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Comparative Life-Cycle Assessment of Laundry Detergent Formulations in the UK

Part I: Environmental fingerprint of five detergent formulations in 2001

The environmental profiles of five different Procter & Gamble (P&G) laundry detergents on the UK market in 2001 are analysed using Life-Cycle Assessment (LCA). Products analysed are: regular powder (RP), compact powder (CP), powder tablet (PT), compact liquid (CL) and liquid unit-dose system (LT). The analysis represents a 'cradle-to-grave' LCA for 1 wash under UK conditions for wash habits and infrastructure. Under the study's conditions, it is concluded that compact detergents (both powder & liquid) are environmentally preferable detergent formulations, mainly due to the lower use of chemicals, resulting in benefits on aquatic toxicity, eutrophication, ozone depletion and photochemical smog. Less pronounced benefits for CP and CL are also observed on energy requirements and on impact categories such as acidification, human toxicity and climate change. For most indicators, the outcome of the study is dominated (> 70 % contribution) by the use stage (washing machine), which is common to all product formulations. Because of this, no significant differences are observed between scenarios using different laundry products. Hence, the present study demonstrates that for the 'cradle-to-grave' approach there is no single detergent formulation that is clearly outperforming all others on all indicators.

Vergleichende Ökobilanz von Waschmittelformulierungen in Großbritannien. 1. Teil: Ökologische Eigenschaften von fünf Tensidformulierungen im Jahr 2001. Die ökologischen Profile von fünf verschiedenen Procter&Gamble (P&G) Waschmitteln auf dem UK-Markt in 2001 werden auf ihre Ökobilanz untersucht. Die untersuchten Produkte sind: reguläres Pulver, Kompaktpulver, Pulvertabletten, Flüssigwaschmittel und vordosierte Flüssigwaschmittel. Die Untersuchung zeigt eine „cradle-to-grave" Ökobilanz für einen Waschgang unter UK-Bedingungen für Waschgewohnheiten und Infrastruktur. Unter den untersuchten Bedingungen zeigte sich, dass Kompaktwaschmittel (fest und flüssig) ökologisch bevorzugte Waschmittelformulierungen sind, was hauptsächlich im geringeren Chemikalienverbrauch begründet liegt. Das resultiert in Vorteilen für Abwassertoxizität, Eutrophierung, Ozonfreisetzung und photochemischen Smog. Weniger ausgeprägte Vorteile für die Kompaktwaschmittel sind für den Energieverbrauch und „impact categories" wie Absäuerung, Toxizität auf den Menschen und Klimaveränderungen zu finden. Für die meisten Indikatoren ist das Ergebnis der Studie dominiert (> 70 %) durch den verwendeten Standard (Waschmaschine), der für alle Produktformulierungen gleich ist. Daher sind keine deutlichen Unterschiede zwischen den verschiedenen Waschmittelprodukten festzustellen. Die hier vorgelegte Studie zeigt, dass es für den „cradle-to-grave" Ansatz kein einzelnes Waschmittel gibt, das die anderen in seinen Eigenschaften klar überragt.

Introduction

In [1] a time trend analysis from 1988 to 1998 was performed on laundry detergents using life cycle assessment (LCA). The study covered Sweden and the Netherlands. During this period, important technical detergent innovations took place in both countries, moving from traditional, bulky powder detergents to compacts.

Since 1998, unit-dose systems were introduced. Powder tablets were launched in 1998–1999 and liquid unit-dose – i. e. liquid detergent containing pouches that dissolve when immersed in water – were introduced in 2001 [2, 3]. Unit-dose systems meet a specific consumer need, since they significantly simplify the dosing aspects of the washing process. At the same time, chemical usage is optimized. For the liquid category, unit-dose systems provide a new additional step toward compaction. Unit-dose systems are also targeted to overcome a consumer concern of over/underdosing, leading to unsatisfactory consumer value equations (higher cost per wash than traditional systems, low performance).

Whilst in the last decade innovations such as compacts and unit-dose systems were introduced, regular powder formulations have still important market shares in many European countries [4]. These formulations also underwent significant innovations, with amongst others the introduction of new technologies leading to a more compact product (reduction in recommended dosage per wash more than 20 %).[1]

1 Goal and Scope definition

1.1 Goal of the LCA

The goal of the present study is to compare the environmental profiles of P&G laundry detergent formulations in 2001 in the UK. The UK was chosen since in that country regular powder, powder unit-dose systems and compact liquids have important market share (>10 %). In addition, the market share of liquid unit-dose systems in the UK is one of the fastest growing ones in Europe. Although compact powders have been replaced primarily by powder unit-dose systems, it was included for comparative reasons with [1] and Part II of this study [51]. Products selected for this study were: Ariel regular powder (RP), Ariel compact powder (CP), Ariel powder tablets (PT), Ariel compact liquid (CL) and Ariel liquid unit-dose systems (LT). Dilute liquids were not included, as Procter & Gamble does not currently market this product type in the UK.

1 The most significant decrease took place in the late 90's as a result of an industry agreement to reduce overall detergent dosage per capita by 10 % vs. 1996 data [32].

1.2 Scope of the study

1.2.1 Description of the system boundaries and functional unit

The present study is a 'cradle-to-grave' LCA, including the following laundry detergent life cycle stages: production of detergent ingredients ("ingredients"), product formulation ("formulation"), primary and transport packaging of the finished product ("packaging"), distribution from P&G manufacturing plant to retailer ("distribution"), consumer use and disposal (Table 1). The functional unit is 1 wash cycle, using the recommended dosage.

Product specifications such as formula composition information, recommended dosage per wash, packaging material information, product use information (wash temperature selection and prewash incidence) and sewage treatment information are given in Table 2. No additional product usage is assumed for prewashing, due to lack of data.

More than 80 % of the weight of all detergent formulations is covered with LCI data. No reliable surrogate LCI data could be found for the missing ingredients. Because the use stage contributes strongly to the overall results (>70 %), ingredient data gaps have limited impact on the results when comparing 'cradle-to-grave' data [5]. However, these data gaps may limit conclusions on a 'cradle-to-gate' basis (see 4.4). The recommended dosage is the dosage for 4.5 kg of normally soiled textile, washed in water with medium water hardness (18 – 28 mmol $CaCO_3$/L). In terms of packaging, different sizes and packaging types (carton, trial sachet or refill pack) are available per detergent type. For reasons of simplification, the size and packaging type is chosen for each detergent formulation with the highest market share.

Description of the product systems

Within the powder category, three products are analysed. Regular powder is the laundry detergent type with the longest history. A 'fluffy' powder is produced from drying a paste in a large drying tower. In a next step, this powder is dry mixed with some other ingredients. As a result of the drying process, the density of this detergent type is lower compared to their compact variants, leading to larger packages and higher dosing volumes. By contrast, today's P&G compact powders are mixtures of agglomerates, which are pre-processed in fluid-bed dryers. Due to this different drying process, the density of the agglomerates and the resulting compact powder is much higher (33 %). Powder tablets in a way can be seen as compressed compact powder surrounded with a coating. However, since tablets need to keep the balance between fast dissolving (for better performance) and product integrity (not breaking), additional technology is needed. [2, 24, 25].

Within the liquid category, compact liquids are the most successful in the UK market. Compact liquids differ from the dilute variant in that less water is needed to formulate, resulting in smaller packages and lower volumes to dose. Nevertheless, even with compact liquids a significant amount of water is necessary for product stability reasons. Liquid unit-dose systems are the newest invention in the laundry detergent sector. Because the detergent is delivered in pouches, quickly dissolving when immersed in water, highly concentrated liquid formulations can be delivered, resulting in even lower volumes to dose.

1.2.2 Database and data quality requirements

The study was run using TEAM^{TM} software [26] and the database structure, inherent assumptions and calculation methods are consistent with [5]. The necessary data to construct a product LCI originate from the following databases:

- *energy, transport* and associated environmental emissions: ETH database [27] with net calorific values to convert mass into energy units. Other energy databases [20,

	Included	Excluded	Comments/Assumptions
1. Manufacturing of detergent ingredients (ingredients)	• Extraction of raw materials, transport and manufacturing of final chemicals	• Transport from chemical supplier to P&G plant	
2. Product formulation (formulation)	• Formulation of finished detergents		• Manufacturing process of 1992 compact is used for 2001 supercompact and tablets
3. Packaging	• Manufacturing of packaging raw materials • Transport packaging for distribution to retailers	• Assembly of raw materials into pack • Transport packaging of raw materials • Transport to P&G plant • Post-consumer packaging waste treatment	• Post-consumer packaging is counted as solid waste
4. Distribution from P&G plant to retailers	• Diesel truck/ship from manufacturing plant to central location in the UK	• Distribution inside the UK to all retailers	
5. Use	• Product dosage • Wash habit practices (temperature selection and prewash) • Production of tap water	• Transport from consumer's homes to retailer	• Wash habit statistics via AISE diary study (1996)
6. Disposal (sewage water treatment)	• Sewage water treatment infrastructure from 1996 (untreated, mechanical and biological treatment with and without nutrient removal)	• other type of treatment (septic tank, trickling filter, …) • Waste sludge treatment	• Mechanical and biological treatment operating data for the Netherlands assumed representative for the UK • Waste sludge is counted as solid waste
7. Disposal (packaging treatment)		• Packaging disposal is excluded from the system boundaries	• The total packaging waste is counted as solid waste in the disposal stage

Table 1 Description of the life cycle stages for year 2001 P&G laundry detergents in the UK

	Powder formulations			Liquid formulations	
	Regular	Compact	Tablet	Compact	Tablet
Formula specifications					
Ingredient inventories included[1]	92.0 %	86.4 %	83.4 %	93.2 %	91.6 %
Acetic acid [6]			×		
Alcohol ethoxysulfate (AE3S-pc) [7]	×	×	×		
Alcohol ethoxylate (AE7-pc) [8]	×	×	×	×	×
Alcohol ethoxylate (AE11-PO) [8]	×	×	×		
Alcohol sulfate (AS-pc) [9]	×	×	×		
Antifoam [10]	×	×	×	×	
Brightener (FWA DAS-1) [11]	×	×	×	×	×
Cationic surfactant 1 [11]	×	×	×		
Citric acid [12]	×	×	×	×	×
Carboxy methylcellulose (CMC) [11]	×	×	×		
Cyclohexanedimethanol [6]			×		
Ethanol [12]				×	
Monoethanolamine (MEA) [13]				×	×
Linear alkylbenzenesulfonate (LAS-pc) [14]	×	×	×	×	×
Layered sodium silicate [11]	×	×	×		
Percarbonate [11]	×	×	×		
Polyacrylate [11]	×		×		
Polyethyleneglycol [13]			×		
Propanediol [15]				×	×
Savinase 10 TA+ [16]	×	×	×	×	×
Soap (coconut oil/tallow) [17]	×		×		
Soap (palm kernel oil/palm oil) [17]	×	×	×	×	×
Sodium carbonate [18]	×	×	×		
Sodium chloride [19]	×		×		
Sodium cumenesulfonate [13]				×	
Sodium hydroxide [19]				×	
Sodium silicate [11]	×	×	×		
Sodium sulfate [20]	×	×	×		
Starch [12]	×	×	×		
Water [21]				×	×
Zeolite A powder [11]	×	×	×		
Ingredient inventories missing					
Dye	×	×		×	×
P&G proprietary ingredient	×	×	×	×	×
Perfume	×	×	×	×	×
Phosphonate	×	×	×	×	×
Tetraacetylethylenediamine (TAED)	×	×	×		
Polymer	×	×	×	×	×
Soil release polymer	×	×			
Sorbitol		×			
Ethylene diamine dissuccinate (SS-EDDS)	×	×	×		
Silica		×			
Adipic acid			×		
Boric acid				×	
Calcium chloride				×	×
Cationic surfactant[2]				×	×
Formic acid					×
Moisture	4.6 %	7.1 %	3.9 %	–	–
Packaging specifications					
Type	Refill	Refill	Carton	Refill	Carton
Total packaging weight (g/pack)	147.7	31.5	108.8	82.8	173.4
primary (g/pack)	20.2	13.3	100.4	21	121.5
transport (g/pack)	127.5	18.2	8.4	61.8	51.9
Package capacity	2.43 kg	1.35 kg	48 tabs	1.5 L	12 tabs
Washes per pack[2]	20	18	24	20	12
Corrugated cardboard [20]	125	17	1.9	60.5	50.2
Greyboard [20]	–	–	86	–	72
Paper [20]	–	–	–	–	3.6
Polyethylene [22]	22.7	14.5	6.5	22.3	8.6
Polypropylene [22]	–	–	14.4	–	39
Distribution specifications					
Distribution via road (km)	50	350	350	285	285
Distribution via ship (km)	–	51	51	51	51
Use specifications					
Recommended dosage (g/wash)	121.5	75	86	78	54
prewash [4]	6			3	
30 °C	5			6	
40 °C	58			61	
60 °C	34			31	
> 60 °C	3			2	
Sewage water treatment infrastructure [4, 23]					
untreated (%)	10				
mechanical treatment (%)	10				
biological treatment, no nutrient removal (%)	62				
biological treatment, nutrient removal (%)	18				

[1] Surfactant abbreviations refer to sourcing, i.e. pc = petrochemical, PO = palm oil. Result is expressed as total % of the formula with ingredient LCI data
[2] at recommended dosage per wash

Table 2 Specifications on product composition, packaging and use for year 2001 P&G laundry detergent formulations in the UK

28, 29] were also used when data were missing on raw material production, formulation, packaging and transportation.

- *detergent ingredient LCI data* were obtained from published sources [6–9, 11, 14, 16, 17, 21, 22, 30]
- *detergent manufacturing LCI data* are from [31]
- raw materials in detergent *packaging* are delivered with the software and are from BUWAL 250 and APME [20, 28]
- LCI data for the *washing process* are obtained from the European Washing Machine Manufacturer Association (CECED) and from the Association Internationale de la Savonnerie, de la Détergence et des Produits d'Entretien (AISE) [32]
- LCI data on the *production of tap water* are from [33]
- *sewage treatment* data are derived from country statistics [23]

The P&G LCI database on laundry detergents [5] is available in TEAM^{TM} and has been peer reviewed by PriceWaterhouseCoopers.

Packaging raw materials are considered solid waste after use and are included as such in the total solid waste figure. A similar approach is followed for sludge generated at the water treatment plant. All of the raw material data (chemicals and packaging) is of high quality and representative of the average European situation. However, most detergent ingredient data originate from the period 1990–1995. It is very likely that since data collection, process improvements have taken place, but more up-to-date figures are presently unavailable. Detergent manufacturing data are from 1993. More up-to-date figures on specific P&G manufacturing processes are available but is not yet critically reviewed and therefore not used in this study.

Distribution is assumed to take place from the P&G manufacturing plant to a single delivery point in the UK (London area) with travelling distances between 50 and 350 km. Modes of transport are via road and ship. The LCI data for transportation [27] are representative for Europe and of high quality.

The original water production LCI data are for Switzerland and include capital equipment. For consistency reasons with the system boundaries of the majority of unit processes in this study, the data is recalculated excluding capital equipment. The data is considered of high quality, but medium/low representativity. However, since the contribution in the overall results is small, data quality is acceptable for the purpose of this study.

The LCI data for the operation of sewage treatment are in [5].

2 Life Cycle Inventory (LCI)

2.1 Allocation procedures

No allocation rules had to be defined since the system is a single output system. The allocation rules of the individual published LCI data were not altered.

2.2 Calculation procedures

The same calculation procedures are followed as in [5], with the following exceptions:

- primary energy is further distinguished into renewable and non-renewable energy or fuel and feedstock energy, following the TEAM^{TM} data format.
- airborne emissions listed are: fossil CO_2, CO, CH_4, NO_x (as NO_2), SO_x (as SO_2), N_2O, particulates and non-methane volatile organic compounds (nmVOC).
- waterborne emissions listed are: Biological oxygen demand (BOD), chemical oxygen demand (COD), phosphates (as PO_4^{3-}) and suspended matter
- solid waste is listed only as a total amount (in kg), but consists of approximately 20 different types.

The results of the 'cradle-to-grave' LCI are reported in Table 3.

3 Life Cycle Impact Assessment (LCIA)

For the impact assessment phase [34–36], the following impact categories were chosen:

- acidification [37],
- eutrophication [37],
- climate change (100 year time horizon), IPCC [38],
- ozone depletion [39],
- photochemical ozone creation, [40],
- aquatic toxicity [37] and
- human toxicity [37]

These impact categories were chosen for the following reasons:

- Eutrophication and toxicity indicators (human/environmental) represent a key societal concern for detergents. Whilst not always using the best science, we prefer to have a set of sector specific indicators to assess products.
- The other impact categories are a commonly applied set of indicators associated with products and supported by the inventory data in the present study.
- Other impact categories (e. g. land use) are not chosen since the majority of the inventory data has not the necessary level of detail.

The indicator for acidification has scientific limitations due to its dependence on site-specific conditions (soil buffering capacity). Recently, a new method is proposed taking this into account for average European conditions [41]. Since the scope of this study is focused on the UK, it was decided to follow the method as proposed in [37].

The eutrophication category assumes all organic waterborne emissions contribute to eutrophication via oxygen depletion. Since many of the detergent waterborne emissions are organic in nature, these emissions are accounted for by converting them to an equivalent amount of COD. Eutrophication is often connoted with phosphates in detergents. In the present study, however, all formulations are free of phosphate. This indicator in this study therefore reflects primarily release of organic matter from detergents to surface waters.

Climate change, ozone depletion and photochemical ozone creation are indicators developed on an international level for which a broad scientific consensus exists.

Whilst the chosen methodology on human and aquatic toxicity have some clear scientific limitations and newer methods are proposed [41, 42], it was selected because it is relatively easy to calculate aquatic toxicity characterisation factors for detergent specific waterborne emissions. These emissions are very relevant for the aquatic toxicity impact category [43] and should therefore be taken into account. New characterisation factors for aquatic toxicity were calculated by taking the inverse of the long term effect (LTE) concentration as listed in the Detergent Ingredient Database [44] and from internal databases for proprietary ingredients. In case no chronic data were available, they were supplemented with acute toxicity data with application factors.

Results for the 'cradle-to-grave' LCIA are given in Table 4.

		Powder			Liquid	
	Unit	Regular	Compact	Tablet	Compact	Tablet
Primary energy	MJ	17.6	16.2	16.8	15.7	17.2
Solid waste	g	173	142	146	132	154
Airborne emissions						
fossil CO_2	g	963	889	928	865	921
CO	g	0.96	0.86	0.91	0.80	0.91
CH_4	g	3.0	2.7	2.9	2.7	2.9
NO_x (as NO_2)	g	2.1	1.9	1.9	1.8	2.0
SO_x (as SO_2)	g	4.1	3.5	3.5	3.0	3.3
N_2O	mg	49	68	58	7.8	8.1
particulates	g	0.69	0.57	0.57	0.43	0.52
non-methane VOC	g	0.45	0.49	0.42	0.47	0.59
Waterborne emissions						
BOD	g	4.5	4.8	6.9	9.5	11.9
COD	g	11	11	18	23	28
Phosphates (as PO_4^{3-})[1]	mg	7.5	6.5	7.1	1.4	0.7
Suspended matter	g	1.22	0.85	0.92	0.23	0.22

[1] All 2001 formulations are free of phosphates. The figures shown are primarily coming from phosphate releases in the supply chain (production of some detergent ingredients)

Table 3 Energy consumption and emissions for 1 wash under UK conditions with year 2001 P&G laundry formulations

		Powder			Liquid	
	Unit	Regular	Compact	Tablet	Compact	Tablet
Acidification	g SO_2eq	0.19	0.16	0.16	0.14	0.15
Aquatic toxicity	m^3 PW	33	24	29	26	36
Eutrophication	g PO_4eq	0.66	0.67	0.85	0.92	1.08
Human toxicity	g BW	7.6	6.5	6.6	5.8	6.4
Climate change	g CO_2eq	1053	978	1018	933	994
Ozone depletion	ug CFC-11eq	53	36	43	24	29
Photochemical smog	g C_2H_4eq	0.75	0.83	1.18	0.41	0.50

PW = polluted water, BW = body weight

Table 4 Life cycle impact categories per wash cycle for year 2001 formulations in the UK

4 Interpretation and Discussion

Since LCA results are relative in nature due to the choice of the functional unit, regular powder is selected as the reference for the following discussion. This choice is based on its highest market share.

4.1 Results related to dosage and packaging of laundry detergents

From a consumer point of view, the most obvious differences between the 5 different laundry detergents subjected to this study are (1) differences in appearance (liquid vs. powder), (2) size (compact vs. regular) or (3) dosing method (measured dose vs. unit-dose). Packaging and recommended dose are strongly related to these three key differences. Whilst these 2 parameters are not inherently part of the LCA, it is worth studying them separately, as they may influence some inventory results significantly (e. g. post-consumer packaging has an effect on total solid waste, recommended dosage on many inventory results).

Recommended dosage per wash is highest for RP, followed by PT (index 71 vs. RP), CL (index 64) and CP (index 62) and LT (index 45). On packaging, LT is highest (index 117 vs. RP), followed by PT (index 74), CL (index 56) and CP (index 21). Absolute results are in Table 2.

Generally, packaging decreases with compact products. However, since for unit-dose systems more stringent packaging requirements exist to protect the product integrity (tablets should not break/leak), increased packaging is observed vs. normal compact variants. This explains the significant higher amounts (more than twofold) of packaging per wash for PT vs. CP and for LT vs. CL.

4.2 Results from the inventory analysis and impact assessment

The differences in overall LCI and LCIA results are relatively small amongst laundry formulations (Table 3 and Table 4). This is because the use stage is a key driver (> 70 % of overall contribution) for many indicators, related to the electricity requirements and associated emissions for heating the water in the washing machine. Since wash temperatures between the different formulations are very similar (Table 2), this results in small or no visible differences when looking at the whole system (Figure 1). To better analyse the contribution of the other life cycle stages, the overwhelming effect of the use stage has to be excluded.

Hence, the following sections will discuss results including and excluding the use stage. The first comparison is used to understand differences in environmental profiles of laundry products and how wash habits have an effect on it. The second is important for product designers to understand how formula design may have an effect in the environmental profiles in other stages of a laundry detergent's life cycle.

4.2.1 Primary energy, solid waste, fossil CO_2 and BOD emissions

From a cradle-to-grave analysis, all laundry forms studied show very similar profiles on primary energy and CO_2 emission. Also on solid waste, small differences are observed. RP is highest followed by LT, PT, CP and CL. Results are in Figure 2.

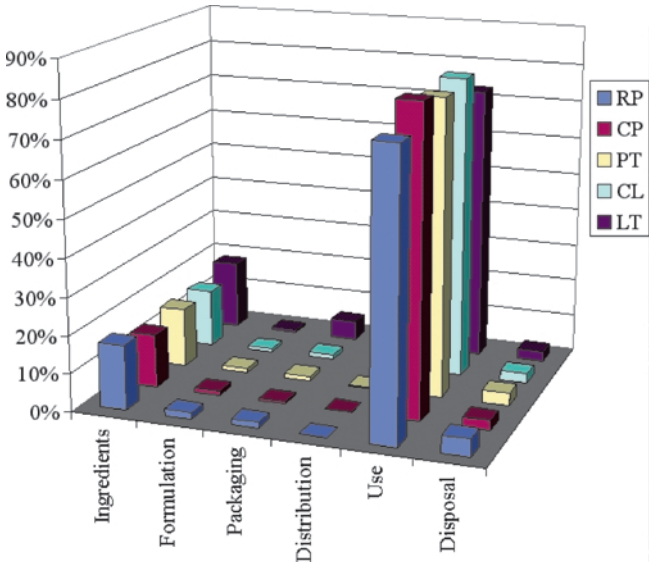

Figure 1 Contribution from the various life cycle stages to primary energy for year 2001 UK laundry formulations

The same profile is observed excluding the use stage, with more pronounced differences for energy, CO_2 and solid waste (Figure 3).

Biological oxygen demand (BOD) emission is highest for liquids. Even with lower dosages per wash, BOD emission is highest for unit dose systems vs. traditional dosing systems. For PT this is due to extra use of organic material for the tablet coating, for LT it can be attributed to higher surfactant levels. Figure 3 shows that from a *formulation point of view,*

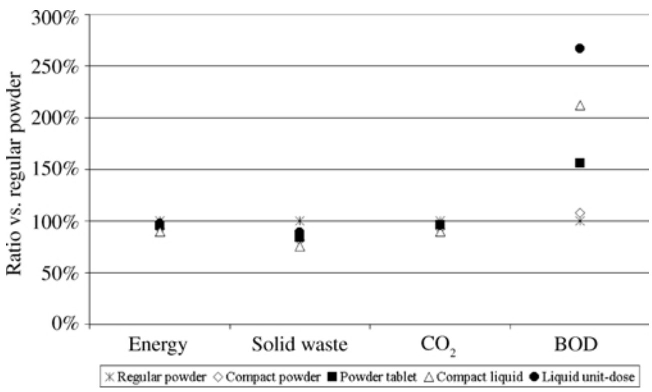

Figure 2 Energy, solid waste, CO_2 and BOD for 1 wash relative to RP (all stages included)

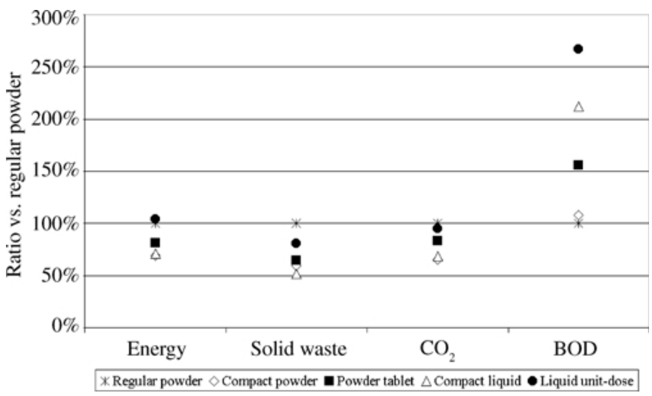

Figure 3 Energy, solid waste, CO_2 and BOD for 1 wash relative to RP excluding the use stage

CP and CL are preferable vs. RP in terms of energy requirements, CO_2 emission and solid waste.[2]

4.2.2 Impact Assessment

Climate change is not very different ($\leq 20\,\%$) for all variants vs. RP when the use stage is included. This impact category is mainly driven by energy related emissions (CO_2) associated with energy use. The use stage drives energy (Figure 1) and related emissions, resulting in small differences amongst the different detergent formulations (Figure 4). When the use stage is excluded, differences become more pronounced with CP and CL more than 20 % lower vs. RP (Figure 5).

- On *acidification and human toxicity*, only CL is considerably lower vs. all other formulations (Figure 4). These impact categories are driven by NO_x and SO_x emissions, which are highly correlated with energy use.
- On *eutrophication*, RP is lowest, with liquid detergent formulations being highest (Figure 4). Since all formulations in this study are free of phosphate, eutrophication is primarily driven by organic waterborne emissions[3].
- On *aquatic toxicity*, LT and RP are highest (Figure 4). Whether or not the use stage is included does not have a great influence, as aquatic toxicity is primarily driven by waterborne emissions not removed in water treatment (Figure 5). Within the powder category, RP is highest due to highest use of chemicals per wash; within the liquid category LT is highest due to high perfume contribution.

Key detergent ingredients contributing to aquatic toxicity (Figure 6) are primarily surfactants, followed by perfume, MEA (used as neutralizer in liquids) and adipic acid (coating for PT). It should be acknowledged that MEA and adipic acid are not very toxic [45, 46], but due to lack of chronic data, acute toxicity data is used with high application factors. A second group of chemicals contributing to aquatic toxicity is mercury and phenol, which are released at the production of sodium carbonate and sodium sulfate[4]. Since those ingredients are only used in powder formulations, they bring some extra aquatic toxicity vs. liquids. Note, LT is equal to RP, despite a lower dosage (index 45 vs. RP), due to high perfume levels in LT (index 240 vs. RP) and more mercury emissions with RP.

Figure 7 demonstrates that unremoved detergent chemicals mainly drive aquatic toxicity after sewage treatment. It also shows that from an aquatic toxicity indicator point of view, liquid formulations are least preferable. Within the powder category, PT is highest driven by higher perfume contributions. Due to the unit-dose form, higher perfume levels are required to provide a similar level of fresh scent.

- On *ozone depletion*, RP is highest and liquid detergent types are lowest (Figure 4). Ozone depletion is driven by Halon 1301 (CF_3Br), which is emitted mainly at the ingredients production stage and the use stage[4]. Key ingredients contributing to Halon 1301 are zeolite, carbonate and sodium sulfate. These chemicals are only used in powder detergents, with highest amounts for RP. Hence, differences are larger when the use stage is excluded (Figure 5).

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2 A difference of less than 20 % is not considered significant due to the uncertainties associated with LCA.

3 COD is used in the calculation; COD is mainly driven by organic chemicals in the detergent released to surface waters due to direct discharge or low removal in mechanical treatment systems.

4 No specific reason or indication is given in the life cycle inventory of these ingredients why these emissions occur.

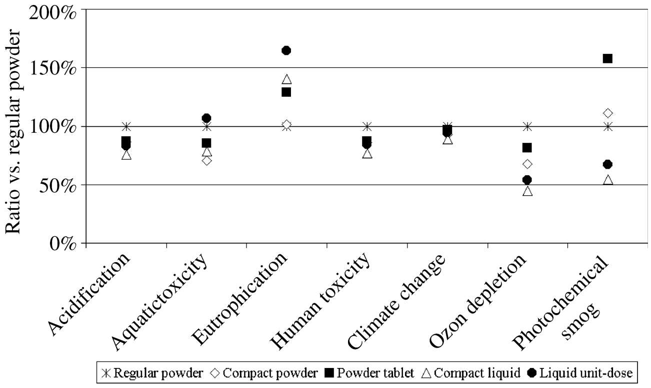

Figure 4 Impact assessment categories for 1 wash in 2001 under UK conditions relative to RP (all stages included)

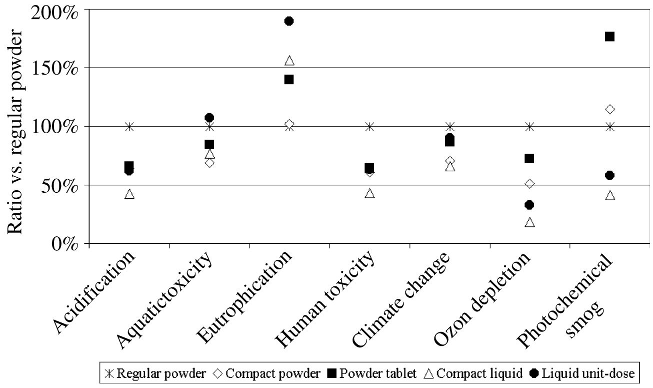

Figure 5 Impact assessment categories for 1 wash in 2001 under UK conditions relative to RP excluding the use stage

- On *photochemical smog*, the ingredients production stage is also the key driver. Hydrocarbon emissions are the primary source for photochemical smog creation. Silicone production for suds controlling agents used in powders is the most important one, followed by various types of surfactants. Since liquid detergent forms require much lower levels of suds control (~20 times), photochemical smog is lower vs. powders (Figure 4). Amongst powders, higher levels of surfactants per wash with CP and tablets explain why photochemical smog is higher for these detergent formulations vs. RP.

4.3 Summary of results

An inherent property in LCA is the multitude of data and indicators, which makes the comparison of multiple products informative, but difficult to overlook. Therefore, within P&G 2 presentations are used to communicate complex LCA results, rather than aggregating into single scores:

- semi-quantitative presentation using H, M and L classes and
- a visual presentation using a spider web graphical presentation ("environmental fingerprint")

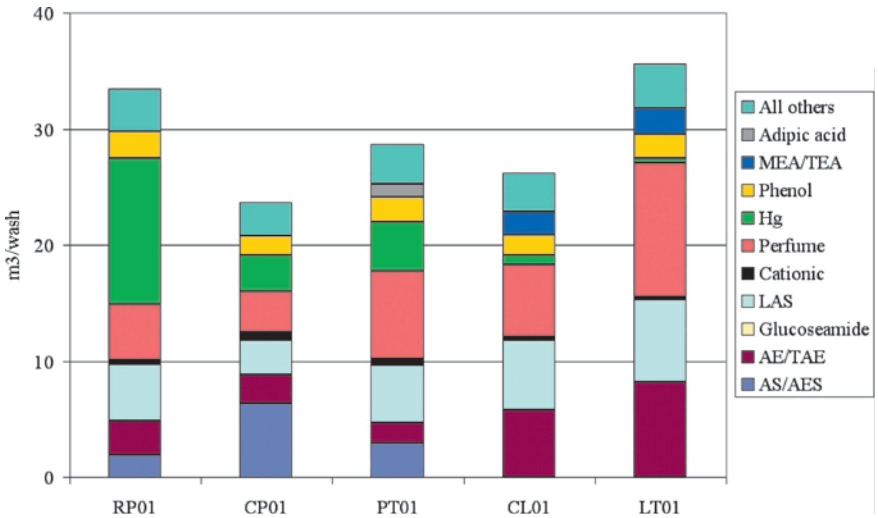

Figure 6 Aquatic toxicity for 1 wash in 2001 under UK conditions (all stages included)

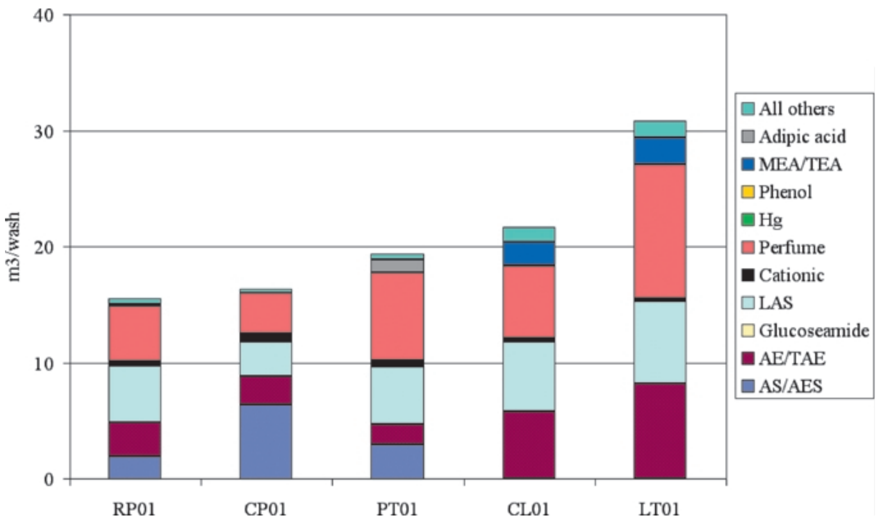

Figure 7 Aquatic toxicity for 1 wash in 2001 under UK conditions for emissions at the sewage treatment plant only

Environmental assessments on products are based on this type of information, together with information on product safety, regulatory information etc. all fitting within the P&G environmental framework [2, 47].

4.3.1 Semi-quantitative table presentation

In this presentation, results on LCA indicators are classified in 3 classes:

- class L stands for lower range result,
- class M represents results in the medium range and
- class H is for higher range result.

The classification process is done in four steps. First, the highest and lowest value is determined for each indicator. Second, the middle value (MV) is calculated by taking the average from both values. Third, a lower limit value (LLV) is calculated as 80 % of the MV and a higher limit value (HLV) is calculated by adding 20 % to the MV. Fourth, all indicators are compared to the LLV and HLV. Numbers equal or below the LLV are classified as "L", numbers equal or greater than the HLV classified as "H" and all other values are classified "M".

Because only the extreme values are used to calculate the MV, LLV and HLV, the method is independent of the distribution of the 'intermediate' values, which makes it more robust vs. taking a mean of all values. In a table format, it allows for a quick evaluation of strengths and weaknesses for each indicator and product variant. For LCA studies, this is extremely helpful given the number of indicators and product variants.

However, the limitation of this presentation is that results are transferred from a continuous scale to a discrete system with 3 classes and working with an arbitrary cut-off rule of 20 % vs. the MV. As a consequence, it is impossible to discriminate between large and extremely large differences. Calculations for key indicators are in Table 5.

From Table 6 it is clear that within the powder category, CP is the preferred detergent formulation with no indicator classified "H" and the largest number of "L" indicators. CL is for the same reason the preferred detergent variant within the liquid category. Even with the observed differences, it should also be acknowledged that there is no single detergent formulation clearly outperforming all others on all indicators.

4.3.2 Quantitative visual presentation ("environmental fingerprint")

The visual presentation shows results on indicators on a continuous scale. One of the product variants is chosen as a reference (in this study RP) against which all indicators are normalised. This normalisation is necessary to overcome scaling issues amongst different indicators. Each axis in the "environmental fingerprint" represents one indicator. When all points on the various axes are connected an area is formed for both the reference and the alternative products.

The benefit of this presentation is that the continuity of results is maintained, thus discriminating large (> 20 %) and very large (> 100 %) differences.

The limitation of the "environmental fingerprint" lies in the limited number of product variants and axes that can be shown on a single graph. From 4.3.1, it should be clear that both presentations are complimentary.

Versus RP, CP and CL are clearly preferable from an environmental view (Figure 8 to 11).

	RP	CP	PT	CL	LT
Energy, solid waste, acidification, human toxicity and climate change	M	M	M	M	M
Recommended dosage	H	M	M	M	L
Packaging	H	L	M	M	H
Aquatic toxicity	M	L	M	M	H
Eutrophication	L	L	M	M	H
Ozone depletion	H	M	M	L	L
Photochemical smog	M	M	H	L	L

L = lower range, M = middle range, H = higher range

Table 6 Summary of key indicators related to 1 wash with year 2001 P&G laundry detergents in the UK

4.4 Limitations of this analysis

The key benefit of an LCA is that this tool is comparative in its nature. The impact assessment methodology (CML92) used in this study has for some impact categories (e. g. toxicity) some clear scientific outages, i. e. exclusion of fate and exposure. Whilst new methods have aimed to improve on these impact categories [48–50] and other efforts are ongoing [42], the chosen methodology was applied for its easy applicability.

Limitations with respect to data availability and interpretation as mentioned in [1] are also of relevance for this study.

5 Conclusion

The present analysis across different detergent formulations indicates that compact powder and compact liquid detergent formulations are environmentally preferable within their category. However, there is no single detergent formulation clearly outperforming the others on all indicators, since the use stage (washing) dominates most indicators, making differences smaller. System improvement is therefore most successful when a formulation can be developed providing good cleaning at low wash temperatures. The good score for compacts is essentially driven by the lower use of chemicals per wash for these detergent formulations.

	Unit	RP	CP	PT	CL	LT	MV	LLV	HLV
Recommended dosage	g	121.5	75	86	78	54	88	70	106
Packaging	g	148	32	109	83	173	103	82	123
Energy	MJ	17.6	16.2	16.8	15.7	17.2	16.7	13.3	20.0
Solid waste	g	173	142	146	132	154	153	122	183
Acidification	g SO_2eq	0.19	0.16	0.16	0.14	0.15	0.17	0.13	0.20
Aquatic toxicity	m^3 PW	33	24	29	26	36	30	24	36
Eutrophication	g PO_4eq	0.66	0.67	0.85	0.92	1.08	0.87	0.70	1.04
Human toxicity	g BW	7.6	6.5	6.6	5.8	6.4	6.7	5.4	8.0
Climate change	g CO_2eq	1053	978	1018	933	994	993	794	1192
Ozone depletion	ug CFC-11eq	53	36	43	24	29	39	31	46
Photochemical smog	g C_2H_4eq	0.75	0.83	1.18	0.41	0.50	0.80	0.64	1.15

MV = middle value, LLV = lower limit value, HLV = higher limit value

Table 5 Calculation of the MV, LV and HV for various indicators related to 1 wash with year 2001 P&G laundry detergents

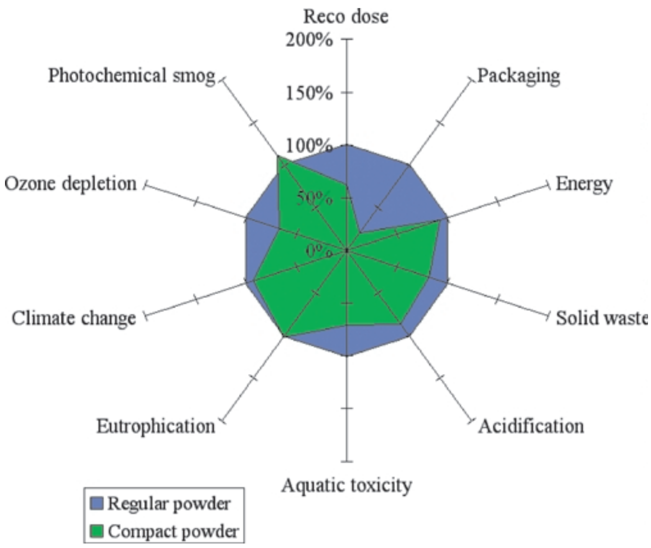

Figure 8 CP vs. RP environmental fingerprint based on LCA and key indicators for 1 wash in the UK

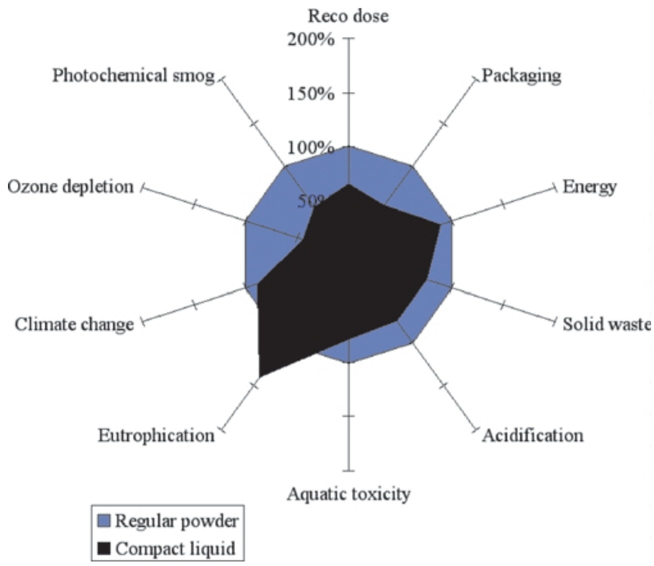

Figure 10 CL vs. RP environmental fingerprint based on LCA and key indicators for 1 wash in the UK

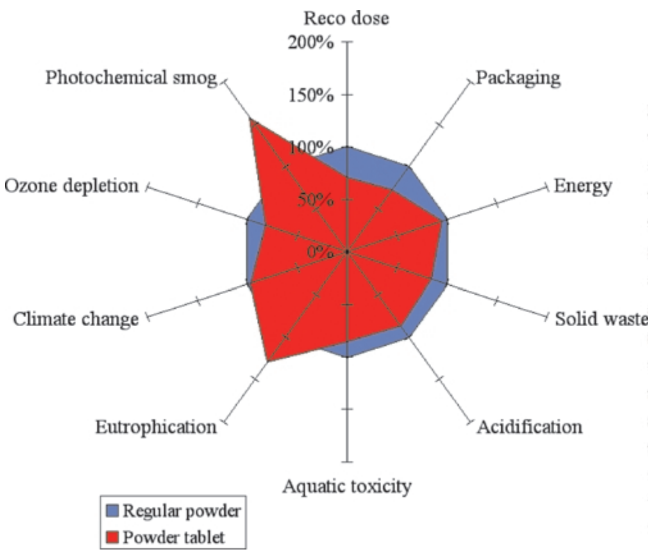

Figure 9 PT vs. RP environmental fingerprint based on LCA and key indicators for 1 wash in the UK

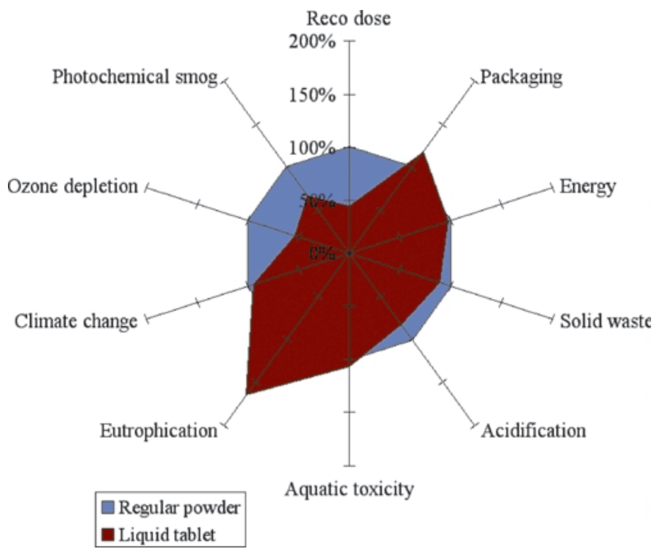

Figure 11 LT vs. RP environmental fingerprint based on LCA and key indicators for 1 wash in the UK

Firstly, this results in lower energy requirements and benefits are observed on energy and on impact categories such as acidification, human toxicity and climate change. Secondly, a lower use of chemicals also results in lower aquatic emissions with benefits on eutrophication (even in absence of phosphate in all detergent formulations) and aquatic toxicity. Thirdly, due to a lower use of some chemicals, benefits are observed on photochemical smog (silicone) and ozone depletion (zeolite, sodium sulfate and sodium carbonate). Emissions occurring during the manufacturing of these ingredients are key drivers for these indicators. An update on the underlying LCI data for these chemicals is therefore highly desired.

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