Waste prevention in liquid detergent distribution: A comparison based on life cycle assessment

Simone Nessi *, Lucia Rigamonti [1], Mario Grosso [1]

Politecnico di Milano, DICA—Environmental section, Piazza Leonardo da Vinci 32, Milano 20133, Italy

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1. Introduction and objective

Liquid detergents in Italy are traditionally distributed with single-use plastic containers. However, an alternative distribution method has recently been tested by some producers, with the aim of reducing waste generation and the impacts on the environment. Retail establishments are equipped with an automatic self-dispensing system from which different types of detergent can be withdrawn by means of refillable plastic containers available at the store. Due to the estimated waste prevention potential, this practice has been included in the set of waste prevention measures (WPMs) identified by the national waste prevention programme (Ministero dell'Ambiente e della Tutela del Territorio e del Mare, 2013). The programme has been adopted in 2013 in compliance with the European Waste Framework Directive 2008/98/EC (European Parliament and Council, 2008) and sets specific waste reduction targets for 2020. It is then a task of each Region to elaborate detailed regional prevention programmes to fulfil such requirements. The ultimate aim of such programmes and associated WPMs is not to pursue merely waste reduction, but to break the link between economic growth and the environmental impacts associated with the generation of waste.

The actual effectiveness of a WPM in reducing overall waste generation and environmental impacts needs however to be proven with a life

* Corresponding author. Tel.: +39 02 23996415.
E-mail addresses: simone.nessi@polimi.it (S. Nessi), lucia.rigamonti@polimi.it (L. Rigamonti), mario.grosso@polimi.it (M. Grosso).
[1] Tel.: +39 02 23996415.

cycle perspective before its implementation. In fact, as originally conceived, a WPM may not allow to achieve the expected improvements. In other cases, these improvements are achieved only under particular conditions. An example is the substitution of single-use plastic bottles by refillable glass ones for drinking water distribution, which is advantageous only if the latter is transported within a certain distance (e.g., Nessi et al., 2012). The effectiveness of a WPM is also often heavily dependent on citizens' behaviour and on the way the measure itself is actually implemented. This happens, for instance, when bottled water is replaced by refined water delivered from public fountains (e.g., Nessi et al., 2012). The benefits of this substitution depend on whether a car is used to reach the fountain or not (consumer behaviour), by the travelled distance (implementation of the WPM) and by the volume of water withdrawn and transported (consumer behaviour). The use of a life cycle approach will then allow designers to identify any critical points of a WPM, possible improvements and the way a WPM can be best implemented in a particular geographical context to actually achieve the expected benefits. Furthermore, it will also allow to provide citizens with the recommendations needed to fruitfully contribute to the success of a WPM. Other than the case study reported in Nessi et al. (2012), another recent example of the application of the life cycle assessment (LCA) methodology to the evaluation of the environmental impacts of a WPM is the one described in Cleary (2013). This study examines the substitution of single-use glass bottles by lightweight and refillable packages for wine and spirit delivery to the citizens of Toronto. Individually, all the examined packaging alternatives had lower end point level impacts than single-use glass bottles, although some of them had an increased midpoint level impact for one or more impact categories. At the municipal level, the substitution instead allows for a 40–42% reduction of the end point level impacts and a 10–45% of midpoint level ones.

The present study uses LCA to compare the distribution of liquid detergents through self-dispensing systems with the one based on single-use plastic containers. The first objective of the study is to evaluate whether, and under which conditions, distribution through self-dispensing systems allows to reduce waste generation, the overall potential impacts on the environment and on human health and the total energy demand, compared to distribution with single-use containers. If this was the case, the second objective is to quantify achievable waste prevention and impact reduction potentials. Out of the five categories of detergents that are currently distributed loose, the study focuses on those which presumably have the highest market shares, i.e., laundry detergents, fabric softeners and hand dishwashing detergents. Detergents intended for washing of delicate garments and floor cleaning were thus excluded.

Different formulations for powder and liquid laundry detergents and relative distribution methods have been compared in a number of LCAs carried out by researchers of Procter and Gamble (Saouter et al., 2002; Van Hoof et al., 2003a, 2003b; Dewaele et al., 2006). These studies found that packages are generally responsible for only a small portion of the overall impact, although their end of life is excluded. Most impact categories are indeed dominated by the washing stage (heating of the water or waterborne emissions) or by the production of detergent ingredients. However, packages contribute approximately to 7–15% of total solid waste generation.

Two potentially less waste-generating methods for liquid detergent distribution have recently been compared with traditional methods in two separate LCAs (Bolzonella and Gittoi, 2011 and CURA, 2012). Both are screening assessments and focus on climate change only. In the first study (Bolzonella and Gittoi, 2011), detergents are delivered to retailers by means of 20 L, reusable, high-density polyethylene (HDPE) tanks. From these tanks, the consumer can then withdraw directly the product with 1 L refillable HDPE containers. Under the assumption that tanks are used 115 times overall and containers 20 times, this alternative method allows approximately for a 44% reduction of the impact on climate change compared to distribution with 1 L single-use HDPE containers. In the second study (CURA, 2012), detergent distribution is made by means of 20 L disposable "bag-in-box" containers (plastic pouches included into corrugated cardboard boxes). These packages are used to refill a simple self-dispensing system from which the product can be withdrawn manually by means of dedicated 1 L refillable HDPE containers. Compared to traditional distribution with 1 L single-use HDPE containers, this alternative method is responsible approximately for a 78% lower impact on climate change if containers are used 30 times overall.

To the authors' knowledge, only one comparative LCA study (carried out on behalf of Assocasa[2]) focused on an alternative distribution system similar to the one examined in the present work. Nevertheless, only a brief summary of the results was disclosed to the public. The major conclusion of the study is that, for most indicators, a minimum of 5–10 uses of the refillable container are needed for the alternative system to be advantageous compared to traditional distribution. However, for some indicators, the best "traditional" scenarios proved to be comparable or preferable to the alternative system even beyond 10 uses.

2. Materials and methods

The LCA methodology (ISO, 14040) was applied in all its four basic stages: goal and scope definition, inventory analysis, impact assessment and interpretation. The assessment was carried out with the support of the SimaPro software (version 7.3.3), which facilitated the creation of a parametric model of the two compared distribution systems (Section 2.7) and the calculation of the respective potential impacts (Section 2.5).

2.1. Analysed scenarios

The approach used in the assessment was to compare a first set of scenarios where the detergent is distributed by means of single-use containers (baseline scenarios) with two scenarios where it is distributed loose (waste prevention scenarios; Table 1). Baseline scenarios differ in the material with which the disposable container is made and in its size. They were defined based on an extensive survey of the types of containers used during 2013 for the distribution of the major brands of the three considered categories of detergents in Italy. Such brands covered presumably more than 80% of the market for laundry detergents, 35% for fabric softeners and 50% for hand dishwashing detergents. A better approach would have been the definition of a unique baseline scenario for each detergent category. In this unique scenario, each type of single-use container is used in proportion to the respective market share, so that the actual mix of substituted packages is taken into account in the comparison with waste prevention scenarios. Unfortunately, no publicly accessible data on the popularity of each type of container were available and, therefore, we were unable to define an average unique scenario.

The two waste prevention scenarios were defined with reference to the pilot experiences of distribution through self-dispensing systems currently implemented by two Italian producers of detergents. The two scenarios differ primarily in the size of the refillable container (or in its mass in the case of hand dishwashing detergents). Moreover, in waste prevention scenario 1, reusable caps are transported to retail outlets with dedicated packagings. In waste prevention scenario 2, caps are instead screwed directly on the refillable containers at the packaging plant and, consequently, transported together with containers inside the same packages.

[2] Assocasa is the association of Italian companies dealing with cleaning, maintenance and hygiene products.

Table 1
Alternative scenarios for liquid detergent distribution analysed in the present LCA study.

Categories of detergent	Baseline scenarios		Waste prevention scenarios
	Distribution with single-use HDPE[a] containers with a size (in ml) of[b]	Distribution with single-use PET[a] containers with a size (in ml) of[b]	Distribution through self-dispensing systems with the provision to the consumer of a refillable virgin HDPE container with a size (in ml) of[b]
Laundry detergents	750; 1000; (1500–1518); (1820–2100); (2409–2625); (3000–3066); (3900–4000); 5000	750; 924; 1848	1000 (scenario 1)[c] 3000 (scenario 2)
Fabric softeners	750; 1000; (1500–1560); (2000–2015); 2460; (2990–3000); 4000	750; 1000; 1500; 2000	1000 (scenario 1)[c] 2000 (scenario 2)
Hand dishwashing detergents	750; (1000–1110); 1250; 1500; 2000; 3000; 4000; 5000	(500–650); 750; 1000; 1250; 1500	1000 (62 g; scenario 1)[c] 1000 (71.5 g; scenario 2)

[a] As a base case, containers were assumed to be entirely produced from virgin material. However, the use of 100% recycled material was also explored in a sensitivity analysis (Section 2.6).
[b] Each size or size class coincides with a specific scenario. In the case of size classes, scenarios foresee the distribution by means of single-use containers with a size that can ideally range from the lower bound to the upper bound of the respective class.
[c] The first waste prevention scenario is identical for all detergent categories. This is because in the real experience of distribution through self-dispensing systems assumed as a reference in that scenario, the same container is provided to the consumer for the withdrawal of all types of detergents offered loose.

2.2. Functional unit

The function of the compared systems is the delivery of liquid detergent to a generic Italian consumer who makes his own purchasing activities nearby the large-scale retail trade. The functional unit used in the study is thus "the distribution of 1000 litres of detergent nearby a retail outlet of the large-scale retail trade in Italy." This represents the unit used as a reference for the calculation of waste generation, of the potential impacts and of the energy demand of the compared scenarios.

2.3. System description

This section describes briefly the two alternative distribution systems compared in this study. The description is mostly based on the evidence gathered during a field survey at the manufacturing plant of an Italian producer of liquid detergents. Information retrieved from direct contacts with other producers was also taken into account.

2.3.1. Distribution with single-use plastic containers (baseline scenarios)

At the manufacturing plant detergents are firstly packed into HDPE or PET single-use containers. These are subsequently capped with polypropylene (PP) caps and labelled with paper or plastic labels. For transportation purposes, filled containers are placed inside disposable corrugated cardboard boxes. Each box normally includes from 4 to 20 containers, depending on the size. Boxes are then loaded on reusable wooden pallets and wrapped with a disposable linear low-density polyethylene (LLDPE) stretch film, which assures the stability of the whole load. Complete load units are then stocked until they will be transported to the distribution platforms of the different supermarket chains and, subsequently, to the single retail outlets. During the return trip, empty pallets from previous deliveries are transported back to the packaging plant, where they are reused to build new load units. At retail outlets, film and boxes are removed and become commercial wastes. Empty containers and respective caps, which are discarded by the consumer at the household, are instead collected as municipal solid wastes and are managed accordingly.

2.3.2. Distribution with self-dispensing systems (waste prevention scenarios)

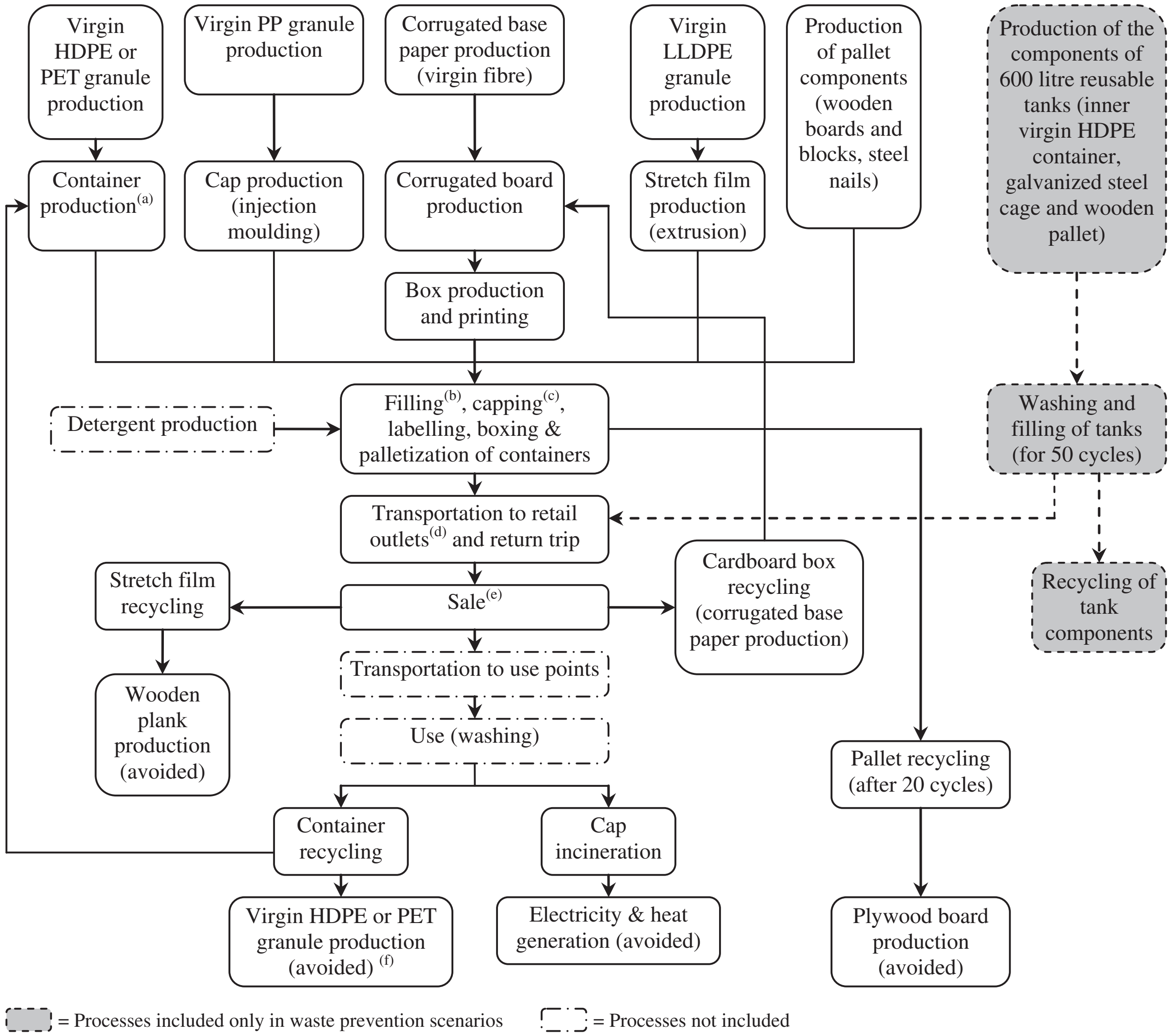
At the manufacturing plant the detergent is filled inside 600 or 1000 L reusable tanks. These consist of an inner virgin HDPE container, an external cage made of galvanized tubular steel and a wooden pallet on which the cage is fixed (Fig. S1 of the Supplementary material). Filled tanks are then transported to the distribution platforms of the different supermarket chains first, and to the respective retail outlets afterwards. Empty refillable containers and their caps are transported as well to retail outlets, following the same pathway. To this purpose, empty refillable containers are placed, like single-use ones, inside disposable corrugated cardboard boxes, which are subsequently loaded on reusable wooden pallets and wrapped with a disposable LLDPE stretch film. However, since empty containers are lighter than full ones, boxes are bigger and can include many more containers (up to 100 in the examined experiences). A lower amount of boxes is thus needed, overall, per load unit.

At retail outlets, the detergent contained in reusable tanks is used to refill an automatic self-dispensing system (Fig. S2 of the Supplementary material). This system is equipped with smaller tanks, each of which can hold a given type of detergent. Generally, four tanks with a volume of 80 L each are available. The detergents stored in the system can eventually be withdrawn by the consumer with the provided refillable containers, which will be completely filled.

Disposable packagings used for the transportation of containers and caps (boxes and stretch film) become commercial wastes at retail outlets. Wooden pallets used for the same purpose and reusable tanks are instead collected during the subsequent deliveries and transported back to the packaging plant. Here, reusable tanks are washed with network water and refilled, while pallets are reused to build new load units. Like single-use containers and caps, end-of-life refillable containers and their caps are discarded by the consumer as municipal wastes and are managed as such.

2.4. System boundaries

The major processes included in the system boundaries in both baseline and waste prevention scenarios are represented in Fig. 1. In both cases, system boundaries include the life cycle of containers (single-use or refillable), of their caps and of their transport packages; all the operations carried out at the packaging plant; the transportation of palletized containers to retail outlets; and the return trip with empty reusable pallets from previous deliveries. In addition, waste prevention scenarios include also the life cycle of reusable tanks, their transportation to retail outlets, the return trip with empty tanks from previous deliveries, product purchase from the self-dispensing system, its refilling and the life cycle of its main components. Detergent production is instead always excluded since it is assumed to be the same in all compared scenarios (all types of liquid detergents can be distributed loose). For the same reason, the purchasing roundtrip possibly



(a) HDPE containers are produced at the packaging plant by extrusion blow moulding of virgin or recycled HDPE granules. PET containers are instead produced by stretch-blow moulding of PET preforms, which in turn are produced in an external facility by means of injection moulding of loose PET granules. Note also that the input of recycled granules is included only when a 100% recycled content is assumed for single-use containers (sensitivity analysis; Section 2.6).

(b) Filling of containers is carried out only in baseline scenarios

(c) In waste prevention scenario 1, reusable caps are transported separately from refillable containers, which are therefore not capped. In this case, the life cycle of the packages used for cap transportation is included as well in the system boundaries. These packages are identical to those used for containers, although a disposable LDPE bag is used in addition. Loose caps are firstly placed in this bag and then packed in cardboard boxes. Packing and palletization operations are also included in the system. These operations are directly carried out by the cap producer (i.e. they are not made at the detergent packaging plant). In this scenario also refillable containers are directly packed and palletized by the respective producer.

(d) Generally, palletized items are firstly transported to distribution centres of single supermarket chains. Here, according to the specific needs of single retail outlets, new load units consisting of different packed products are built and subsequently transported to the intended destinations. Due to the extreme variability of this stage, palletized items were assumed to be directly transported to retail outlets.

(e) The major burdens of sale and purchase activities are generally those associated with the operation of retail establishments (lighting, conditioning, etc.) and with the use of fork-lift trucks for the handling of palletized products. However, these burdens are likely very similar in both baseline and waste prevention scenarios. No specific burdens are thus attributed to sale and purchase activities in baseline scenarios. Conversely, waste prevention scenarios include the additional burdens associated with the operation of the self-dispensing system and with the life cycle of its main components.

(f) When single-use containers are assumed to be entirely produced from recycled material (sensitivity analysis; Section 2.6), the whole amount of secondary HDPE or PET granules obtained from container recycling is used for container production. No avoided primary production of plastic granules is hence credited to the system in this case.

Fig. 1. Main processes included in (and excluded from) the system boundaries in the baseline and waste prevention scenarios compared in the present LCA study.

performed with a private car by the consumer and the washing stage at the household are excluded as well. Finally, the whole life cycle of labels applied to containers is excluded since the amount of material used per functional unit is small (approximately 1–3 g/L of detergent) and the contribution to the total impacts is deemed to be negligible.

2.5. Considered impact categories and impact assessment models

First of all, the generation of waste was calculated. This indicator was used as a first term of comparison between the analysed scenarios and to provide estimates of the waste prevention potentials.

Thirteen environmental and human health impact categories, evaluated at the midpoint level, were then considered: *climate change*, *ozone depletion*, *photochemical ozone formation*, *acidification*, *eutrophication* (terrestrial, freshwater and marine), *freshwater ecotoxicity*, *human toxicity* (cancer effects and non-cancer effects), *particulate matter*, *water resource depletion* and *mineral and fossil resource depletion*. These categories were selected out of those for which a recommended impact assessment model is identified by the Joint Research Centre (JRC) of the European Commission in the framework of the International Reference Life Cycle Data System (EC-JRC, 2011). The selection was made in the attempt to cover all the potentially relevant environmental issues for the examined product systems. The two impact categories, *ionising radiation (human health)* and *land use* were thus excluded. No processes involving significant emissions of radioactive substances or important changes in land use are indeed included in the studied systems. A list of the impact assessment models used for the considered impact categories is provided in Table S1 of the Supplementary material. The *cumulative energy demand* (CED) indicator was ultimately calculated, according to the method described in Hischier et al. (2010), in order to assess the energetic performance of the compared scenarios.

2.6. Sensitivity analysis

Single-use containers were initially assumed to be produced from virgin material (extruded plastic granules). Nevertheless, up to 100% of recycled polymers can also be used for this purpose, especially for dull coloured containers. The potential impacts of baseline scenarios were thus recalculated also under the assumption that single-use containers are entirely made from recycled HDPE or PET granules. The impacts of waste prevention scenarios were instead calculated as a function of the number of uses of the refillable container. The aim was to evaluate how the behaviour of the consumer affects the ultimate performance of such scenarios. The calculation of the impacts was thus repeated for a number of utilisation cycles ranging from 1 to 50.

2.7. Modelling of scenarios

A parametric model of the two alternative distribution systems was created in the SimaPro software. A relatively easy transition from one scenario to the other and from one category of detergent to the other could thus be performed by adjusting a set of parameters. The most important parameters are the average masses of containers, caps, cardboard boxes and stretch film needed per functional unit (baseline scenarios) or per litre of detergent (waste prevention scenarios), the average number of pallets needed (all scenarios), as well as the number of uses considered for the refillable container (waste prevention scenarios). Other parameters are the average detergent density and one indicating the waste prevention scenario to be assessed (no. 1 or 2).

The following sections describe briefly how input data were defined for the different life cycle stages included in the virtual model of the compared systems. The approach adopted and the assumptions performed for the same purpose are also described. Further details are available in the Supplementary material (Section S3).

2.7.1. Primary and transport packaging life cycle

The average mass of single-use containers, caps and cardboard boxes needed per functional unit in each baseline scenario was estimated experimentally. To this purpose, 219 single-use containers and respective caps were weighed, along with 133 cardboard boxes. Similarly, the average number of pallets needed per functional unit in the baseline scenarios was estimated based on a sample of real pallet compositions,[3] acquired from detergent producers or from retailers. A brief description of the estimation procedure used for each packaging and the obtained results are available in Section S3.1.1 of the Supplementary material. The amount of stretch film needed per functional unit was estimated based on annual consumption and production data acquired from an Italian manufacturer of liquid detergents. The same estimate (0.62 g of stretch film per litre of detergent) was then assumed in all baseline scenarios. No product-specific data were indeed available.

The masses of the different types of refillable containers and of the respective caps were also measured experimentally. Conversely, the masses of the packages used for the transportation of such containers and caps were acquired from their producers, along with the composition of the respective pallet. The average masses of the different components of reusable tanks were directly provided by their producer, as well. All the mentioned data are available in the Supplementary material (Tables S11 to S14).

Based on collected evidence, we assumed that all packages are produced from virgin material except the disposable cardboard boxes, which were assumed entirely produced from recycled fibres. As for the reusable tank, according to Classen et al. (2009), 37% of the steel cage is produced from post-consumer iron scraps. The remaining components (inner HDPE container and pallet) are instead produced from virgin material.

Regarding the end of life, we assumed that all packages are recycled except the caps, which are incinerated in a waste to energy plant after being sorted as residues from plastic wastes. Even the different components of the reusable tank are recycled at the end of their useful life, which was assumed equal to 50 cycles of transport. Further details on the type of recycling process considered for each packaging and for tank components are available in Section S3.1.2 of the Supplementary material. Inventory data on the unit processes characterising the life cycle of primary and transport packages were derived from the *ecoinvent* database (directly or with some adaptations and updates), from elaborations on literature data (e.g., for plastic recycling) or from equipment manufacturers (e.g., for HDPE tank recycling). See Section S3.1.3 of the Supplementary material for further details.

2.7.2. Packing operations

Operations carried out at the manufacturing plant for detergent packing were modelled based on primary data related to a medium-sized plant located in central Italy. In this plant, different types of liquid detergents are formulated and packed in single-use containers or in reusable tanks for their subsequent distribution through self-dispensing systems. The burdens associated with packing and palletization of refillable containers and respective caps were estimated based on data referring to the same plant. Specific consumptions attributed to all packing operations are reported in detail in the Supplementary material (-Section S3.2), along with the sources of inventory data for such inputs.

2.7.3. Transportation to retail outlets

In both baseline and waste prevention scenarios, packed detergents were assumed to be transported to retail outlets along an overall average distance of 340 km. This was estimated based on the location of the plants where the major brands of laundry detergents marketed in Italy are produced. The same distance was assumed also for fabric softeners and hand dishwashing detergents.

In order to estimate the average mass of detergent transported per functional unit, an average density was measured experimentally for each of the three categories of detergent. A brief description of the procedure and the obtained results can be found in the Supplementary material (Section S3.3). Inventory data on the transportation stage with a truck were derived from the *ecoinvent* database.

[3] A pallet composition indicates the number of cardboard boxes loaded on that pallet.

2.7.4. Detergent sale and purchase

Both refilling of the automatic self-dispensing system and withdrawal by the consumer require electricity. An overall consumption of about 0.0037 kWh/L of delivered detergent was estimated, based on the technical features of the equipment used in one of the examined experiences. The masses of the main components of the self-dispensing system were also estimated based on the same data (Table S17 of the Supplementary material). The estimate focused on major steel components (frame and other steel parts), on HDPE tanks and on expanded polyvinylchloride (PVC) covering panels. All these components were assumed to be produced from virgin material except the steel, which is partly produced from sorted iron scraps. At the end of their useful life, all the components are recycled, except for PVC panels, which are incinerated in a waste to energy plant. A useful life of 10 years was assumed for the self-dispensing system, along with an annual supply of about 75,000 L.

The source of inventory data for unit processes pertaining to the sale stage is mainly the *ecoinvent* database, but data from the literature and from equipment manufacturers were also used (further details are available in Section S3.4 of the Supplementary material).

2.7.5. Modelling of recycling

Product recycling was modelled according to the so-called *recyclability substitution approach* (EC-JRC, 2010), which is more commonly known as *avoided burden approach*. The avoided burdens of the primary production of substituted virgin products were thus credited to the system. In particular, the "average primary production mix" was credited. When the recycled product had a lower quality than the substituted virgin product, the primary production of a lower amount was credited. Since the amount of product actually substituted was unknown, the substitution factors provided in Rigamonti et al. (2010) were adopted in the calculation. These factors take into account the difference in the market value of the recycled and the virgin products, or in their inherent technical properties.

3. Results and discussion

3.1. Waste generation

In baseline scenarios, the generation of waste includes primary packagings (containers and caps) and the respective transport packages (cardboard boxes, stretch film and pallets). In waste prevention scenarios, reusable tanks were also included, as well as the packages possibly used for reusable cap transportation. In this case, the calculation was carried out for a number of uses of the refillable container ranging from 1 to 50. The results for the laundry detergents are represented in Fig. 2, while those for fabric softeners and hand dishwashing detergents are shown in Fig. S3 of the Supplementary material. Table 2 reports, for the laundry detergents, the difference between the best waste prevention scenario and the two extreme baseline scenarios (i.e., those in which the lowest and the highest amount of waste is generated). Results obtained for the other two categories of detergents are reported in Tables S18 and S19 of the Supplementary material. Note that negative variations per functional unit represent the waste prevention potentials achievable by distributing a particular category of detergent through self-dispensing systems.

For laundry detergents and fabric softeners, the best waste prevention scenario is the one with a bigger container (i.e., waste prevention scenario 2). On the contrary, for hand-dishwashing detergents, it is the one with a lighter container (i.e., waste prevention scenario 1). The comparison with baseline scenarios was thus made by focusing directly on these less-waste generating waste prevention scenarios.

If the refillable container is used just once, the distribution of laundry detergents and fabric softeners through self-dispensing systems does not significantly reduce waste generation compared to the best baseline scenario (Tables 2 and S18). For hand dishwashing detergents, waste generation will even increase by about 24% (21.5 kg/functional unit, Table S19). Compared to the worst baseline scenario, a reduction can instead be observed: 48% for laundry detergents (80 kg/functional unit), 32% for fabric softeners (49 kg/functional unit) and 24% for hand dishwashing detergents (45 kg/functional unit). This is because in the waste prevention scenario a bigger container is used and many more empty containers are transported in each cardboard box. The amount of primary and transport packages, which are wasted per functional unit, is thus lower, even if the container is used only once.

A much more important reduction in waste generation is obviously obtained with the increase of uses of the refillable container. For 50 uses, a maximum reduction in the range of 97–98% is obtained compared to the worst baseline scenario. A similar percentage reduction (about 96% for all detergent categories) is observed also when the comparison is made with the best baseline scenario. However, the decrease per functional unit is lower (85–103 kg versus 150–164 kg).

As expected, container reuse is the main driver for achieving such significant reductions in waste generation. Reuse allows a larger volume of detergent to be delivered by each container over its whole life cycle, with a consequent lower amount of required primary and transport packages. A lower amount of waste is thus generated overall in waste prevention scenarios, even if reusable tanks are used in addition to containers, caps and their transport packages. The additional contribution provided by tanks is indeed limited (about 1.8 kg per functional unit),

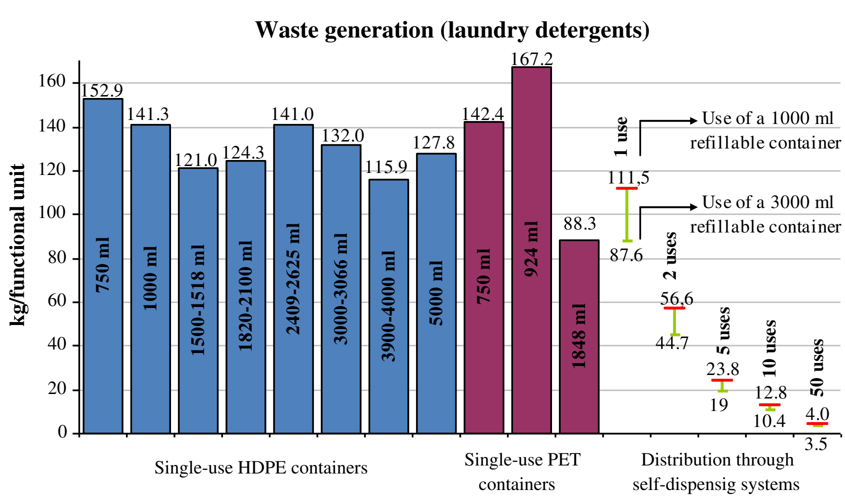


Fig. 2. Waste generated in laundry detergent distribution. Bars are the baseline scenarios, while horizontal dashes are the two waste prevention scenarios for different number of uses of the refillable container.

Table 2
Difference between the amount of waste generated in the scenario where laundry detergents are distributed loose with a 3000 ml refillable container (waste prevention scenario generating less waste) and that generated in the two respective baseline scenarios with the lowest and the highest generation of waste.

Reference baseline scenario	Number of uses of the 3000 ml refillable container				
	1	2	5	10	50
Distribution with a 1848 ml PET container (baseline scenario generating less waste)	−0.69 kg/fu[a,b] (−0.78%)	−43.6 kg/fu (−49.4%)	−69.3 kg/fu (−78.5%)	−77.9 kg/fu (−88.2%)	−84.7 kg/fu (−96.0%)
Distribution with a 924 ml PET container (baseline scenario generating most waste)	−79.6 kg/fu (−47.6%)	−122.5 kg/fu (−73.3%)	−148.2 kg/fu (88.6%)	−156.8 kg/fu (−93.8%)	−163.6 kg/fu (−97.9%)

[a] fu = functional unit.
[b] Negative variations per functional unit represent the waste prevention potentials achievable with distribution of laundry detergents through self-dispensing systems. They are expressed as the amount of waste prevented per 1000 L of detergent distributed loose rather than packed in a single-use container of the type considered in the baseline scenario of reference.

since a very large volume of detergent is delivered over their whole life cycle (30,000 L in this study).

Finally, it is worth noting that, starting from 5 uses of the refillable container, the difference between the two waste prevention scenarios is decreasing and tending to zero. Provided that this minimum target is achieved, and hopefully exceeded, the effectiveness of the distribution through self-dispensing systems is then not significantly affected by the size (or the mass) chosen for refillable containers.

3.2. Life cycle impact assessment (LCIA) results

For all the three categories of detergent, most of calculated impact indicators show a profile similar to the one of *climate change*, represented in the upper part of Fig. 3 for laundry detergents. The *human toxicity, cancer effects* indicator is instead characterized by a slightly different profile, as shown in the lower part of Fig. 3, always for laundry detergents. The profile of the same indicators calculated for fabric softeners and hand dishwashing detergents, as well as that of the remaining indicators for laundry detergents, is available in Section S4.2 of the Supplementary material. An overview of the impacts of all baseline scenarios and of the two waste prevention scenarios for increasing uses of the refillable container can be found in Tables 3 and 4 for laundry detergents. For fabric softeners and hand dishwashing detergents, an overview is provided in Tables S21, S22, S25 and S26 of the Supplementary material.

3.2.1. Laundry detergents

Out of the two waste prevention scenarios, the one based on 1000 ml refillable containers has the highest impact for all categories except for the *human toxicity, non-cancer effects* one (Table 4). If such a container is used at least 10 times, distribution through self-dispensing systems is preferable for all impact categories except those related to human toxicity[4] (Fig. 3, Figures S4 to S9 of the Supplementary material and Table S20). In the prevention scenario based on 3000 ml refillable containers, only 5 uses are needed as the minimum threshold for an improved environmental performance (Table 5).

For the *human toxicity, non-cancer effects* impact category, in both waste prevention scenarios, the distribution through self-dispensing systems outperforms the single-use based one only starting from 25 uses (Fig. S7 of the Supplementary material, Table S20 and Table 5). For the category *human toxicity, cancer effects*, waste prevention scenarios are instead preferable to the vast majority of baseline scenarios starting from 10 uses, but they remain comparable to the best baseline scenario even up to 50 uses (Fig. 3, Table S20 of the Supplementary material and Table 5). The toxicity indicators are the most uncertain, since a complex mechanism relates emissions of toxic substances to their ultimate effects. One has thus to be aware that the use of a different impact assessment model could lead to different results for these indicators.

The variation of the impacts between the waste prevention scenario based on 3000 ml refillable containers and the best baseline scenario is reported in Table 5. With the exclusion of the human toxicity categories, a 12–53% reduction of the total impact for 5 uses and 24–73% for 50 uses is observed. A 54–90% decrease for 5 uses and 58–94% for 50 uses is instead observed compared to the worst baseline scenario (Table 6).

As expected, this overall impact reduction is mainly a result of the decrease in the impact of the life cycle of primary packages (containers and caps), which can reach 100%. On average, the life cycle of primary packages contributes to about 50% of the total impacts of baseline scenarios if human toxicity categories are excluded. The observed percentage reductions in impact are thus significant also with respect to the functional unit.

A significant percentage reduction in the impact of the life cycle of packages used for detergent transportation is also observed in waste prevention scenarios (up to 98%). However, for most impact categories, the contribution provided by the life cycle of detergent transport packages to the total impact of baseline scenarios is modest (about 17% on average if human toxicity categories are excluded). Therefore, impact reductions per functional unit are limited, too.

The impact of the transportation stage, which on average contributes to about 29% of the total impacts of baseline scenarios, is comparable in both examined distribution systems. As it is also the impact provided by the remaining life cycle stages, which altogether are on average responsible for less than 3% of the total impacts of baseline scenarios and for less than 16% of those of waste prevention scenarios.

Even the lower benefits achievable in waste prevention scenarios for human toxicity impact categories can be explained by looking at the variation of the impacts of the most important life cycle stages. For these categories, a reduction in the impact of the life cycle of primary packages up to 99% is still observed. However, this is partially or totally compensated by an increase in the impact of the life cycle of packages used for detergent transportation. Such increase can be as high as 300% for the *human toxicity, cancer effects* and 41% for the *human toxicity, non-cancer effects*. Responsibility for this increase is in charge to the tanks made of a galvanized steel component (Fig. S1 of the Supplementary material). In fact, for carcinogenic effects, about 73% of the human health impact associated with the life cycle of transport packages is caused by waterborne emissions of chromium from the landfilling of slag generated during the production and the recycling of the steel used by the cage of the tanks. Direct airborne emissions of zinc resulting from its primary production and from its subsequent use for the coating of the cage are instead responsible for about 80% of the overall human health impact in the case of non-carcinogenic effects.

3.2.2. Hand dishwashing detergents

Most of the comparative considerations between the two alternative distribution methods made for laundry detergents can be extended also to hand dishwashing detergents, although a few differences are

[4] Due to uncertainties included in the analysis, only differences (positive or negative) between scenario impacts larger than 10% were considered significant in this study. Therefore, distribution through self-dispensing systems was considered preferable to that based on single-use containers only when the impact of the respective waste prevention scenario was lower than the impact of the best baseline scenario for at least 10%.

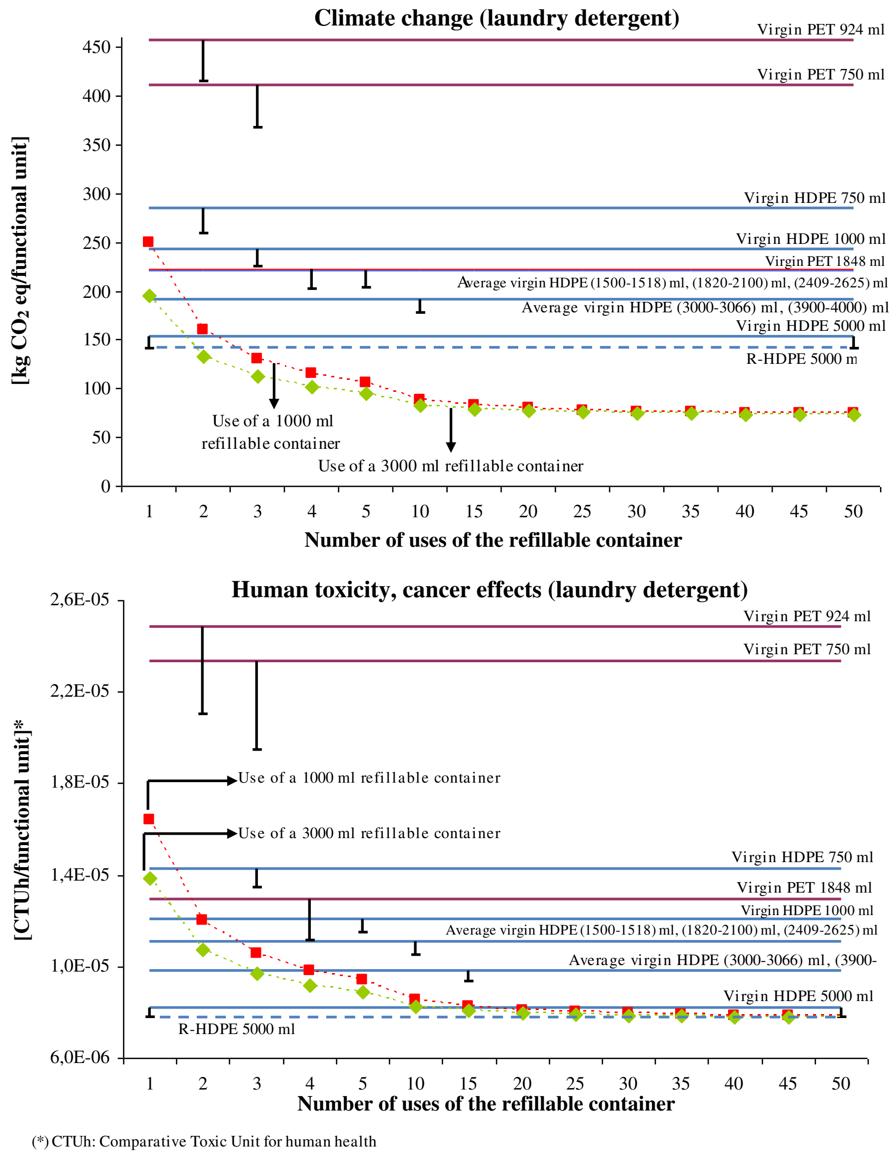


Fig. 3. *Climate change* and *human toxicity, cancer effects* impact indicators for laundry detergents. Horizontal lines represent the impacts of baseline scenarios, while squares and rhombuses the impacts of the two waste prevention scenarios as a function of the number of uses of the refillable container. Error bars represent the variation of the impacts when single-use containers are produced entirely from recycled material.

observed. First of all, starting from the same minimum number of uses, the distribution in refillable containers is preferable to the single-use-based one with respect to all impact categories, except for the only *human toxicity, cancer effects*. Moreover, with the exclusion of the human toxicity categories, impact reductions achieved in waste prevention scenarios are moderately lower than those obtained for laundry detergents (Tables S27 and S28 of the Supplementary material). This is because the impacts of waste prevention scenarios are higher compared to laundry detergents, since smaller (or lighter) refillable containers are used. Moreover, the impacts of the two extreme baseline scenarios are slightly or moderately lower than for laundry detergents.

Finally, for the *human toxicity, cancer effects* impact category, distribution through self-dispensing systems starts being comparable with the best baseline scenario from a greater number of uses of the refillable container than laundry detergents. In the best waste prevention scenario[5] this happens starting from 15 uses, while in the worst[6] 20 uses are needed. For laundry detergents, such a threshold was 10 uses, for both waste prevention scenarios.

3.2.3. Fabric softeners

Out of the two waste prevention scenarios, the one based on a 2000 ml refillable container shows the lowest impact for all categories except for *human toxicity, non-cancer effects* and *marine eutrophication*. However, starting from 4 uses, in both waste prevention scenarios, the distribution through self-dispensing systems is preferable to that based on single-use containers with respect to all impact categories except for the *human toxicity, cancer effects* one. For this category, the two waste prevention scenarios start to be comparable with the best baseline scenario from 10 uses of the container, similarly to laundry detergents.

With the exclusion of human toxicity categories, impact reductions achieved in the best waste prevention scenario are similar to those

[5] The waste prevention scenario where a 1000 ml refillable container weighing 62 g is provided to the consumer shows the lowest impact for all the considered impact categories.

[6] The waste prevention scenario where a 1000 ml refillable container weighing 71.5 g is provided to the consumer shows the highest impact for all the considered impact categories.

Table 3
Potential impacts of baseline scenarios for laundry detergents. Values in parentheses refer to containers being produced entirely from recycled material (as considered in the sensitivity analysis).

		Scenario										
		Distribution with single-use HDPE containers with a size of:								Distribution with single-use PET containers with a size of:		
		750 ml	1000 ml	1500–1518 ml	1820–2100 ml	2409–2625 ml	3000–3066 ml	3900–4000 ml	5000 ml	750 ml	924 ml	1848 ml
Climate change	kg CO_2 eq.	285 (259)	244 (225)	221 (205)	223 (205)	218 (202)	193 (179)	189 (177)	153 (141)	411 (368)	457 (415)	222 (202)
Ozone depletion	kg CFC-11 eq.	2.77E−5 (2.77E−5)	2.50E−5 (2.50E−5)	2.32E−5 (2.32E−5)	2.28E−5 (2.28E−5)	2.24E−05 (2.24E−05)	2.01E−5 (2.00E−5)	1.97E−5 (1.97E−5)	1.62E−5 (1.62E−5)	8.53E−5 (8.31E−5)	9.11E−5 (8.89E−5)	4.36E−5 (4.25E−5)
Photochemical ozone formation	kg NMVOC eq.	1.20 (1.08)	1.08 (0.992)	0.998 (0.927)	1.01 (0.934)	1.02 (0.944)	0.942 (0.879)	0.927 (0.873)	0.834 (0.781)	1.40 (1.27)	1.52 (1.39)	0.941 (0.882)
Acidification	mol H^+ eq.	1.43 (1.33)	1.23 (1.16)	1.12 (1.06)	1.15 (1.08)	1.14 (1.08)	1.04 (0.979)	1.02 (0.968)	0.881 (0.834)	1.95 (1.75)	2.08 (1.88)	1.17 (1.07)
Terrestrial eutrophication	mol N eq.	3.91 (3.72)	3.56 (3.43)	3.32 (3.20)	3.37 (3.24)	3.43 (3.31)	3.19 (3.08)	3.19 (3.11)	2.83 (2.75)	4.66 (4.32)	5.02 (4.68)	3.28 (3.12)
Freshwater eutrophication	kg P eq.	0.103 (0.103)	0.0827 (0.0824)	0.0723 (0.0721)	0.0757 (0.0755)	0.0741 (0.0739)	0.0638 (0.0636)	0.0629 (0.0627)	0.0483 (0.0481)	0.192 (0.172)	0.202 (0.182)	0.0974 (0.088)
Marine eutrophication	kg N eq.	0.403 (0.386)	0.367 (0.355)	0.340 (0.329)	0.344 (0.332)	0.354 (0.344)	0.324 (0.315)	0.334 (0.326)	0.277 (0.269)	0.485 (0.451)	0.531 (0.497)	0.338 (0.322)
Freshwater ecotoxicity	CTU_e	340 (305)	295 (270)	265 (244)	266 (242)	271 (249)	232 (213)	245 (229)	167 (151)	520 (415)	589 (484)	285 (235)
Human toxicity (cancer effects)	CTU_h	1.43E−5 (1.34E−5)	1.21E−5 (1.15E−5)	1.09E−05 (1.04E−05)	1.12E−5 (1.06E−5)	1.11E−5 (1.06E−5)	9.91E−6 (9.45E−6)	9.70E−6 (9.30E−6)	8.17E−6 (7.79E−6)	2.34E−5 (1.95E−5)	2.49E−5 (2.10E−5)	1.30E−5 (1.11E−5)
Human toxicity (non−cancer effects)	CTU_h	1.96E−5 (1.95E−5)	1.81E−5 (1.80E−5)	1.63E−05 (1.62E−05)	1.62E−5 (1.61E−5)	1.79E−5 (1.78E−5)	1.50E−5 (1.49E−5)	1.80E−5 (1.80E−5)	9.89E−6 (9.84E−6)	2.70E−5 (2.36E−5)	3.15E−5 (2.81E−5)	1.79E−5 (1.62E−5)
Particulate matter	kg $PM_{2.5}$ eq.	0.137 (0.125)	0.116 (0.107)	0.105 (0.0969)	0.107 (0.0988)	0.107 (0.0989)	0.0945 (0.0876)	0.0946 (0.0886)	0.0757 (0.0699)	0.178 (0.154)	0.194 (0.170)	0.103 (0.091)
Water resource depletion	m^3 water eq.	1.22 (1.15)	0.985 (0.934)	0.869 (0.826)	0.906 (0.858)	0.877 (0.833)	0.764 (0.726)	0.738 (0.705)	0.597 (0.566)	2.99 (2.73)	3.10 (2.85)	1.49 (1.37)
Mineral and fossil resource depletion	kg Sb eq.	0.965 (0.784)	0.810 (0.679)	0.729 (0.618)	0.744 (0.621)	0.723 (0.610)	0.639 (0.540)	0.617 (0.532)	0.512 (0.430)	1.32 (1.13)	1.46 (1.27)	0.707 (0.616)
Cumulative energy demand	MJ eq.	6412 (5378)	5354 (4602)	4794 (4157)	4910 (4204)	4796 (4148)	4216 (3649)	4098 (3610)	3339 (2869)	8507 (7385)	9383 (8272)	4557 (4027)

Table 4
Potential impacts of the two waste prevention scenarios for laundry detergents as a function of the number of uses of the refillable container.

Impact category	Unit of measure	Waste prevention scenario 1					Waste prevention scenario 2				
		Number of uses of the 1000 ml refillable container					Number of uses of the 3000 ml refillable container				
		1	2	5	10	50	1	2	5	10	50
Climate change	kg CO_2 eq.	249	160	106	88.4	74.1	195	133	95.5	83	73.0
Ozone depletion	kg CFC−11 eq.	2.51E−5	1.76E−5	1.31E−05	1.17E−5	1.05E−05	2.03E−5	1.52E−05	1.22E−5	1.12E−5	1.04E−5
Photochemical ozone formation	kg NMVOC eq.	1.13	0.852	0.686	0.631	0.587	0.976	0.776	0.656	0.616	0.584
Acidification	mol H^+ eq.	1.30	0.903	0.663	0.583	0.518	1.08	0.79	0.62	0.56	0.51
Terrestrial eutrophication	mol N eq.	3.66	2.87	2.39	2.23	2.11	3.3	2.7	2.3	2.2	2.1
Freshwater eutrophication	kg P eq.	0.0875	0.0496	0.0269	0.0193	0.0132	0.0658	0.0388	0.0225	0.0171	0.0128
Marine eutrophication	kg N eq.	0.358	0.275	0.224	0.207	0.194	0.328	0.259	0.218	0.204	0.193
Freshwater ecotoxicity	CTU_e	307	204	142	121	105	262	181	133	117	104
Human toxicity (cancer effects)	CTU_h	1.64E−5	1.20E−5	9.40E−6	8.52E−6	7.82E−6	1.39E−5	1.08E−5	8.89E−6	8.27E−6	7.77E−6
Human toxicity (non-cancer effects)	CTU_h	1.69E−5	1.27E−5	1.02E−5	9.30E−6	8.62E−6	1.77E−5	1.31E−5	1.03E−5	9.38E−6	8.64E−6
Particulate matter	kg $PM_{2.5}$ eq.	0.118	0.0762	0.0510	0.0426	0.0359	0.0956	0.0649	0.0465	0.0404	0.0355
Water resource depletion	m^3 water eq.	1.05	0.614	0.350	0.262	0.191	0.789	0.481	0.297	0.235	0.186
Mineral and fossil resource depletion	kg Sb eq.	0.844	0.526	0.335	0.271	0.221	0.645	0.426	0.295	0.252	0.217
Cumulative energy demand	MJ eq.	5521	3370	2078	1648	1304	4219	2719	1818	1518	1278

obtained for laundry and hand dishwashing detergents when the comparison is made with the best baseline scenario (Table S23 of the Supplementary Material). Compared to the worst baseline scenario, achieved reductions are instead lower than those obtained for laundry detergents, but comparable with those obtained for hand dishwashing detergents (Table S24 of the Supplementary material). This is mainly because the impacts of the reference baseline scenario are lower than those of laundry detergents.

3.2.4. General remarks

One last important overall result is that most of the reduction of the impacts of waste prevention scenarios takes place between 2 and 5–10 uses of the container, depending on the impact category. After this threshold, such impacts tend to stabilize over an asymptotic value and increasingly smaller and negligible differences are observed between the impacts of the two waste prevention scenarios. Conversely, if the container is used for less than 10 times, differences are more pronounced and waste prevention scenarios where a bigger or a lighter refillable container is used are preferable (at least for most impact categories).

4. Conclusions and recommendations

Life Cycle Assessment was used to evaluate whether detergent distribution through self-dispensing systems actually allows to achieve the expected reduction in waste generation and environmental impacts. Laundry detergents, fabric softeners and hand dishwashing detergents were analysed, by defining a set of baseline single-use scenarios and two alternative waste prevention scenarios.

Results showed that if the refillable container is used at least 5 times, the distribution through self-dispensing systems allows for an actual reduction of municipal waste generation compared to the distribution with the main types of single-use plastic containers available in the Italian market. Depending on the category of detergent and on the reference baseline scenario, a 74–89% reduction for 5 uses of the container and 95.5–98% for 50 uses is achieved. When referred to the functional unit, the reduction ranges from 66 kg to 148 kg for 5 uses and from 85 kg to 164 kg for 50 uses.

Distribution through self-dispensing systems allows also for a progressive reduction of the energy demand and of most of the potential impacts, starting from a minimum number of uses of the refillable container. For laundry and hand dishwashing detergents, at least 5–10 uses are needed, depending on the scenario. For fabric softeners, 4 uses are enough in both waste prevention scenarios. The potential impact on human health due to total life cycle emissions of toxic substances with non-carcinogenic effects is reduced as well. This happens starting from 4 uses of the refillable container for fabric softeners and from 5 uses for hand dishwashing detergents, but at least 25 uses are needed for laundry detergents. Distribution through self-dispensing systems involves instead a potential impact on human health due to total life cycle emissions of carcinogenic substances comparable to that of the distribution with big-sized single-use HDPE containers[7] made from recycled material even for 50 uses of the refillable container. The results obtained for human toxicity impact categories are however characterized by greater uncertainty than other categories and may vary depending on the impact assessment model used for their calculation.

If distribution through self-dispensing systems is to be implemented as a WPM, the consumer shall be adequately made aware that the number of uses of the refillable container plays a key role on the ultimate environmental and energy performance. As a general rule, at least 10–15 uses of the refillable container should be encouraged. However, all the efforts should be made to use the container as far as this is technically feasible.

An improvement of the benefits on the impacts on human health could be obtained by targeting the packaging used for detergent transportation (reusable tanks). In particular, the amount of steel used for the production of the cage surrounding the tank could be reduced, or an alternative material could be employed. Moreover, all the efforts should be made by both detergent producers and retailers to extend as much as possible the useful life of tanks (which in this study was conservatively assumed equal to 50 transportation cycles). Finally, also a reduction of the distance from packaging plants to retailers could be very beneficial. In fact, detergent transportation is one of the two major contributors to the total impact of waste prevention scenarios in the human toxicity categories, along with the life cycle of reusable tanks. The travelled distance depends on the actual location of packaging plants and cannot be easily changed. However, retailers should be encouraged to prefer the distribution of detergents produced or packed as nearest as possible to the respective retail outlets. Distance reduction would obviously be advantageous also for many other impact categories, where the detergent transportation stage is responsible for most of the overall impact.

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[7] The size of the container is 5000 ml for laundry and hand-dishwashing detergents and 4000 ml for fabric softeners.

Table 5
Percentage variation between the impacts of the 3000 ml-based prevention scenario for laundry detergents and those of the respective best baseline scenario for each category (i.e., the one based on 5000 ml single-use HDPE containers made from recycled material).

Impact category	Number of uses of the 3000 ml refillable container													
	1	2	3	4	5	10	15	20	25	30	35	40	45	50
Climate change	37.9	−6.1	−20.8	−28.1	−32.5	−41.3	−44.3	−45.7	−46.6	−47.2	−47.6	−47.9	−48.2	−48.4
Ozone depletion	24.9	−6.3	−16.7	−21.9	−25.0	−31.2	−33.3	−34.3	−35.0	−35.4	−35.7	−35.9	−36.1	−36.2
Photochemical ozone formation	24.9	−0.7	−9.2	−13.5	−16.1	−21.2	−22.9	−23.8	−24.3	−24.6	−24.9	−25.0	−25.2	−25.3
Acidification	29.1	−5.3	−16.8	−22.5	−26.0	−32.9	−35.2	−36.3	−37.0	−37.5	−37.8	−38.0	−38.2	−38.4
Terrestrial eutrophication	20.0	−2.2	−9.7	−13.4	−15.6	−20.0	−21.5	−22.3	−22.7	−23.0	−23.2	−23.4	−23.5	−23.6
Freshwater eutrophication	36.8	−19.5	−38.2	−47.6	−53.2	−64.4	−68.2	−70.0	−71.2	−71.9	−72.5	−72.9	−73.2	−73.4
Marine eutrophication	22.0	−3.5	−12.1	−16.3	−18.9	−24.0	−25.7	−26.5	−27.1	−27.4	−27.6	−27.8	−28.0	−28.1
Freshwater ecotoxicity	73.1	19.8	2.0	−6.9	−12.2	−22.9	−26.4	−28.2	−29.3	−30.0	−30.5	−30.9	−31.2	−31.4
Human toxicity (cancer effects)	77.9	38.0	24.7	18.1	14.1	6.1	3.5	2.1	1.3	0.8	0.4	0.1	−0.1	−0.3
Human toxicity (non-cancer effects)	79.8	32.8	17.2	9.4	4.7	−4.7	−7.8	−9.4	−10.3	−11.0	−11.4	−11.7	−12.0	−12.2
Particulate matter	36.8	−7.1	−21.7	−29.1	−33.5	−42.2	−45.2	−46.6	−47.5	−48.1	−48.5	−48.8	−49.1	−49.3
Water resource depletion	39.5	−14.9	−33.0	−42.1	−47.6	−58.4	−62.1	−63.9	−65.0	−65.7	−66.2	−66.6	−66.9	−67.1
Mineral and fossil resource depletion	50.1	−0.8	−17.7	−26.2	−31.3	−41.5	−44.9	−46.6	−47.6	−48.3	−48.8	−49.1	−49.4	−49.6
Cumulative energy demand	47.1	−5.2	−22.7	−31.4	−36.6	−47.1	−50.6	−52.3	−53.4	−54.1	−54.6	−54.9	−55.2	−55.5

Table 6
Percentage variation between the 3000 ml-based prevention scenario for laundry detergents and those of the respective worst baseline scenario for each category (i.e., the one based on 924 ml single-use PET containers made from virgin material).

Impact category	Number of uses of the 3000 ml refillable container													
	1	2	3	4	5	10	15	20	25	30	35	40	45	50
Climate change	−57.3	−70.9	−75.5	−77.7	−79.1	−81.8	−82.7	−83.2	−83.5	−83.6	−83.8	−83.9	−83.9	−84.0
Ozone depletion	−77.8	−83.3	−85.2	−86.1	−86.6	−87.8	−88.1	−88.3	−88.4	−88.5	−88.5	−88.6	−88.6	−88.6
Photochemical ozone formation	−35.6	−48.8	−53.2	−55.4	−56.7	−59.4	−60.3	−60.7	−61.0	−61.1	−61.3	−61.4	−61.4	−61.5
Acidification	−48.3	−62.1	−66.6	−68.9	−70.3	−73.1	−74.0	−74.5	−74.7	−74.9	−75.1	−75.2	−75.2	−75.3
Terrestrial eutrophication	−34.4	−46.5	−50.6	−52.6	−53.8	−56.3	−57.1	−57.5	−57.7	−57.9	−58.0	−58.1	−58.2	−58.2
Freshwater eutrophication	−67.3	−80.8	−85.2	−87.5	−88.8	−91.5	−92.4	−92.8	−93.1	−93.3	−93.4	−93.5	−93.6	−93.7
Marine eutrophication	−38.1	−51.1	−55.4	−57.6	−58.9	−61.5	−62.3	−62.8	−63.0	−63.2	−63.3	−63.4	−63.5	−63.6
Freshwater ecotoxicity	−55.5	−69.2	−73.8	−76.0	−77.4	−80.2	−81.1	−81.5	−81.8	−82.0	−82.1	−82.2	−82.3	−82.4
Human toxicity (cancer effects)	−44.3	−56.7	−60.9	−63.0	−64.2	−66.7	−67.6	−68.0	−68.2	−68.4	−68.5	−68.6	−68.7	−68.7
Human toxicity (non-cancer effects)	−43.8	−58.5	−63.4	−65.8	−67.3	−70.2	−71.2	−71.7	−72.0	−72.2	−72.3	−72.4	−72.5	−72.6
Particulate matter	−50.7	−66.5	−71.8	−74.4	−76.0	−79.2	−80.2	−80.8	−81.1	−81.3	−81.4	−81.6	−81.6	−81.7
Water resource depletion	−74.6	−84.5	−87.8	−89.4	−90.4	−92.4	−93.1	−93.4	−93.6	−93.7	−93.8	−93.9	−94.0	−94.0
Mineral and fossil resource depletion	−55.7	−70.7	−75.7	−78.2	−79.7	−82.7	−83.7	−84.2	−84.5	−84.7	−84.9	−85.0	−85.1	−85.1
Cumulative energy demand	−55.0	−71.0	−76.4	−79.0	−80.6	−83.8	−84.9	−85.4	−85.7	−86.0	−86.1	−86.2	−86.3	−86.4

Appendix A. Supplementary data

Supplementary data to this article can be found online .

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