+6%	+5%

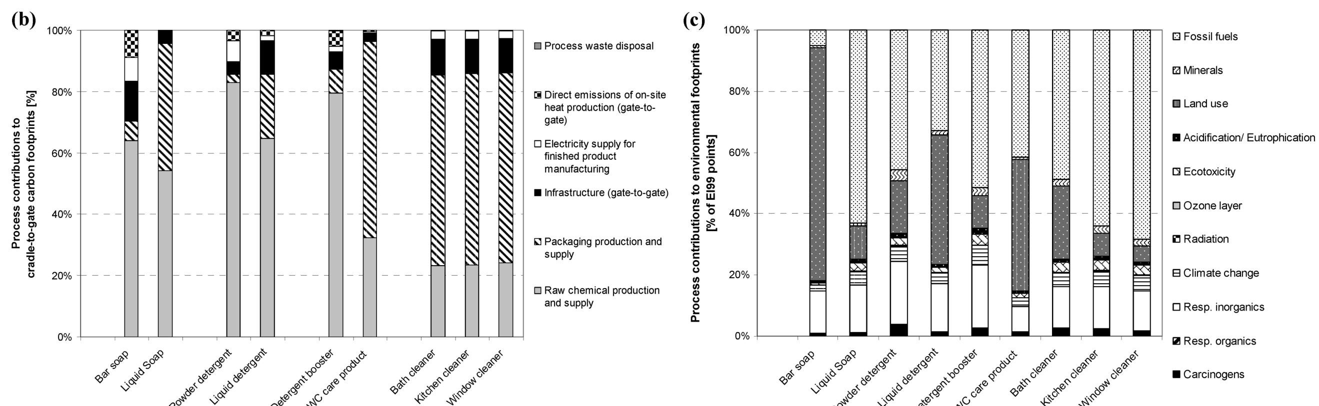

FIGURE 1. Cradle-to-gate: (a) energy footprints divided into fossil feedstock and energy-related CED_{fossil}; process contributions to (b) carbon footprints (GWP), and (c) environmental footprints (EI99 points).

share is associated with the raw-chemical supply stage (up to 86% for detergent powder) and the packaging-material production (up to 77% for bath cleaner), respectively. Finished-product formulation, including the energy consumption for bottling and packaging, generally contributes less than 11% to total CED_{fossil}, except for bar soap (40%). Infrastructure expenditures and supply chain transport are negligible (<4%). For soaps and detergents, the majority of embodied primary energy is represented by fossil feedstock for raw-chemical production (up to 70% for powder detergent). Fossil feedstock for packaging fabrication, in contrast, dominates the overall CED_{fossil} of the cleaning agents and toilet-care product (up to 63% for bathroom cleaner). Particularly low contributions from packaging are observed for detergent powder, detergent booster, and bar soap. Energy-related processes moderately add to the cradle-to-gate energy footprint (between 15% for liquid soap and 33% for detergent booster), a substantial contribution is observed only for bar soap (69%).

Parallel to CED_{fossil}, the overall results for the carbon and environmental footprints show equal rankings across and within the product groups (with the exception of the EI99 score for bar soap) (Figure 1b,c, and SI S7.1). Cradle-to-gate GWP values span a range of 0.6−2.6 kg CO_2-equivalents per kg of finished product, with the household cleaners exhibiting the lowest, and the toilet cleaner the highest, mass-based GWP. Both climate-change impacts and EI99 scores of detergents and soaps are substantially driven by the raw-material supply chain (>53% of total impacts), while packaging production for cleaning agents has the highest contribution to both indicators (>51%), showing broad correlation with CED_{fossil} results. For only detergent powder and booster, process energy supply for final-product manufacturing constitutes the largest proportion of the overall GWP results, accounting for up to 10%. All other system parts including infrastructure investments, transport, and process-waste disposal, have minor influence on carbon and environmental footprints.

A detailed analysis of climate-change impacts highlights that carbon-dioxide emissions are responsible for the biggest share of the cradle-to-gate GWP (>90%). For bar soap, biogenic methane emissions from agricultural production play a significant role, adding 0.3 kg to the total 1.0 kg CO_2-equiv./kg. The environmental footprints expressed in EI99 points are generally heavily driven by fossil-fuel consumption (32%−68%) which correlates well with CED_{fossil}. For bar soap, liquid detergent, and toilet cleaner, which all contain bio-based feedstock, EI99 scores are strongly influenced by land use impacts, contributing more than 40%, and in the case of bar soap 76%, of EI99 points. Respiratory inorganic emissions also contribute 8−21% of the total environmental impact (Figure 1c).

Product Life-Cycle Comparisons Based on Cradle-to-Grave Analysis. In the cradle-to-grave analysis, the relative contributions of the life-cycle stages to the overall primary-energy footprints, carbon footprints, and EI99 profiles were compared (Figure 2). Detailed results are given in SI S7.2. Note that the results reflect the specific functional units chosen per product application (Table 1) and are presented here for the base case. All the carbon, energy, and environmental footprints are heavily affected by the use phase with average contributions of 50−75% to the overall GWP and 45−75% to total CED_{fossil} and EI99 scores (with some exceptions for the application of bar soap and the toilet cleaner) (Figure 2a,b). The production stage, which comprises raw-chemical production, packaging fabrication, and finished-product manufacturing, accounts for an average share of 15−30% of life-cycle GWP and 20−55% of total environmental footprint. Sales and distribution (1−11% of GWP and 1−7% of EI99 scores) and product end-of-life management (5−20% of GWP and 1−6% of EI99 scores) are generally of minor relevance, except for the toilet cleaner. Overall, the EI99 results are supported by the IMPACT2002+ calculations providing an analogous relevance ranking of the various life-cycle stages (production: 21−45%; use: 40−67%; sales: 4−9%; end-of-life: 1−9%). The fossil primary-energy footprint correlates well with the GWP shares of the life-cycle phases and related subprocesses.

For soaps and detergents, environmental impacts caused by consumer use are mainly driven by warm-water supply, which accounts for 90−99% of the use-phase associated GWP, EI99, and IMPACT2002+ scores (see examples of soap products in Figure 2c,d). Interestingly, home transport by car (6 km) of household cleaners, which contain significant water amounts, has the largest life-cycle contribution to all environmental indicators analyzed (40−50%). Larger shopping distances of up to 15 km increase this contribution to about 55−70% (SI S7.2). In product end-of-life mainly wastewater treatment influences the carbon and overall environmental footprints. For some packaging-intensive consumer products, packaging incineration also contributes to some degree. Note, however, that credits granted for energy recovery in waste disposal partly reduce the life-cycle impacts (SI S7.2).

When analyzing the bar soap and toilet-care products, slight deviations from the standard profiles of the other consumer goods become visible. The use and end-of-life phases of toilet cleaners contribute (almost) equally to total GWP (42% and 47%) and EI99 scores (approximately 35% each), while the production phase is less relevant (10% of GWP and 23% of EI99 scores). The life-cycle impacts of bar soap are strongly controlled by the consumer-use stage, which amounts to up to 88% of the carbon and environmental footprints. Hand washing with liquid soap, by contrast, shows considerable differences (Figure 2c,d): major GWP and EI99 shares stem from both the product-manufacturing chain (28−52%) and the use stage (42−49%). Note that GWP and EI99 scores display different rankings regarding the life-cycle stages of liquid soap: consumer use is more influential for GWP and the production stage for EI99 scores, which is also in line with the IMPACT2002+ results.

Similar to the cradle-to-gate analysis, fossil-fuel consumption substantially dominates the cradle-to-grave EI99 and IMPACT2002+ scores (36−66% and 36−39%). Depending on the product and life-cycle stage, climate-change impacts (7−11% and 30−34%) and the emission of respiratory inorganics (11−27%) stemming mainly from energy generation and transports are among the top three causes of environmental burdens. Land-use impacts are pronounced by the EI99 assessment (4−18%). Aquatic freshwater ecotoxicity becomes relevant when assessed on disaggregated characterization level as the emission of chemical product ingredients after wastewater treatment significantly contributes to the life-cycle freshwater ecotoxicity (9−98%) (SI S7.2).

Scenario Analysis of Consumer Behavior and Waste-Management Options. The scenario analysis of consumer choices and behavioral patterns indicates substantial variations in carbon and environmental profiles (Table 2 and SI S7.3 for detailed analysis of liquid soap). Note that some scenarios apply to selected product groups only (Table 1). Overdosage of soaps and detergents induces an increase in GWP and EI99 scores of a maximum of 59% with the carbon footprint showing smaller changes than the EI99 profiles. For household cleaners, in contrast, product overuse multiplies the environmental impacts by a maximum factor of 3.5 with major contributions due to higher home-transport burdens. Excessive warm-water use during product application generally provokes a moderate rise in climate-change and overall environmental damages (28−46%), with the

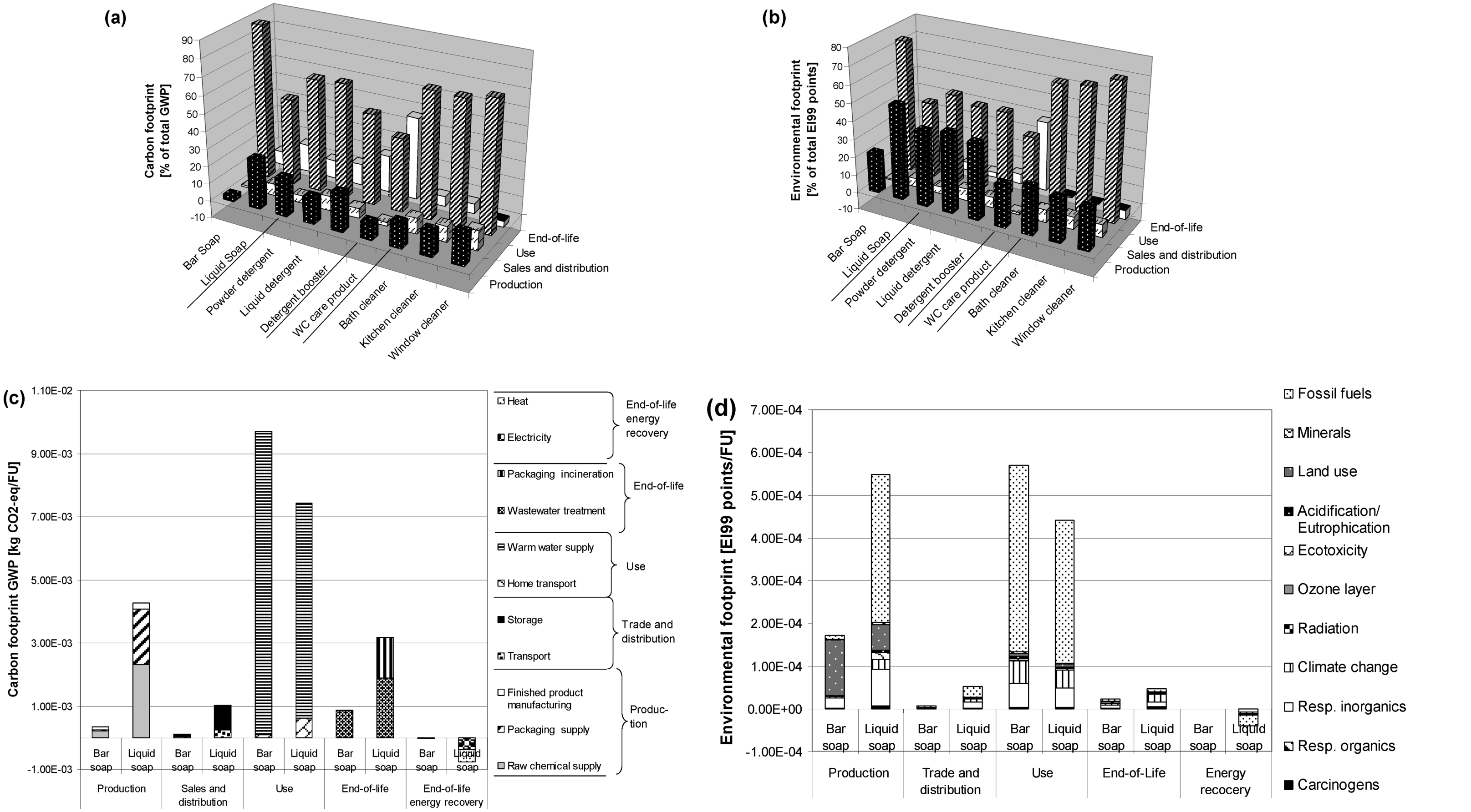

FIGURE 2. Cradle-to-grave analysis: life-cycle carbon footprints (a) and environmental footprints (b) shown as relative contributions of the life-cycle phases to total product life-cycle impacts (per individual functional unit); detailed analysis of soap products: (c) life-cycle carbon footprints differentiated by subprocesses modeled and (d) environmental footprints differentiated by impact categories.

TABLE 2. Results of Scenario Analysis of Consumer Habits, Behavioral Patterns, and Waste-Management Options and Relevance Analysis

	bar soap		liquid soap		powder detergent		liquid detergent		detergent booster		toilet-care product		bath cleaner		kitchen cleaner		window cleaner	
	ΔGWP	ΔEI99	ΔGWP	ΔEI99	ΔGWP	ΔEI99	ΔGWP	ΔEI99	ΔGWP	ΔEI99	ΔGWP	ΔEI99	ΔGWP	ΔEI99	ΔGWP	ΔEI99	ΔGWP	ΔEI99
	[%]																	
scenario analysis: scenarios (2)−(9)																		
overdosage	10	23	53	59	33	47	33	51	22	27			206	218	206	218	252	205
excessive water use	90	76	46	39									31	28	31	28		
water temperature	−25	−46	−29	−24	50	38	49	34					−20	−17	−20	−18		
refillable packages			−12	−11							−3	−3	−8	−7			−11	−8
auxiliary-materials use																	48	95
technology choice	118	51	61	27	98	79	97	70			32	29	41	19	41	19		
home-transport by bike	−1	−1	−4	−4	−2	−3	−4	−4			−19	−36	−41	−42	−41	−43	−50	−41
plastic recycling			4	−5									0.4	−1	0.4	−1		
waste landfilling			−0.1	5									−4	2	−4	2		
relevance analysis																		
freshwater consumption				1		4												<1

exception of the bar soap (76−90%). Lowering the water temperature to 20 °C for hand washing and cleaning reduces the ecological impacts by 17−46%, whereas the choice of 60 °C for laundry washing deteriorates the environmental performance (increase by up to 50%). The use of refillable packages helps to slightly lower the global warming and total environmental impacts (reduction of 3−12%). Similarly, home transport by bike only marginally influences the environmental performance of soap and detergent products, whereas abstaining from car transport in the case of cleaning products can reduce the environmental impacts by more than 40%. Quite significant increases in environmental burdens can arise from the use of old, inefficient washing machines and water boilers causing particularly the GWP to double for soap application and laundry washing (increase by 97%−118%).

Product-packaging disposal in different waste-management systems indicates only minor changes in the overall outcome. Landfilling of plastic, paper, and core board packaging material somewhat reduces the global-warming impacts due to temporary carbon storage, whereas the overall environmental impacts increase by 5% at most. Recycling of plastic packaging combined with incineration of other wastes enlarges the climate-change impacts by approximately 5%, but can also slightly diminish other ecological damages as expressed by the EI99 scores.

Relevance Analysis. Including the impact assessment of freshwater consumption reveals only small increases of EI99 scores (up to 4%, Table 2). More significant changes are observed for the ecosystem-quality EI99 subcategory. Ecosystem damages are enhanced by a maximum of 12%, whereas the contribution to resource depletion is less prominent. Freshwater-consumption associated impacts are mainly driven by water use during product application (51% for laundry washing with powder detergent), water evaporation in cooling processes of electricity generation (10−20%), and industrial processes (~65% for the window cleaner) (SI S7.4).

Looking at the overall environmental relevance, the annual use of all nine household and personal-hygiene products shows a visible contribution to the total per capita global-warming burdens of European citizens. When applied on a regular basis, 1.3% of the total GWP of 10.4 tonnes of CO_2-equivalents caused by an European consumer (*19*) relates to the application of such consumer goods (SI S6.2).

Discussion

Cradle-to-Gate Environmental Performance and Producers' Sphere of Influence. The choice of both raw chemicals and packaging materials substantially influences the cradle-to-gate environmental performance of all products investigated. The environmental pressures caused by raw-chemical supply generally grow with increasing numbers of product ingredients (e.g., Figure 1a,b for powder detergents and detergent boosters). There is an observable increase in the values of energy-related CED_{fossil} and fossil feedstock as more chemical components are included (Figure 1a). Similar findings for overall energy requirements of powder laundry detergents (>80% of CED_{fossil} stemming from raw-material supply) are reported by Saouter et al. (*3*). Also, as the final product water content increases, raw-chemical supply becomes less influential and the packaging value-chain becomes more important. This is particularly the case for household-cleaning agents, the toilet-care product, and liquid soap: they exhibit extraordinarily high water shares (up to >90%) and bulky plastic packaging (e.g., dispenser bottles). Products manufactured almost exclusively from vegetable oils such as bar soap show very small fossil-feedstock footprints. Yet, their overall environmental profile is highly driven by land-use impacts caused during bio-based feedstock production (Figure 1c). The addition of further chemical compounds in bar-soap formulation would slightly enhance the environmental burdens.

In general, finished-product manufacturing only marginally affects the environmental performance, which is in line with findings of Saouter et al. (*3*) and van Hoof et al. (*5*). For solid products (e.g., detergent powder) the energy intensive spray-drying slightly enhances the contribution of product formulation to energy, carbon, and overall environmental footprints. Note that other formulation technologies (e.g., nontower technology) apply pre-formulated compounds that are spray-dried by the suppliers, and thus only mixed in final-product manufacturing, resulting in a shift of environmental burdens to the supply chain. All other products are formulated by pure mixing of chemical ingredients and are therefore significantly less energy-consuming. Thus, only a small potential remains for the final-product manufacturers to optimize the products' cradle-to-gate environmental profile within the borders of their own production site. However, this study shows that the producers' choice of environmentally preferable raw chemicals and ecologically sound packaging is eminently important. If biobased raw chemicals are chosen, this selection requires a thorough consideration of a broad spectrum of environmental consequences, as land-use and water-use associated impacts may prove dominant (Figure 1c). They very much depend on agricultural practices and geographical location.

Further improvements potentials can be identified for packaging-intensive toilet-care and cleaning products. Because packaging supply dictates all environmental indicators (SI S7.2), cleaning-agent concentrates offered in pouches could represent reasonable alternative product variations. The manufacturing of such concentrates with substantially smaller water contents could considerably reduce packaging demand and transport expenditures and thereby lower the overall environmental damage from production and subsequent life-cycle phases.

Overall, the cradle-to-gate LCI modeling represents state-of-the-art production technologies and average values for technical inputs and outputs. The approximation of the raw chemicals TAED and limonene with inventory data for generic mixes of organic chemicals is regarded reasonable considering the small chemical amounts used. LCI estimations were necessary for other chemical ingredients (e.g., hydroxyethylcellulose). Therefore, significantly more supply chain studies should be conducted to overcome the lack of industrial production data and give advice on how to improve environmental performance. Alternatively, a new molecular-structure-based model can help in estimating inventory data and associated environmental impacts of chemical production (*20*) and thereby assist in chemical selection.

Relevance of Life-Cycle Phases. The cradle-to-grave analysis encompasses all product life-cycle stages, and thus returns environmental profiles which are characteristic for the product functions as a whole rather than for specific product features. Besides product compositions, factors such as consumer practices and technology choices taken by the consumer, as well as infrastructure characteristics (e.g., energy-supply and waste-management systems) (Table 1), strongly influence the consumer-goods' life-cycle performance. Compared to carbon footprints, the EI99 and IMPACTS2002+ results show a similar ranking of life-cycle phases. Yet, the production phase becomes slightly more relevant due to fossil feedstock embedded in chemical ingredients and packaging, and land-use impacts caused in agricultural production of biobased oils. Both these environmental interventions are not correlated with the production-stage associated GWP. Consumer use plays a very prominent role in the overall environmental outcome: substantial energy consumption for water heating when using soaps and detergents, and for home-transport of cleaning agents by car, are major life-cycle ecological drivers. This latter finding seems reasonable, as impacts from the cleaner's production are low due to small chemical amounts included and transport expenditures are high because of considerable product volumes, mainly composed of water, being transported along with large packaging.

In general, cleaning agents reveal very similar environmental profiles because of similar consumer applications, equivalent packaging systems, and minor differences in chemical composition. Although the cradle-to-gate environmental footprint of producing 1 kg of bar soap performs worse than that of liquid soap (Figure 1c), hand-washing with bar soap overall proves to be preferential to liquid soap for all indicators studied. The soap commodities show clear trade-offs: hand-washing with bar soap requires smaller soap amounts, and thus causes considerably lower impacts in the bar-soap supply chain (except for land-use impacts). However, larger warm-water volumes are needed for bar-soap application, and accordingly use-phase related environmental burdens are higher (Figure 2c,d). In the toilet-care product's life cycle, relatively high plastic-packaging quantities cause the substantial contribution of the waste-management stage. Expressed in quantitative terms, the waste-disposal related environmental damages are, however, relatively low for toilet flushing as compared to other product applications (SI S7.2).

Ecotoxicological impacts induced by chemical product-components, which are released with wastewater effluents, only slightly add to the overall environmental footprint because they are given a low weight in the EI99 scheme. Although substance-elimination rates in sewage treatment and effect-concentration thresholds are generally relatively high (SI S5), the small substance release to surface water still remains the major contributor to the total life-cycle freshwater ecotoxicity. Freshwater-use related impacts are insignificant because freshwater shares evaporated or integrated into products and thus lost for ecosystems are very small. Increased use of biobased feedstock in product manufacturing, however, may substantially enlarge the water footprint and cause enhanced damages from freshwater consumption particularly in areas with water scarcity. Given these results, it becomes apparent that detailed analyses on disaggregated levels are also necessary to cover all relevant ecological consequences of producing and using personal consumer products.

Influence of Consumer Behavior and End-of-Life Options. Consumer habits and choices eminently affect the environmental performance of product applications. Whenever energy-consuming processes such as water heating, car transport, and equipment operation, particularly with low efficiencies are involved, substantial environmental burdens can be observed for the consumer-use phase. Generally, the choice of smaller water amounts of colder temperature and energy- and water-saving appliances (washing machines, boilers, toilets) can generate desired environmental benefits. Replacing significantly outdated household appliances can improve the life-cycle energy performance of product application. However, in terms of more comprehensive environmental indicators (e.g., EI99) this consumer decision may become less favorable due to additional impacts from appliance production not associated with energy use (*21*). Product overdosage can multiply the ecological damages from the production chain, especially for products containing many chemical components (e.g., detergents). Adequate dosage instructions given by product manufacturers may thus significantly reduce adverse consequences on the environment. Also, the use of refillable packages proves to be environmentally beneficial, and therefore should be considered in the producers' and retailers' product portfolio.

In contrast, different waste-management systems, including incineration, plastic recycling, and landfilling, tend to only marginally influence the products' life-cycle performance, because differences in waste-management technologies are superimposed by environmental credits granted for energy and material recovery.

Despite the influential power of the consumer, public information on consumer decision-making and actual use-patterns remains scarce and demands additional research. Since the use of all nine home-care and personal-hygiene products noticeably contributes 1.3% to the overall annual environmental profile of a consumer, we advocate enhanced applications of life-cycle assessments to close data gaps and advance identification of major contributors to environmental impacts of chemical production. Such research results can further stimulate ecological improvements in product development and supply chain management as well as guide sustainable product policy making.

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Supporting Information Available

In-depth descriptions of methods applied, calculation procedures, and detailed results for all environmental indicators chosen. This material is available free of charge via the Internet at http://pubs.acs.org.

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