Packaging waste prevention activities: A life cycle assessment of the effects on a regional waste management system

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Introduction

Waste prevention is now one of the main priorities of the waste management policy and legislation of developed countries. In Europe, each member state is specifically required to develop a national waste prevention programme, defining waste prevention objectives and suitable measures for their achievement (European Parliament and Council, 2008). Moreover, in Italy, each region is required to elaborate a specific regional programme, defining further objectives and tangible activities to be implemented locally (Legislative Decree n. 205, 2010).

Several life cycle assessments (LCAs) of integrated municipal waste management systems have been published in the scientific literature over the last two decades (see Laurent et al., 2014 for a comprehensive review). However, to the authors' knowledge, only a few recent LCA studies have explicitly accounted for the effects of specific waste prevention activities (Cleary, 2014; Gentil et al., 2011; Matsuda et al., 2012; and, partially, Slagstad and Brattebø, 2012). This is likely because, first of all, a well-defined methodology was initially lacking. In fact, the methodological adjustments needed to carry out this type of assessment have been discussed only recently (Cleary, 2010; Gentil et al., 2011; Nessi et al., 2013). Moreover, this type of assessment is generally more complex, as it requires the calculation of more parameters (such as the waste prevention potential), to collect or estimate a larger quantity of data and to deepen the knowledge of those supply chains upstream waste collection, which are affected by waste prevention activities. Another reason could be that, in many countries, the focus has until recently been on moving from landfilling to material and energy recovery, rather than on reducing the generation or hazardousness of waste (Wilson et al., 2010). Last but not least, the lack of a complete understanding of the concept of waste prevention and, especially, of its effects on the different aspect of societal metabolism, has certainly played an important role.

For a hypothetical European municipality, Gentil et al. (2011) evaluated the effects of partially preventing food waste (surplus), unsolicited mail waste and beverage packaging waste (through the partial conversion from disposable to reusable containers). When the avoided production of these prevented waste fractions was taken into account in the modelling, the overall benefits of the waste management system were substantially increased, compared to a baseline non-preventative scenario, for a number of impact categories (global warming, acidification, nutrient enrichment and human toxicity via soil).

Matsuda et al. (2012) evaluated the consequences of a partial reduction in edible food losses (leftovers and untouched food), combined with the introduction of the separate collection of the food waste, in Kyoto, Japan. Separate collection is assumed to enhance food loss reduction, which is achieved by reduced food preparation and/or purchasing (and not by increased food consumption). Compared to the reference situation (where the food waste is incinerated), a 17% reduction in total greenhouse gas emissions from combustible waste management in Kyoto was observed.

Finally, Cleary (2014) evaluated the effects of contemporaneously implementing five waste prevention and diversion activities on the impacts from residential waste management in Toronto, Canada. The activities included the reduced generation of unaddressed advertising mail, the reuse of disposable shopping bags, the substitution of newspaper articles available online for those printed on newsprint, the substitution of refillable and lightweight containers for conventional single-use glass bottles for wines and spirits, as well as grass-cycling (waste diversion). The implementation of these activities reduced most of the midpoint level impacts by 2% to 55% and endpoint level impacts by 13% to 961% (with the latter value being the result of the shifting from an adverse to an avoided impact).

Both Cleary (2014) and Gentil et al. (2011) conclude their studies by recommending further research on the effects of waste prevention activities on the potential impacts of municipal waste management, by possibly focusing on other significant waste fractions and on other waste prevention activities currently available. Similarly, Laurent et al. (2014) encouraged practitioners to focus further on waste prevention activities in future applications of LCA to solid waste management systems.

This LCA study, building up on recent research devoted to the assessment of two specific packaging waste prevention activities (Nessi et al., 2012, 2014), investigates the potential effects of their implementation on the overall municipal waste management system at the regional scale. The Lombardia region (Italy) is specifically considered, as the municipal waste from this region is managed according to an advanced treatment scheme, reaching high levels of material and energy recovery and with nearly zero-landfilling. Moreover, the municipal waste management system of Lombardia has already been characterised, in a life cycle perspective, in a recent LCA study aimed at supporting the drafting of the new regional waste management programme (Grosso et al., 2012; partly summarised in Rigamonti et al., 2013). Finally, Lombardia has recently adopted a regional waste prevention programme, as part of the new waste management programme (Regione Lombardia, 2014), which sets specific waste reduction targets for 2020. To facilitate their achievement, a set of waste prevention activities is suggested, which also includes those examined in this study.

The objective of the assessment is to evaluate whether the examined waste prevention activities are actually capable of improving, and to which extent, the overall environmental and energy performance of municipal waste management at the regional level. A reduction in waste generation, in fact, does not automatically imply also a reduction in the overall environmental and energy impacts. This might be the case when waste prevention is not achieved through the simple reduction in the consumption of goods or services, but through other mechanisms such as the substitution by alternative, less waste-generating goods or services, product reuse or lifespan extension. In these situations, additional waste and impacts are involved, which might exceed those avoided. A careful evaluation of the net impacts of the prevention activity is thus needed, in order to avoid possible shifting of burdens.

The implementation of a municipal waste prevention programme can be a complex process, requiring important investments and the involvement of many actors, potentially belonging to the whole supply chain of goods and services (e.g. producers, retailers, etc.). It is thus necessary to prioritise those prevention measures that provide the greatest environmental and energy benefits to the waste management system. By evaluating the magnitude of these potential benefits for two specific prevention activities, this study is also an attempt to provide useful elements to support local waste managers and decision makers in this selection and implementation process. Finally, by considering the whole waste management system, waste managers will be able to compare the impacts of the examined prevention activities with those of the traditional components of the system and, thus, to better understand the relative significance of waste prevention with respect to the management options that are commonly applied to the generated waste.

Methodology

The LCA methodology (ISO, 2006) was applied, following most of the methodological choices traditionally performed when assessing integrated waste management systems (e.g. Clift et al., 2000). However, the adjustments reported in Nessi et al. (2013) and Cleary (2010) were taken into account for the definition of a functional unit and of system boundaries which were suitable for the assessment of the effects of waste prevention activities (see the 'Functional unit' and 'System boundaries' sections for a description of the practical implementation of these conceptual adjustments in this case study).

Analysed waste management scenarios

Five scenarios for municipal waste management in Lombardia region were analysed: a baseline and four waste prevention scenarios, where two waste prevention activities are either singularly or contemporaneously implemented (Table 1). The baseline scenario is a 2020 perspective scenario and is used as a reference. It was defined based on forecasted increases in population and per-capita waste generation compared to 2009, along with an inertial increase in separate collection (see the 'Waste flows' section for details on the forecasts and waste flows).

In the first waste prevention scenario (WPS1), bottled water consumed domestically is entirely substituted by public potable water withdrawn from the tap directly at the household, assuming that both products are completely equivalent for those citizens implementing the substitution. Waste prevention scenarios 2a

Table 1. Scenarios for municipal waste management in Lombardia compared in this study and respective quantities of waste generated and prevented.

Scenario	2020 baseline scenario	Waste prevention scenario 1	Waste prevention scenario 2a	Waste prevention scenario 2b	Waste prevention scenario 3
Waste prevention activity implemented	None	Substitution of bottled water consumed domestically by public potable water from the tap	Substitution of single-use packaged liquid detergents[a] by those distributed loose through self-dispensing systems and refillable containers		Both product substitutions of waste prevention scenarios 1 and 2a
Washing performances of loose detergents[b]	–	–	Same as substituted detergents[c]	Worse than substituted detergents[d]	Same as substituted detergents[c]
Total waste [t] of which:	4,838,297	4,813,172	4,831,370	4,832,281	4,806,245
Source separated waste (mono-material collection)	2,883,429	2,861,283	2,877,402	2,878,195	2,855,256
Source separated waste (multi-material collection)	311,002	308,023	310,101	310,220	307,123
Residual waste	1,643,866				
Prevented waste [t]	–	25,125 (0.52%)[e]	6,927 (0.14%)[e]	6,016 (0.12%)[e]	32,052 (0.66%)[e]

[a]Laundry detergents (machine and hand wash), fabric softeners and hand dishwashing detergents are considered.
[b]That is, average number of washings per litre of detergent.
[c]Machine laundry detergents: 15.1 washings/litre; hand wash laundry detergents: 17.2 washings/litre; fabric softeners: 28 washings/litre; hand dishwashing detergents: 101 washings/litre. For each type of detergent, these average values are based on a survey of the average washing performances of the detergent by type and size of the container, and on estimates of the respective market shares in Italy (see the section titled 'Estimate of the waste prevention potential' for more details on the latter estimates).
[d]Laundry detergents (both machine and hand wash): 10 washings/litre; fabric softeners: 10 washings/litre; hand dishwashing detergents: 51 washings/litre. These values refer to the detergents used in the real pilot experiences of distribution through self-dispensing systems recently implemented in Lombardia (Italy).
[e]Of the total waste.

and 2b (WPS2a and WPS2b) implements the same prevention activity, i.e. the complete substitution of liquid detergents packaged in single-use plastic containers by those distributed 'loose' through self-dispensing systems and refillable containers. The substitution was specifically applied to liquid laundry detergents (machine and hand wash), fabric softeners and hand-dishwashing detergents sold through all traditional retail channels. In WPS2a the loose detergents were assumed to have the same average washing performances (i.e. number of washings per litre) as the substituted traditional ones (Table 1). The scenario implements an improved prevention measure compared to the pilot experiences implemented so far in Italy, where the loose detergents are generally characterised by lower washing performances. This real situation is modelled in WPS2b, where a greater volume of loose detergents is thus needed to perform the same average number of washings as those packaged in single-use containers. The lower washing performances of the loose detergents were specifically assumed to be entirely due to a lower concentration of the product, although differences in its formulation may also exist in reality. The additional volume of loose product purchased is thus represented by demineralised water used to further dilute the active ingredients of the detergent itself.

In the last waste prevention scenario (WPS3), both waste prevention activities are implemented together, again assuming a complete substitution of the traditional products. The loose detergents were assumed having the same average washing performances as substituted traditional ones (as in WPS2a). Each waste prevention scenario was individually compared with the baseline, to evaluate the effects of the waste prevention activity(ies) on the overall environmental and energy performance of the waste management system as a whole.

Functional unit

The functional unit is defined as '*the management of the waste potentially generated in Lombardia in 2020*', equal to 4,838,297 tonnes. The waste potentially generated includes the waste actually produced, collected and managed through conventional treatment operations, as well as the waste possibly prevented thanks to the implemented waste prevention activity(ies), by which the prevented waste is managed. In fact, waste prevention activities were assumed to be an actual waste management method, exactly like the operations applicable to the collected waste (Nessi et al., 2013; Cleary, 2010). The potentially generated waste is thus identical in all the compared scenarios.

Following the suggestion by Cleary (2010), one or more secondary functional units were also defined in each waste prevention scenario, depending on the type and number of waste prevention activities implemented. Secondary functional units are used to ensure that the amount of product service provided to the citizens of Lombardia by the product systems affected by the waste prevention activity(ies) is equivalent in both baseline and waste prevention scenarios. For the bottled water substitution, the secondary functional unit is the delivery to the citizens of the volume of drinking water subject to the substitution (1188 million litres). For the liquid detergent substitution, the secondary functional unit is the overall number of washings performed by the citizens with each type of detergent involved in the substitution (Table 2, where the overall volume of detergent used to carry

Table 2. Overall number of washings performed yearly in Lombardia with the different types of liquid detergents subject to product substitution in WPS2a and WPS2b and the corresponding volume of detergent needed in each compared waste management scenario.

Type of detergent	Number of washings	Volume of detergent (litres)	
		Baseline scenario and waste prevention scenarios 2a and 3	Waste prevention scenario 2b
Machine laundry detergents	904,172,560	59,868,546	90,417,256
Hand wash laundry detergents	14,366,458	833,157	1,436,646
Fabric softeners	1,152,848,153	41,197,621	115,284,815
Hand dishwashing detergents	4,481,623,610	44,332,239	87,874,973

out these washings in each waste prevention scenario is also reported). These estimates are based on the sales of detergents in Lombardia by type and size of the container (estimated as briefly described in the section titled 'Estimate of the waste prevention potential') and on the respective average washing performances (average number of washings per litre). The latter refer to a sample of packaged liquid detergents of different brands, currently retailed in Lombardia and in most of Italy.

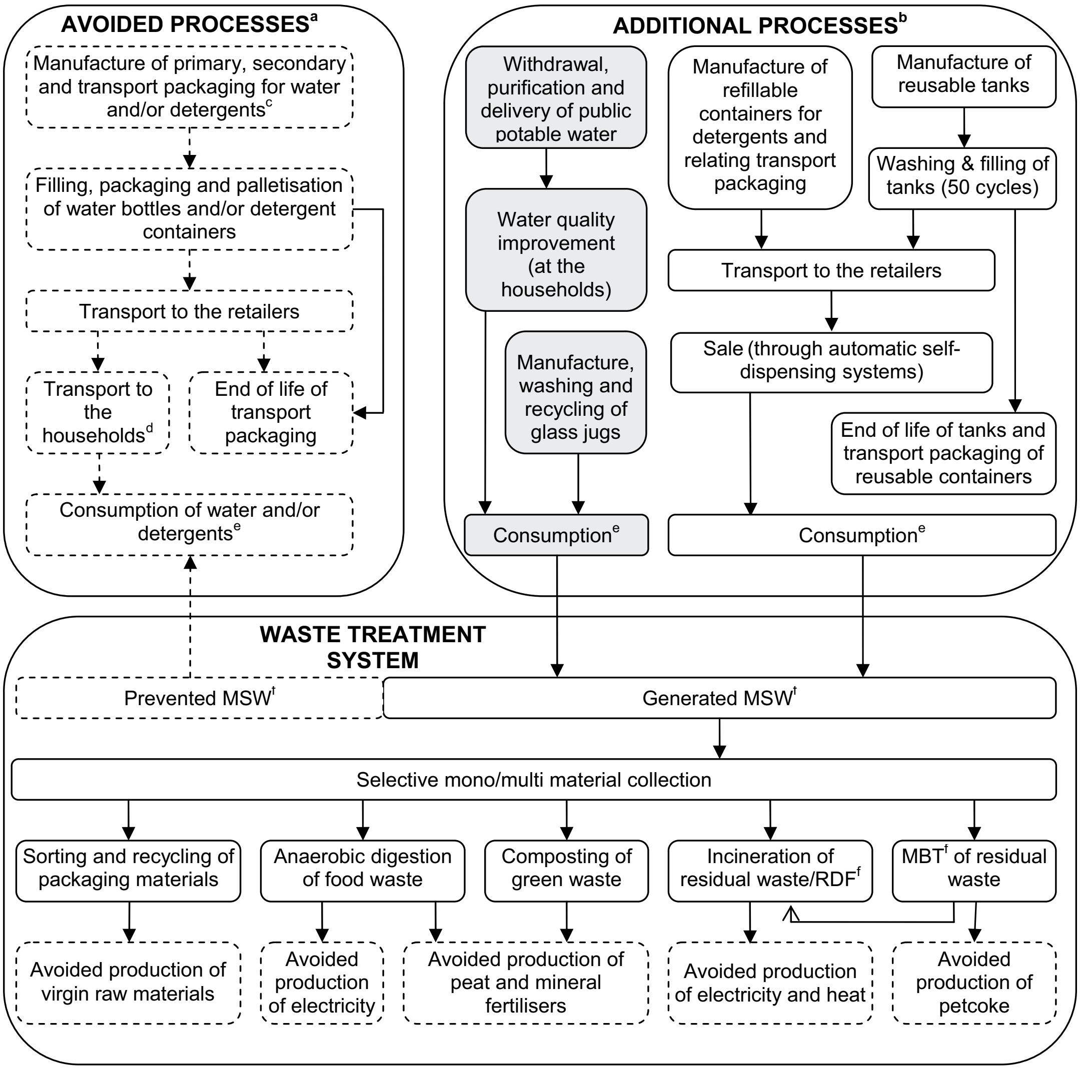
System boundaries

Figure 1 provides a simplified representation of the boundaries of the waste management system in the baseline and waste prevention scenarios. As usual, in each scenario the system includes all the operations applied to the different flows of generated waste. In particular, the system accounts for all the operations from the moment the waste is collected to when it becomes an emission to air and water, an inert material in a landfill, a secondary raw material or an energy flow. Moreover, according to the commonly applied 'avoided burden method' (Finnveden et al., 2009), the system is expanded to include avoided primary production processes of the materials and energy recovered from waste.

In waste prevention scenarios, the system boundaries are further expanded upstream waste collection, to include the upstream processes that are avoided or that take place as a consequence of managing the prevented waste through the implemented waste prevention activity(ies) (Nessi et al., 2013). The avoided processes are those belonging to the whole upstream life cycle of the substituted traditional products. The additional processes are those belonging to the whole upstream life cycle of the alternative products that potentially generate less waste. Thus, in WPS1 (bottled water substitution) the system includes the avoided withdrawal, packaging, palletisation, and transport to the retailers and to the point of use of the substituted volume of bottled water. Moreover, it includes the additional processes of withdrawal, purification and delivery to users of an equivalent volume of public potable water, as well as water quality improvement and withdrawal at the domestic level. Similarly, in WPS2a and WPS2b, upstream system boundaries are expanded to include the avoided packaging, palletisation and transport to the retailers of the substituted volume of single-use packaged detergent, as well as the additional processes of packaging in reusable tanks and transport to the retailers of an equivalent amount of 'loose' detergent. Packaging and palletisation of refillable containers and their transport to the retailers are also included as additional upstream processes, as well as the operation of the self-dispensing systems (refilling and withdrawal) and the life cycle of its main components. Finally, when a lower washing performance is considered for the replacing loose detergents (due to a lower concentration level; WPS2b), the production of the additional volume of demineralised water used for dilution is included, as well as its transport to the retailers and subsequent withdrawal from self-dispensing systems by means of refillable containers. The production of the active ingredients of both loose and packaged detergents was excluded, as they were assumed to be formulated by using the same amount of the same active substances (which in the loose detergents of WPS2b are further diluted with demineralised water). In WPS3, the avoided and additional upstream processes included in both WPS1 and WPS2a are taken into account.

Impact categories and impact assessment methods

Thirteen environmental and human health impact categories, evaluated at the midpoint level, were considered in this study: *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 in the attempt to cover all the potentially relevant environmental issues for the examined waste management and product systems. The selection was restricted to those categories for which a recommended model for impact assessment in the European context is identified by ILCD (International Reference Life Cycle Data System; EC-JRC, 2011). A list of the midpoint level impact indicators and of the specific impact assessment models considered for the selected impact categories is provided in Supplementary table S.1 online. The *cumulative energy demand* (CED) indicator was finally calculated, according to the method described in Hischier et al. (2010), in order to assess also the energy performance of the compared systems.



(a) Avoided upstream processes related to the life cycle of bottled water are included in waste prevention scenarios 1 and 3, while those related to the life cycle of single-use packaged liquid detergents are included in waste prevention scenarios 2a, 2b and 3.

(b) Additional upstream processes related to the life cycle of public potable water (grey boxes) are included in waste prevention scenarios 1 and 3, while those related to the life cycle of loose detergents (white boxes) are included in waste prevention scenarios 2a, 2b and 3. Waste prevention scenario 2b includes also the additional production of demineralised water used to further dilute the detergents (compared to traditional substituted ones), the transport of this water to the retailers and its withdrawal from self-dispensing systems by means of refillable containers.

(c) Primary packaging includes bottles/containers, caps and labels (these latter only for water bottles). Secondary packaging is used only for bottled water (heat-shrink film of the bundles containing bottles). Transport packaging includes cardboard boxes (for detergents only), pallets, stretch film, and cardboard interlayers (for water only).

(d) Avoided transport to the households is included only for bottled water, as for detergents the burdens of this stage are identical for both the traditional and the loose products (the same average number of purchasing roundtrips to retail stores was assumed for both products, which are purchased in such amounts that the same number of washings can be performed with both of them).

(e) Consumption involves no impacts (note: the use of detergents for washing is excluded, as it is identical for both the traditional and the loose products).

(f) MBT: mechanical-biological treatment; MSW: municipal solid waste; RDF: refuse derived fuel

Figure 1. Boundaries of the waste management system in the compared scenarios (the components upstream of waste collection, i.e. avoided and additional upstream processes, are included only in waste prevention scenarios).

Estimate of the waste prevention potential

For each waste prevention activity, the quantities of waste removed from and added to the waste management system were estimated. The balance between avoided and additional waste (i.e. the waste prevention potential of the activities) was also calculated (Table 3).

Available statistics on municipal waste generation (e.g. the annual reports by ARPA[1] or national packaging consortia) were inadequate to estimate the quantity of waste avoided and the

Table 3. Types and quantities of waste added to and removed from the waste management system by the examined waste prevention activities.

Waste prevention activity	Type of waste	Quantity	
		[tonnes]	[% of total waste for 2020]
Substitution of bottled water by public potable water	Avoided waste	30,769	0.64
	Bottles (PET)	*25,581*	*0.53*
	Caps (HDPE)	*1583*	*0.03*
	Labels (paper)	*226*	*0.01*
	Labels (plastic)[a]	*499*	*0.01*
	Heat-shrink film (LDPE)	*2880*	*0.06*
	Additional waste	5644	0.12
	Glass jugs	*5644*	*0.12*
	Prevention potential	25,125	0.52
Substitution of single-use packaged liquid detergents by loose detergents	Avoided waste	7786	0.16
	Single-use containers (HDPE)	*4388*	*0.09*
	Single-use containers (PET)	*2454*	*0.05*
	Caps (PP)	*944*	*0.02*
	Additional waste	859 (1770)[b]	0.018 (0.037)
	Refillable containers (HDPE)	*772 (1589)*	*0.016 (0.033)*
	Reusable caps (PP)	*87 (181)*	*0.002 (0.004)*
	Prevention potential	6927 (6016)	0.14 (0.12)

Acronyms: HDPE = high-density polyethylene; LDPE = linear low-density polyethylene; PET = polyethylene terephthalate; PP = polypropylene.
[a]In this study, plastic labels were assumed to be made out of polypropylene.
[b]Values in parenthesis refer to the case in which the washing performances of the replacing loose detergents are worse than the average ones of substituted packaged detergents (due to lower concentration).

corresponding amount of product (water or detergent) subject to substitution. In fact, such statistics focus on major collected waste fractions (e.g. plastic, glass, residual waste, etc.), without differentiating among the different items composing such fractions, including those targeted for prevention (i.e. water bottles and detergent containers). It was thus necessary to adopt a reverse procedure which, on the basis of the amount of product undergoing substitution, estimates the amounts of avoided and additional waste. For this purpose, data on the Italian market of the substituted products in 2013 were acquired, from market databases or market research institutes. For bottled water, data on volume sales by type and size of bottle were available. For single-use packaged liquid detergents, only the total volume retailed was available. An empirical subdivision of the total sales by type and size of container was thus performed. This was based on an average packaging composition, estimated by observing the frequencies with which each type and size of container was available in some retail stores of Lombardia (see the fourth column of Supplementary tables S.4–S.7 online for details on the estimated compositions).

The consumption of bottled water and single-use packaged liquid detergents by type and size of packaging was then estimated for Lombardia, based on national sales and on the ratio between the regional population expected for 2020 (10,557,381 inhabitants; ISTAT, 2014) and the national population in 2013. For bottled water, the substitution was assumed to involve only water packaged in 1, 1.5 and 2 litre one-way polyethylene terephthalate (PET) bottles. Water packaged in one-way PET bottles with a size lower than 1000 ml was instead excluded from the substitution, as it is mainly used for outdoor consumption. Glass bottled water was also excluded, as it is mainly characterised by particular properties (e.g. water from thermal springs) and would hardly be replaced with public potable water. However, glass bottled water covers only 4% of the overall consumption. Finally, 5000 ml one-way PET bottled water and that packaged in 500 or 1000 ml bricks were excluded, as they represent an insignificant proportion of the total consumption (0.04% and 0.14%, respectively). For liquid detergents, the whole consumption was assumed to be suitable for the replacement with loose detergents, as there are no specific restrictions.

The total amount of avoided waste was thus calculated (Table 3), based on the estimated avoided consumption of the substituted products by type and size of packaging and on the average mass of the packaging that would have been generated as waste as a consequence of such consumption. For the bottled water substitution, the avoided waste includes bottles, caps and labels, as well as the heat-shrink film of the bundles containing bottles. For these items, the average masses reported in Federambiente (2010) were mostly considered, although experimental estimates were also produced (for 1 litre one-way PET bottles; see Supplementary table S.2 online). For the liquid detergent substitution, the avoided waste is represented by single-use containers and respective caps.[2] Their average specific masses were estimated experimentally, according to the procedure described in Nessi et al. (2014), where the corresponding values are also reported. The whole procedure used for the calculation of the quantities of avoided waste is summarised in Supplementary tables S.2 and S.4-S.7 online, depending on the product subject to substitution.

The amount of waste added to the systems was ultimately calculated (Table 3), based on the estimated consumption of the alternative, less waste-generating products and on the average masses of those goods that are generated as waste from such consumption. Additional waste generated by the bottled water substitution includes 1 litre glass jugs used to withdraw potable water from the tap. By assuming an average mass of 475 g and 100 uses, they contribute 5.644 tonnes of additional waste to the system. For the liquid detergent substitution, the additional waste comprises refillable plastic containers and the respective caps, which were assigned the experimental masses reported in Nessi et al. (2014). According to the recommendations provided in the same study, refillable containers were assumed to be used 10 times overall. The calculation procedure of the quantities of additional waste is illustrated in Supplementary tables S.3 and S.8 online.

Waste flows

The waste flows of each scenario are illustrated in Figure 2, which also quantifies the flows that are unaffected by the waste prevention activities. Table 4 instead quantifies the flows that will change from one scenario to another, because of waste prevention activities. For the 2020 baseline scenario, the waste flows identified in Grosso et al. (2012) were taken into account. These flows were estimated based on 2009 flows, by assuming an 8% increase in the regional population and a 5% increase in the per-capita waste generation, while keeping the composition of the gross waste constant. In turn, 2009 waste flows were defined based on data reported in the annual report on waste by the Regional Environmental Protection Agency (ARPA Lombardia, 2009) and in the database by the Regional Waste Observatory (ORSO: Osservatorio Rifiuti Sovraregionale), which both include figures on regional waste generation and management. In addition, an extensive survey of the treatment plants receiving most of the different waste fractions was carried out in the mentioned study, to quantify missing flows (e.g. the quantities of residues from the different applied treatments). The main waste flows of the baseline scenario are the source separated materials (3,194,431 t, corresponding to 66% of the total waste) and the residual waste (1,643,866 t; 34%). Source separated packaging materials are sent to recycling, after being sorted. Food waste is entirely routed to anaerobic digestion, while green waste is sent to composting. Finally, most of the residual waste (73.7%) is directly routed to energy recovery in dedicated incineration plants, while the rest is subject to mechanical-biological treatments that produce refuse derived fuel (RDF), bio-dried material or, alternatively, an improved material for incineration (sorted residual waste). The RDF is partly incinerated in waste-to-energy plants and partly used to displace pet coke in cement kilns, while the bio-dried material and the sorted residual waste are incinerated.

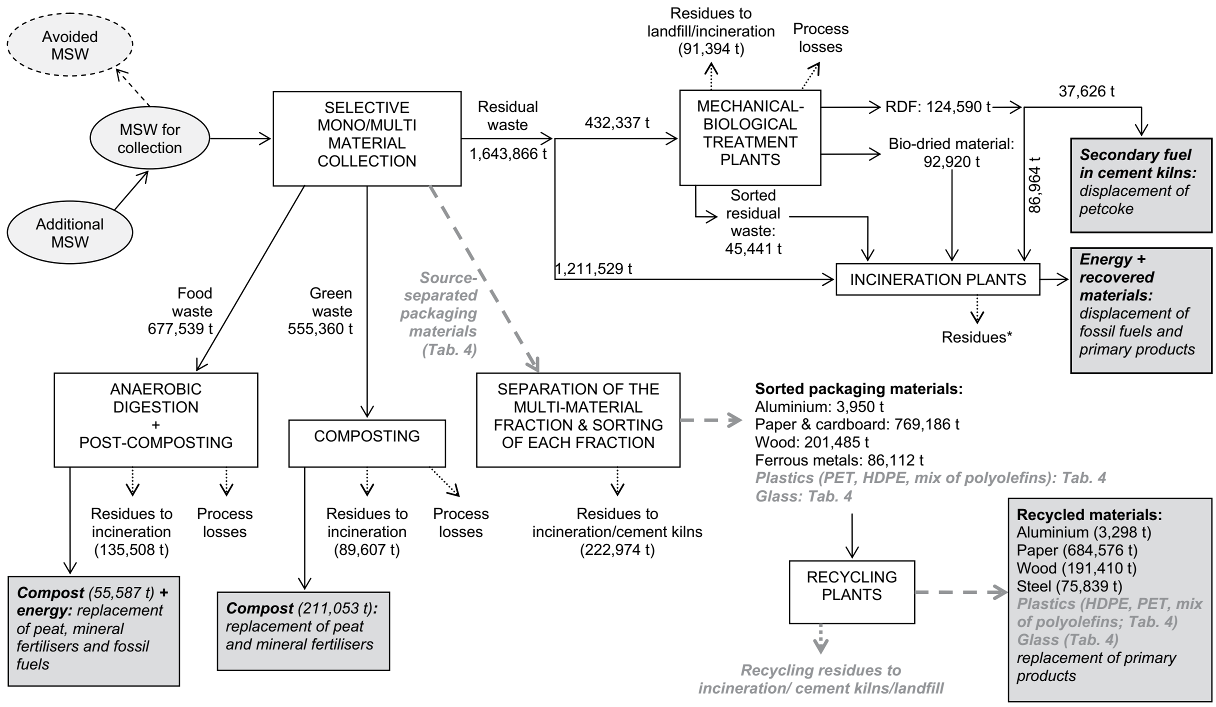
In waste prevention scenarios, these waste flows were adjusted according to the estimated quantities of waste removed and added to the waste management system due to the implemented waste prevention activity(ies). In particular, the avoided and additional waste flows were assumed to affect only the amount of the separately collected fractions, and not the residual waste. In fact, we can state that the products removed from or added to the waste stream can be easily recognised by the citizens as items to be source-separated once they have become waste. Therefore, prevented water PET bottles (with the respective caps and labels) and the heat-shrink film wrapping bottles around affect the quantity of source-separated plastic and multi material fraction. The same happens for single-use (prevented) and refillable (additional) plastic containers for detergents and the respective caps. Reusable glass jugs used for water withdrawal instead affect the quantity of source-separated glass and multi-material fraction. The overall amount of residues produced during the sorting of the source-separated fractions is not affected compared to the baseline scenario, as the avoided and additional waste flows are normally sent to recycling in their entirety. Conversely, reprocessing efficiencies of recycling operations were applied also to these waste streams, except for caps and labels. These items were assumed to be entirely removed during recycling and then rejected, thus affecting the amount of residues coming from the plastic recycling process (PET and HDPE).

Modelling of the waste management system

A model of the whole waste management system was developed in the SimaPro software (version 7.3.3), including the unit processes related to the operations and the activities taking place both downstream and upstream waste generation. This section briefly summarises the way in which these unit processes have been modelled for the assessment.

Waste management operations. The modelling of the process units depicting traditional waste management operations (collection, transport, treatments etc.) was carried out according to the approach described in detail in Grosso et al. (2012) and briefly summarised in Rigamonti et al. (2013). The most important assumptions concern the types of primary products substituted by those obtained from material and energy recovery processes, and on the respective substitution ratio (see Supplementary table S.9 online). This parameter takes into account the possible difference between the quality (inherent technical properties) or the market value, of the secondary and the primary products (see, for instance, Rigamonti et al., 2009 for more details).

For many process units (e.g. paper recycling, anaerobic digestion, composting and incineration of the residual waste) the data on the type and magnitude of inputs and outputs are primary, i.e. directly acquired from the operators of real plants. For other processes such as collection, transport, some recycling processes and primary production processes, inventory data from the ecoinvent database (v2.2) were used. However, they were frequently



(*) Bottom ashes are partly landfilled (coarse fraction) and partly recycled as road construction material (fine fraction). Fly ashes are inactivated and disposed of in exhausted salt mines in Germany, while air pollution control residues are recycled in the production of sodium carbonate. Scrap metal (ferrous metals and aluminium) are recycled.

Figure 2. Yearly flows of waste of the analysed scenarios for waste management in Lombardia region. The waste flows affected by the waste prevention activities are indicated by thicker dashed grey arrows and bold italic grey captions. The magnitude of these waste flows is reported in Table 4.

Table 4. Mass of the yearly waste flows affected by the waste prevention activities, under each waste management scenario analysed.

Waste flow	Mass of waste [t]				
	2020 baseline scenario	Waste prevention scenario 1	Waste prevention scenario 2a	Waste prevention scenario 2b	Waste prevention scenario 3
Avoided MSW	–	–30,769	–7786	–7786	–38,555
Additional MSW	–	5644	859	1770	6503
Total MSW for collection	4,838,297	4,813,172	4,831,370	4,832,281	4,806,245
Source-separated packaging materials (to separation and sorting)[a]					
Plastics	188,822	162,053	182,796	183,588	156,027
Glass	460,949	465,572	460,949	460,949	465,572
Multi-material fraction[b]	311,002	308,023	310,101	310,220	307,123
Sorted packaging materials (to recycling)					
Plastics (total)	171,887	141,118	164,960	165,871	134,191
PET	*92,475*	*64,586*	*89,641*	*89,641*	*61,752*
HDPE	*23,548*	*23,548*	*19,455*	*20,367*	*19,455*
Mix of polyolefins	*55,863*	*52,983*	*55,863*	*55,863*	*52,983*
Glass	505,939	511,583	505,939	505,939	511,583
Recycled materials					
Plastics (total)	124,530	103,489	119,423	120,159	98,381
PET	*69,819*	*50,505*	*67,966*	*67,966*	*48,652*
HDPE	*21,194*	*21,194*	*17,939*	*18,675*	*17,939*
Mix of polyolefins	*33,518*	*31,790*	*33,518*	*33,518*	*31,790*
Glass	505,939	511,583	505,939	505,939	511,583
Recycling residues[c]	152,966	143,239	151,146	151,322	141,419

Acronyms: MSW = municipal solid waste; HDPE = high-density polyethylene; PET = polyethylene terephthalate.

[a]Other than plastics, glass and the multi-material fraction, source-separated packaging materials also include aluminium (1,111 t), paper and cardboard (694,200 t), wood (222,144 t) and ferrous metals (83,304 t). These fractions are unaffected by the waste prevention activities.

[b]The multi-material fraction includes aluminium, paper and cardboard, ferrous metals, plastics and glass, which are collected according to different schemes including a part of these single fractions.

[c]Of all sorted packaging materials sent to recycling.

adapted and/or updated with more recent data from reference documents on best available techniques (BREFs) or other sources. Finally, data available from the technical and scientific literature were used for the remainder of the processes, such as mechanical-biological treatments of the residual waste and plastic recycling.

Activities upstream waste collection

Bottled water substitution. For the bottled water substitution, avoided and additional upstream processes depict, respectively, the whole upstream life cycle of the substituted bottled water and that of the replacing public potable water. These processes were modelled according to the general approach (input data, inventory data etc.) described in Nessi et al. (2012). However, some parameters and assumptions were specifically adapted for this case study. The most important are summarised below.

Regarding bottled water, one-way PET bottles were assumed to be entirely manufactured from virgin raw materials, as recycled raw materials are currently used only to a limited extent. HDPE caps, plastic (PP) labels, heat-shrink wraps (LDPE) and most transport packaging (wooden pallets, stretch film and top covering film) are manufactured from virgin raw materials as well. Paper labels and cardboard interlayers are instead partly (labels) or mostly (interlayers) manufactured from waste paper. The features of each packaging in terms of average mass, capacity and number of uses are summarised in Supplementary table S.10 online and were defined based on experimental estimates by the authors, estimates available in the literature, or data relating to bottling companies located in northern Italy. Regarding the end of life of transport packaging, it was assumed to be entirely recycled because, generally, such items are separately collected within commercial premises or bottling plants and then entrusted to private operators for recycling. However, the recycling processes of this packaging do not belong to the municipal waste treatment system, but to the avoided upstream processes (see Figure 2).

An average distance of 275 km was assumed to be covered by lorry to transport palletised water from bottling plants to retailers. This estimate is based on the location of the facilities where the major brands of bottled water retailed in Italy are packaged. Finally, an overall distance of 10 km was assumed to be covered with a private car by the citizens, during each roundtrip to the retail outlets to purchase bottled water. Each roundtrip was assumed to be carried out to purchase 30 items overall, comprising a typical bundle containing 6 shrink-wrapped water bottles. Thus, each roundtrip was assigned only 1/30 of its overall potential impacts (see the results reported in Nessi et al., 2012 for further details on the impacts of different assumptions on the number of items purchased contemporarily).

Regarding public potable water supply, 94% of the total consumption was assumed to be groundwater withdrawn from natural springs and wells, the remaining 6% being surface water from lakes and mountain streams (Regione Lombardia, 2008). Based on elaboration of the data reported by the same source, 80% of groundwater was assumed to undergo only disinfection with sodium hypochlorite (NaClO), while the remaining 20% was also subject to aeration and activated carbon filtration. Surface water was assumed to be subjected to a more intense purification process carried out in a centralised plant and based on a sequence of chemical and physical treatments. In Lombardia, network losses (abstraction and distribution) amount to 20% on average (Regione Lombardia, 2008). In this study, all these losses were conservatively assumed to take place during distribution, so that 20% of purified water leaving the treatment plants is lost. At the households, water is further refined by means of a device based on activated carbon filtration and reverse osmosis. The latter is the most energy and water demanding technology available for water quality improvement, so that the assumption about the type of device used is conservative. Refined water is finally withdrawn by means of 1 litre refillable glass jugs with an estimated average mass of 475 g. These jugs were assumed to be used 100 times overall and washed in a dishwasher every 5 uses as part of an overall load of 30 items (see the results reported in Nessi et al., 2012 for an overview of the effects of assuming different washing conditions).

Liquid detergent substitution. When single-use packaged liquid detergents are substituted, the processes entailed in their whole upstream life cycle are avoided. Conversely, the upstream processes in the life cycle of the replacing loose detergents take place in addition. The modelling of these processes was carried out according to the data and the assumptions described in Nessi et al. (2014). Most input data for the unit processes depicting the upstream life cycle of primary and transport packaging were determined experimentally (e.g. the average masses of single-use and refillable containers and of their caps), or based on technical information directly acquired from packaging producers, retailers and/or logistic data sheets available online (e.g. average masses of stretch film and pallet compositions). Moreover, a number of assumptions were performed about the origin of the packaging materials (virgin or recycled), the number of uses of refillable/reusable packaging and the end of life of transport packaging. In particular, substituted single-use containers were assumed to be entirely manufactured from virgin raw materials, as this is currently the most common practice. Refillable containers are exclusively produced from virgin raw materials, as well, to ensure their durability over time. According to the recommendations provided in Nessi et al. (2014), such containers were assumed to be used 10 times on average before being discarded by the citizens. Virgin raw materials were used also for the production of caps and of most transport packaging (i.e. the pallets, the stretch-film and the inner container of reusable tanks), while cardboard boxes were entirely produced from recycled fibres. Finally, the steel cage of reusable tanks was partly produced from post-consumer ferrous scrap.

Similarly to the assumptions performed for bottled water, all transport packaging was assumed to be recycled at the end of its useful life, including the different components of the reusable tanks used for the transport of loose detergents. However, these tanks were assumed to be used for 50 cycles of transport before being discarded at the packaging plant and sent to recycling.

For the transport phase, an average distance of 340 km was estimated to deliver by lorry the detergent and the associated packaging to the retailers. The same distance was assumed for both single-use packaged detergents and those distributed loose.

Finally, when loose detergents are used, the burdens of the sale and purchase phases were also taken into account. The modelling included the consumptions of electricity for the refilling of the self-dispensing system and for the withdrawal of the detergent by the consumers, both estimated based on the technical features of a real device. The life cycle of the main components of the system was also taken into account, assuming a useful life of 10 years and an annual supply of about 75,000 litres.

Results and discussion

Environmental performance of the baseline scenario

For the baseline scenario, most of the impact indicators are negative, which is a common result for advanced waste management systems (Figure 3). This means that the overall benefits from material and energy recovery operations compensate for the adverse impacts (loads) from the collection, transport and processing of the different waste flows. Exceptions are the *human toxicity (cancer effects)* and the *freshwater ecotoxicity* indicators, which are both positive. This is because of the huge adverse impact of the recycling of ferrous metals,[3] which, together with other minor positive contributions, by far exceed the limited benefits associated with the recycling of the other source-separated materials. For *human toxicity (non-cancer effects)* the impact is close to zero, as loads and benefits are balanced. In this category, loads are not only associated with collection, transport and sorting of the source-separated fractions. Conversely, also the processing of the residual waste, the biological treatment of food and green waste, and the recycling of ferrous metals and aluminium show an overall adverse impact. Recycling of glass, paper, plastic and wood still involves an overall benefit.

Impact of the bottled water substitution

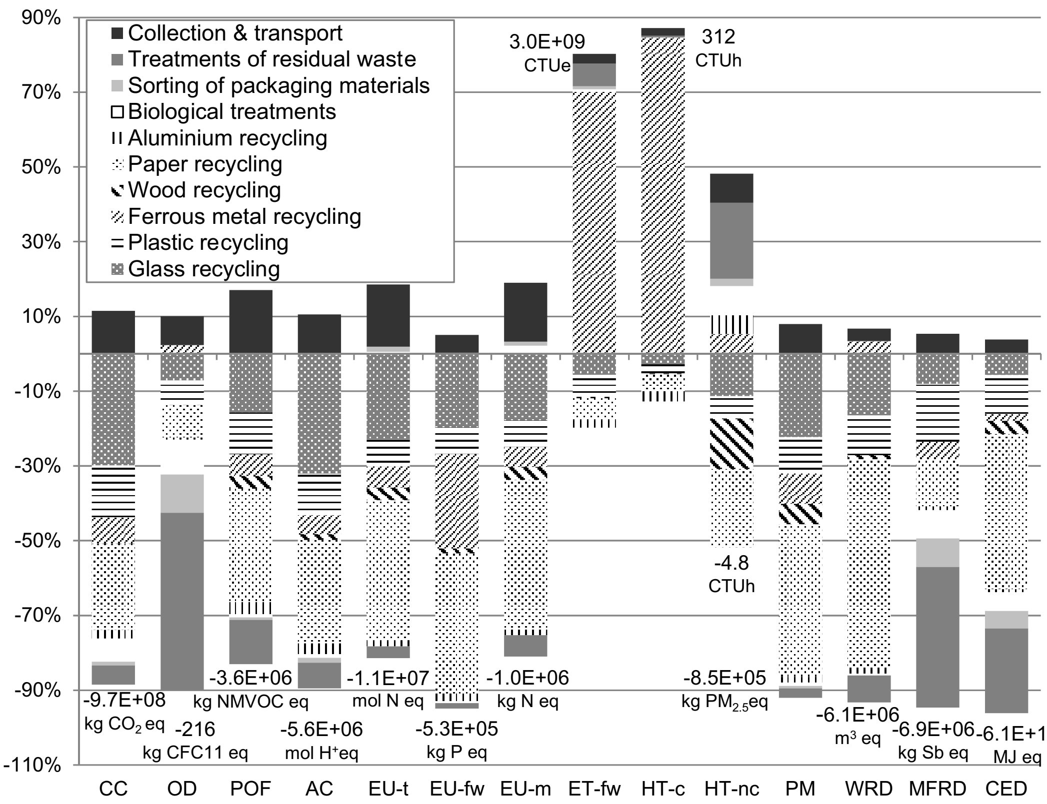
When a complete substitution of bottled water by public water supplies is implemented as a waste prevention activity (WPS1), the overall environmental profile of the system is improved compared to the baseline scenario, although to a different extent among the selected impact categories (Figure 4). For half of them, an increase in benefits larger than 10% is observed: *climate change* (13.5%), *ozone depletion* (14.5%), *photochemical ozone formation* (21%), *acidification* (13.5%), *terrestrial eutrophication* (23%), *marine eutrophication* (22.5%) and *human toxicity*, *non-cancer effects* (158%). The remaining categories show a reduced improvement (increase in benefits or reduction in impacts), which may be considered insignificant if the uncertainties that inevitably affect any LCA study are taken into account.

The improvements are mostly due to the additional benefits introduced upstream waste collection by the implemented waste prevention activity (Figure 5). These benefits are the balance between the savings from the avoided production, transport and purchase of the substituted bottled water and the additional impacts from the production, refining and consumption of the replacing public water supplies. Since the additional upstream impacts are always lower than those avoided, a net upstream benefit is achieved, overall, for all impact categories (Table 5). Conversely, waste prevention has only marginal effects on the impacts of the components of the system downstream waste generation (Figure 5). This is likely because the waste prevented is a very small and relatively harmless fraction of the total waste (0.52%). In particular, the impacts of waste collection and transport decrease by 0.8% on average, while those of sorting of source-separated packaging materials by 9% (see Supplementary table S.11 online). Impacts from recycling activities are instead increased by an average 3.5%, as less material is recycled and the production of a lower amount of virgin raw materials is consequently avoided. The result is an overall increase in net downstream impacts (be it positive or negative) as the increase in recycling impacts exceeds the reduction in the impacts of collection, transport, and sorting of recyclable materials. Even this overall increase is limited (lower than 4% for most categories), so that it is always compensated by the net upstream benefits from the waste prevention activity. Thus, it is not surprising that the most significant improvements in the overall performance of the system generally occur for those impact categories where the contribution of the additional upstream benefits to the total impact of the system is more important (and vice versa). However, some results require a specific interpretation. For instance, the nearly 160% increase in the overall benefits observed for *human toxicity (non-cancer effects)* is a consequence of the fact that the total impact of the baseline scenario is close to zero[4] (−4.8 CTU_h per functional unit) and the additional upstream benefit from waste prevention is two times greater than such an impact (−9.4 CTU_h per functional unit). The avoided production of water bottles and the avoided transport of packaged water to retailers are specifically mainly responsible for this additional benefit.

Impact of the liquid detergent substitution

Figure 6 shows the results obtained when liquid detergents packaged in single-use containers are entirely substituted by those distributed loose through self-dispensing systems and refillable containers (WPS2a and WPS2b).

When the same washing performances are assumed for both types of detergents (second bars in Figure 6), the waste management system is improved only to a minor (and arguably insignificant) extent for most impact categories (from 1 to 3%). *Human toxicity (cancer effects)*, is not affected at all (-0.3%), while *human*



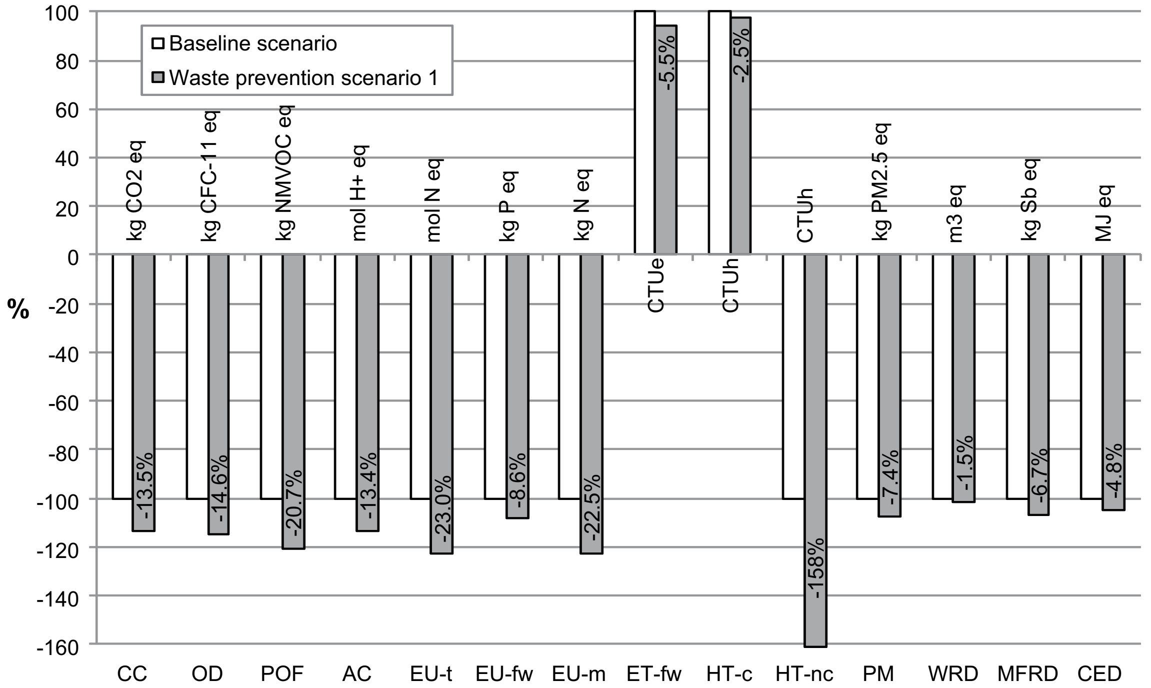
CC: climate change; OD: ozone depletion; HT-c: human toxicity (cancer effects); HT-nc: human toxicity (non-cancer effects); PM: particulate matter; POF: photochemical ozone formation; AC: acidification; EU-t: eutrophication (terrestrial); EU-fw: eutrophication (freshwater); EU-m: eutrophication (marine); ET-fw: ecotoxicity (freshwater); WRD: water resource depletion; MFRD: mineral and fossil resource depletion; CED: cumulative energy demand.

Figure 3. Potential impacts of the baseline scenario for waste management in Lombardia region and main contributions to the total impact.

toxicity (non-cancer effects) improves by 28% (but again due to a minor change applied to very low absolute value).[5] However, it is noteworthy that, as for the bottled water substitution, for nearly all impact categories the observed improvement is proportionally greater compared to the net percentage of revented waste (0.14% of the total waste, as reported in Table 3).

The effects of waste prevention on downstream impacts are again insignificant: 0.2% mean reduction for collection and transport, 2% for sorting of source-separated packaging materials and increase in recycling impacts by an average 0.7% (for the same reason as the bottled water substitution). As a result, the net downstream impacts are increased by only 0.75% on average (see Supplementary table S.12 online). Even the net upstream benefits from waste prevention are generally limited, reaching between 0.4 and 3% of the net impacts of the waste prevention scenario (if the *human toxicity, non-cancer effects* impact category is excluded; Table 6). As shown in Table 6, this is not because the additional impacts of the upstream life cycle of the replacing loose detergents tend to balance the avoided upstream impacts of the life cycle of the substituted, single-use, packaged detergents. Conversely, it is likely that the upstream benefits are limited compared to the impacts of the system as a whole, just because the quantity of material removed from and added to the system is negligible compared to the total waste.

When a worse washing performance is assumed for the loose detergents (third bars in Figure 6), no significant change in the overall performance of the system is involved for most impact categories, all impact variation being lower than 1% compared to the baseline scenario. For some categories an overall worsening is even observed (although it is generally insignificant): *photochemical ozone formation*; *terrestrial eutrophication*; *marine eutrophication* and *human toxicity (non-cancer effects)*. For these categories, the additional upstream impacts from the waste prevention activity exceed the avoided upstream impacts (Table 7), mostly due to an increased impact of transport (which compensate for the reduced impact of primary and transport packaging). In fact, an additional amount of detergent (dilution water) needs to be transported to retailers when the product is distributed loose. Moreover, for *human toxicity, non-cancer effects* (and for toxicity-related impact categories in general), an important additional upstream impact is provided by the life cycle of the reusable tanks used for the transport of the detergent[6]. For most of the remaining categories, more than 50% of the avoided upstream impacts are compensated by the additional upstream impacts,



CC: climate change; OD: ozone depletion; HT-c: human toxicity (cancer effects); HT-nc: human toxicity (non-cancer effects); PM: particulate matter; POF: photochemical ozone formation; AC: acidification; EU-t: eutrophication (terrestrial); EU-fw: eutrophication (freshwater); EU-m: eutrophication (marine); ET-fw: ecotoxicity (freshwater); WRD: water resource depletion; MFRD: mineral and fossil resource depletion; CED: cumulative energy demand.

Figure 4. Comparison between the potential impacts of the baseline scenario and of the waste prevention scenario substituting bottled water by public potable water (percentage impact variations between the latter and the former are also reported within each bar representing the waste prevention scenario).

always because of the largest impact of transport. This explains the negligible improvements achieved in the overall performance of the waste management system for these categories.

Impact of the combined substitution and further remarks

When both the considered product substitutions are implemented in the system as waste prevention activities (WPS3), the comparison with the baseline scenario provides the results reported in Table 8. As expected, the relative improvements in the overall performance of the system are the sum of those obtained by separately implementing the two waste prevention activities (Figures 4 and 6). Specifically, an improvement ranging from 15% to 25% is achieved for half of the impact categories. Most of the remaining categories are improved by 6%-8%, while the improvement achieved for *human toxicity (cancer effects)* and *water resource depletion* is still limited (2.8% and 4%, respectively). The overall effects of implementing any additional waste prevention activities can thus be evaluated in future studies, starting from the results obtained in this assessment (provided the same baseline situation is used as a reference). Moreover, although the potential improvements observed in this study are the highest that can be achieved by implementing the two considered activities (as a complete substitution of the traditional products was assumed), they can be used as the basis to evaluate the improvements achievable also for lower levels of substitution. In fact, we found that such improvements are directly proportional to the substitution level (i.e. the percentage of traditional product substituted by the alternative, less waste-generating one). For instance, a 50% decrease in the substitution level would reduce the potential improvements in the same proportion.

Conclusions and recommendations

This LCA study evaluated the effects of two packaging waste prevention activities on the overall environmental performance of municipal waste management in Lombardia, Italy. A 2020 reference scenario was compared with different waste prevention scenarios, where the two activities are implemented. The first activity was based on the complete substitution of bottled water consumed domestically by public potable water withdrawn from the household tap. The second activity implemented the complete substitution of four categories of liquid detergents packaged in single-use containers by those distributed loose through self-dispensing systems and refillable containers.

The results revealed that, when the substitution is actually beneficial,[7] the percentage improvements in the overall

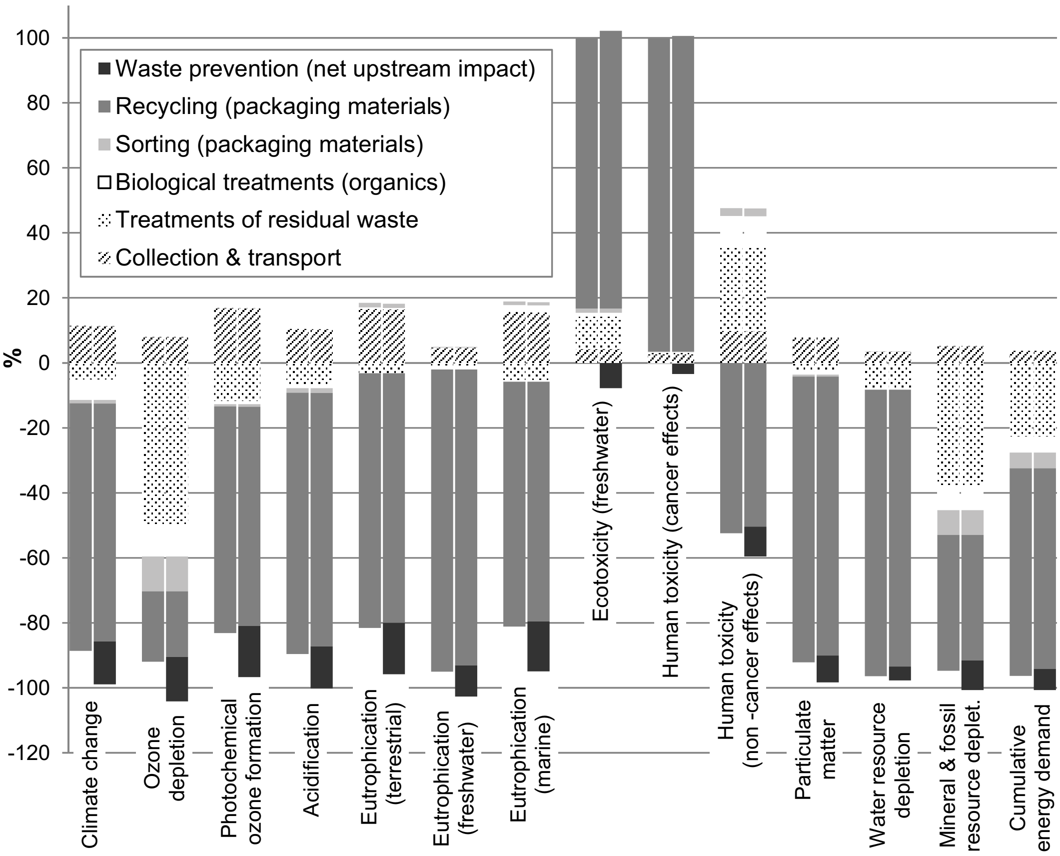


Figure 5. Main contributions to the total impacts of the baseline scenario (left bar of each couple) and of the waste prevention scenario substituting bottled water by public potable water (right bars). (Note: the contributions of the waste prevention scenario are calculated with reference to the impact of the baseline scenario).

environmental performance of the waste management system are higher than the percentage reduction in waste, regardless of the substitution performed. For instance, the percentage increase in the overall benefits of the system was greater than the net percentage decrease in the total waste mass resulting from the substitution.

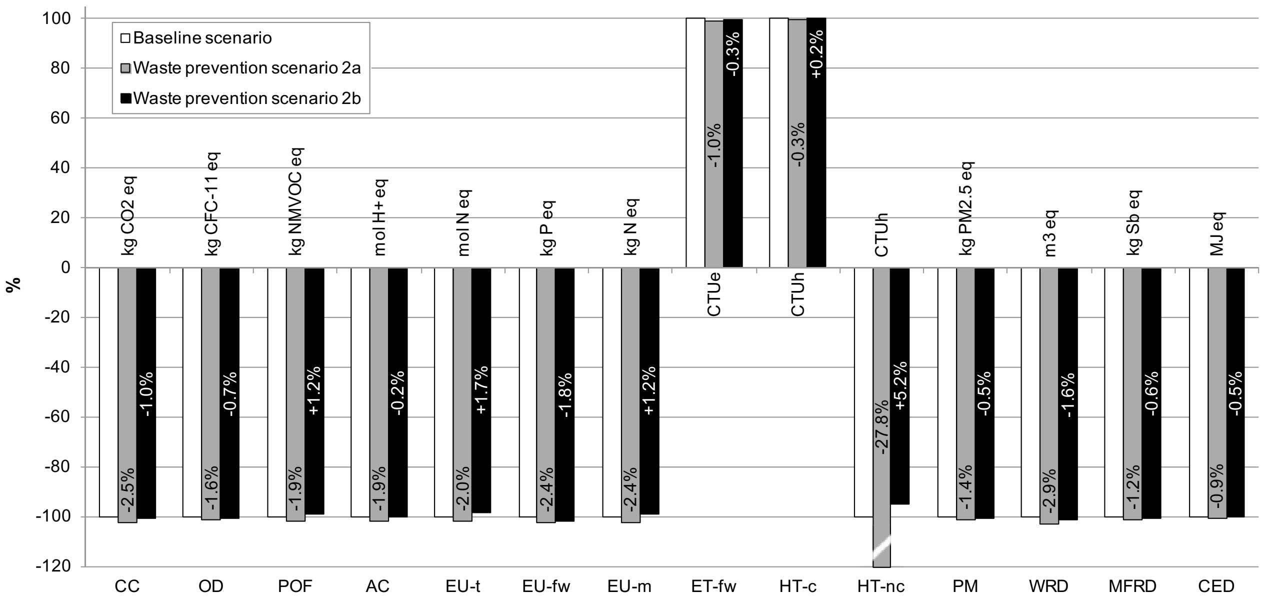
In line with the results of Cleary (2014) and Gentil et al. (2011), these overall improvements were found to be mostly enabled by the upstream benefits of waste prevention, rather than by a reduction in downstream impacts. In fact, an overall increase in the net downstream impacts (be them positive or negative) was generally observed, because the increase in recycling impacts was larger than the decrease in the impacts of collection, transport and sorting of recyclable materials affected by waste prevention. However, this overall increase in downstream impacts was generally limited and widely compensated by the additional upstream benefits from waste prevention. Such benefits are a result of the balance between the benefits from the avoided production distribution and use of the substituted products, and the additional impacts of the production distribution and use of the replacing, less waste-generating products, which are always lower than the former.

Despite the relative improvements in the overall performance of the system were always proportionally greater than the relative reduction in the quantity of waste generated, they were not meaningful for all impact categories. Moreover, not all waste prevention activities produced appreciable improvements. For the activity replacing bottled water with public potable water, a 0.5% reduction of the total waste mass allowed for an improvement (increase in benefits or reduction in impacts), which for most impact categories (11/14) ranged between 5 and 23%. As this prevention activity is relatively easy to undertake by citizens and does not require important structural changes in upstream supply chains, its implementation is encouraged to further improve the performance of waste management at the regional level.

When single-use packaged liquid detergents were entirely replaced by loose detergents with the same washing performance, the improvements in the overall performance of the system were lower than those achieved for the bottled water substitution. Excluding the *human toxicity (non-cancer effects)* impact category (where a 28% increase in the overall benefits was achieved) such improvements never exceeded 3%. This was mostly because the substituted volume of detergent was, for obvious

Table 5. Upstream impacts of the waste prevention activity substituting bottled water by public potable water within waste prevention scenario 1.

Impact category	Unit	Avoided upstream impact	Additional upstream impact	Net upstream impact	% of the net upstream impact out of the total scenario impact
Climate change	kg CO_2 eq.	1.99×10^8	3.22×10^7	-1.67×10^8	−15.2
Ozone depletion	kg CFC-11 eq.	37.5	2.2	−35.3	−14.3
Photochemical ozone formation	kg NMVOC eq.	9.05×10^5	6.26×10^4	-8.43×10^5	−19.6
Acidification	mol H^+ eq.	1.04×10^6	1.26×10^5	-9.18×10^5	−14.4
Terrestrial eutrophication	mol N eq.	2.87×10^6	2.15×10^5	-2.66×10^6	−20.4
Freshwater eutrophication	kg P eq.	6.06×10^4	3.67×10^3	-5.69×10^4	−9.9
Marine eutrophication	kg N eq.	2.72×10^5	2.02×10^4	-2.52×10^5	−20.1
Freshwater ecotoxicity	CTUe	2.58×10^8	2.49×10^7	-2.33×10^8	−8.2
Human toxicity (cancer effects)	CTUh	11.8	1.6	−10.2	−3.4
Human toxicity (non-cancer effects)	CTUh	10.5	1.1	−9.4	−76.9
Particulate matter	kg $PM_{2.5}$ eq.	9.63×10^4	1.22×10^4	-8.41×10^4	−9.2
Water resource depletion	m^3 water eq.	1.10×10^6	8.16×10^5	-2.81×10^5	−4.5
Mineral and fossil resource depletion	kg Sb eq.	7.89×10^5	8.72×10^4	-7.02×10^5	−9.6
Cumulative energy demand	MJ eq.	4.68×10^9	3.81×10^8	-4.29×10^9	−6.7



CC: climate change; OD: ozone depletion; HT-c: human toxicity (cancer effects); HT-nc: human toxicity (non-cancer effects); PM: particulate matter; POF: photochemical ozone formation; AC: acidification; EU-t: eutrophication (terrestrial); EU-fw: eutrophication (freshwater); EU-m: eutrophication (marine); ET-fw: ecotoxicity (freshwater); WRD: water resource depletion; MFRD: mineral and fossil resource depletion; CED: cumulative energy demand.

Figure 6. Comparison between the potential impacts of the baseline scenario and of the waste prevention scenarios substituting single-use packaged liquid detergents by loose detergents (the percentages reported in the bars representing the waste prevention scenarios indicate the impact variation between such scenarios and the baseline).

reasons, smaller compared to bottled water (88% less). As a consequence, the proportion of waste prevented was also limited (0.14% vs 0.5% of total waste mass), although a complete substitution was assumed. With the current levels of consumption of liquid detergents in Italy, the implementation of this waste prevention activity can thus contribute to moderately increase the benefits of a structured set of measures, but it is poorly effective as a stand-alone activity. However, it is fundamental to ensure that the loose detergents have equivalent washing performances compared to substituted traditional ones (i.e. generally, similar concentrations). In this condition, an identical amount of detergent will approximately be used before and after the

Table 6. Upstream impacts of the waste prevention activity substituting single-use packaged liquid detergents by loose detergents within waste prevention scenario 2a (both types of detergents have the same average washing performances).

Impact category	Unit	Avoided upstream impact	Additional upstream impact	Net upstream impact	% of the net upstream impact out of the total scenario impact
Climate change	kg CO_2 eq.	3.87×10^7	6.70×10^6	-3.20×10^7	–3.2
Ozone depletion	kg CFC-11 eq.	4.58	0.57	–4.01	–1.8
Photochemical ozone formation	kg NMVOC eq.	1.30×10^5	3.06×10^4	-9.93×10^4	–2.7
Acidification	mol H^+ eq.	1.79×10^5	3.69×10^4	-1.42×10^5	–2.5
Terrestrial eutrophication	mol N eq.	3.51×10^5	9.35×10^4	-2.57×10^5	–2.4
Freshwater eutrophication	kg P eq.	1.56×10^4	2.05×10^3	-1.35×10^4	–2.5
Marine eutrophication	kg N eq.	3.82×10^4	9.14×10^3	-2.90×10^4	–2.8
Freshwater ecotoxicity	CTUe	5.56×10^7	1.31×10^7	-4.25×10^7	–1.4
Human toxicity (cancer effects)	CTUh	2.09	0.86	–1.23	–0.4
Human toxicity (non-cancer effects)	CTUh	2.44	0.92	–1.52	–24.9
Particulate matter	kg $PM_{2.5}$ eq.	1.94×10^4	3.25×10^3	-1.62×10^4	–1.9
Water resource depletion	m^3 water eq.	2.34×10^5	3.04×10^4	-2.04×10^5	–3.2
Mineral and fossil resource depletion	kg Sb eq.	1.73×10^5	2.66×10^4	-1.46×10^5	–2.1
Cumulative energy demand	MJ eq.	1.09×10^9	1.65×10^8	-9.22×10^8	–1.5

Table 7. Upstream impacts of the waste prevention activity substituting single-use packaged liquid detergents by loose detergents within waste prevention scenario 2b (loose detergents have worse washing performances than substituted traditional ones due to a lower concentration).

Impact category	Unit	Avoided upstream impact	Additional upstream impact	Net upstream impact	% of the net upstream impact out of the total scenario impact
Climate change	kg CO_2 eq.	3.87×10^7	2.23×10^7	-1.64×10^7	–1.7
Ozone depletion	kg CFC-11 eq.	4.58	2.60	–1.98	–0.9
Photochemical ozone formation	kg NMVOC eq.	1.30×10^5	1.45×10^5	1.54×10^4	0.4
Acidification	mol H^+ eq.	1.79×10^5	1.40×10^5	-3.91×10^4	–0.7
Terrestrial eutrophication	mol N eq.	3.51×10^5	4.91×10^5	1.41×10^5	1.3
Freshwater eutrophication	kg P eq.	1.56×10^4	5.11×10^3	-1.04×10^4	–1.9
Marine eutrophication	kg N eq.	3.82×10^4	4.61×10^4	7.96×10^3	0.8
Freshwater ecotoxicity	CTUe	5.56×10^7	3.43×10^7	-2.13×10^7	–0.7
Human toxicity (cancer effects)	CTUh	2.09	2.27	0.18	0.1
Human toxicity (non-cancer effects)	CTUh	2.44	2.49	0.06	1.3
Particulate matter	kg $PM_{2.5}$ eq.	1.94×10^4	1.10×10^4	-8.45×10^3	–1.0
Water resource depletion	m^3 water eq.	2.34×10^5	1.12×10^5	-1.22×10^5	–2.0
Mineral and fossil resource depletion	kg Sb eq.	1.73×10^5	7.98×10^4	-9.32×10^4	–1.4
Cumulative energy demand	MJ eq.	1.09×10^9	4.84×10^8	-6.03×10^8	–1.0

substitution, so that no additional upstream and downstream impacts will be involved by the life cycle of the added detergent. Otherwise, the modelling demonstrated that most of the improvements in the overall performance of the system vanish, and that for some impact categories this waste prevention activity might even prove detrimental.

Table 8. Comparison between the potential impacts of the baseline scenario and of the waste prevention scenario implementing the substitution of both bottled water and liquid detergents (assuming an identical washing performance for both the loose and the traditional products).

Impact category	Unit	Baseline scenario (BLS)	Waste prevention scenario 3 (WPS3)	Variation between BLS and WPS3 (%)
Climate change	kg CO_2 eq.	-9.69×10^8	-1.12×10^9	−16.0
Ozone depletion	kg CFC-11 eq.	−216	−251	−16.2
Photochemical ozone formation	kg NMVOC eq.	-3.56×10^6	-4.36×10^6	−22.6
Acidification	mol H^+ eq.	-5.62×10^6	-6.49×10^6	−15.4
Terrestrial eutrophication	mol N eq.	-1.06×10^7	-1.33×10^7	−25.0
Freshwater eutrophication	kg P eq.	-5.32×10^5	-5.90×10^5	−11.0
Marine eutrophication	kg N eq.	-1.02×10^6	-1.28×10^6	−24.9
Freshwater ecotoxicity	CTUe	3.01×10^9	2.82×10^9	−6.5
Human toxicity (cancer effects)	CTUh	312	303	−2.8
Human toxicity (non-cancer effects)	CTUh	−4.77	−13.6	−186
Particulate matter	kg $PM_{2.5}$ eq.	-8.55×10^5	-9.30×10^5	−8.8
Water resource depletion	m^3 water eq.	-6.13×10^6	-6.40×10^6	−4.4
Mineral and fossil resource depletion	kg Sb eq.	-6.85×10^6	-7.40×10^6	−7.9
Cumulative energy demand	MJ eq.	-6.09×10^{10}	-6.44×10^{10}	−5.7

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Declaration of conflicting interest

The authors declare that there is no conflict of interest.

Notes

1. ARPA is the acronym for the Regional Environmental Protection Agency (Agenzia Regionale per la Protezione dell'Ambiente).
2. The contribution of labels applied to single-use detergent containers was excluded from the calculation of the avoided waste, because no experimental estimates were carried out or were available for the many different types and sizes of container replaced by the prevention activity (see Supplementary tables S.4 to S.7 online). However, the effects of this exclusion are deemed to be negligible as, for bottled water, prevented waste labels contribute only 2.6% of the avoided primary packaging waste (including bottles, caps and labels) and 2.4% of the total avoided waste.
3. For the *human toxicity (cancer effects)* and the *freshwater ecotoxicity* indicators, the adverse impact from the reprocessing of ferrous metals into secondary steel by far exceed the benefit from the avoided production of primary steel. The recycling process of ferrous metals as a whole is thus characterised by an overall positive impact. This is because the mentioned indicators tend to be dominated by waterborne emissions of hexavalent chromium, which are higher for the reprocessing of ferrous scrap within electric arc furnaces rather than for the primary production of steel in basic oxygen furnaces. Specifically, the landfilling of slag from steel making is responsible for most of the emissions for both the process.
4. Because the overall loads and benefits are balanced out (Figure 3).
5. The avoided production of detergent disposable packaging (especially containers and cardboard boxes) is mainly responsible for this overall improvement.
6. For *human toxicity (cancer effects)* this is due to the waterborne emissions of chromium from the landfilling of the slag produced during the manufacture and recycling of the steel of the cage surrounding the tank. For *human toxicity (non-cancer effects)*, the reason is to be found in the airborne emissions of zinc from the primary production of this metal (which is used for the coating of the cage of the tank) and from the coating process itself.
7. That is, when the overall potential impacts of using the alternative less waste-generating product are lower than those associated with the use of the substituted traditional product.

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