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Reusing glass bottles in Italy: A life cycle assessment evaluation

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A R T I C L E I N F O

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A B S T R A C T

Re-use of packaging items plays a key role in the achievement of sustainable management of resources, one of the key aims of the circular economy concept. In this study, the environmental impacts of the life cycle of glass bottles used for mineral water have been assessed as a function of the number of uses (the so-called "rotations") by applying the life cycle assessment (LCA) methodology. The research is part of a wider project on the evaluation of the environmental impacts and benefits associated with the re-use of packaging in Italy. The study has been performed to identify the contribution of the reconditioning process to the total impacts of the life cycle of reusable glass bottles and to compare the environmental performances of this system with those of a system based on single-use bottles. The production of the bottles, their washing and end of life have been included in the system boundaries, as well as the logistic for the delivery to the final user (that differs among the reusable and single-use bottles-based systems). The study was built up mainly on primary data acquired through a detailed inventory questionnaire delivered to some Italian mineral water companies that use reusable glass bottles, and complemented by field visits to two reconditioning plants.

1. Introduction

In recent years, there has been a growing demand for returnable packages from various industrial sectors (Markets and Markets 2018), as well as from the final customers willing to decrease the use of disposable items. Reliable evaluation tools must be adopted to assess the actual environmental benefits of the reuse practice embedded within the circular economy concept and Life Cycle Assessment (LCA) is widely acknowledged as being the most proper. In previous research, other types of reusable packaging items were assessed, always coming to the conclusion that re-use is generally preferable to single-use, but some hotspots might exist in the regeneration stage, that should be addressed (Biganzoli et al., 2018; Biganzoli et al., 2019; Tua et al., 2019).

Contrary to other sectors, the beverage market is still largely dominated by one-way packages. Across Europe, the market share of refillable containers for beverage has dropped from 41% (90 billion units sold) in the year 2000 to 21% (55 billion units) in the year 2015 (Reloop Inc 2019). Despite this decline, refillable bottles can be a valid sustainable alternative to single-use packages in different sectors. For example, in the beer packaging, a recent German study (Deutsche Aluminium Verpackung Recycling GmbH 2010) showed good environmental performances for glass refillable bottles in case of local markets (within 100 km distance) and for at least 25 rotations. Similar results were reported for the French context. A system based on refillable beer glass bottles with 20 reuses and a distribution distance of 250 km showed lower impacts when compared to an equivalent system based on single-use glass bottles: −86% for the acidification, −79% for the climate change, and −76% for the consumption of primary energy (Deroche Consultants 2009). Also in the sector of carbonated soft drinks, refillable glass bottles resulted a sustainable option. A British study assessed that reusing glass bottles three times would make the carbon footprint of drink distribution comparable to that of single-use 0.5 liters virgin PET bottles and aluminum cans (Amienyo et al., 2013). This study aims at evaluating the environmental impacts associated to the Refillable glass Bottles (RBs) system as a function of the number of provided deliveries in the Italian mineral water sector. The analysis is considered of particular interest for Italy, as it is one of the biggest consumers of bottled water at the European and global level (13.5 billion liters in the year 2017, corresponding to 222 liters/inhabitant; (Bevitalia 2018)). Primary data about the reconditioning process and the logistic of distribution were collected from four bottled water companies, representing an overall 25% share in the RBs market in Italy.

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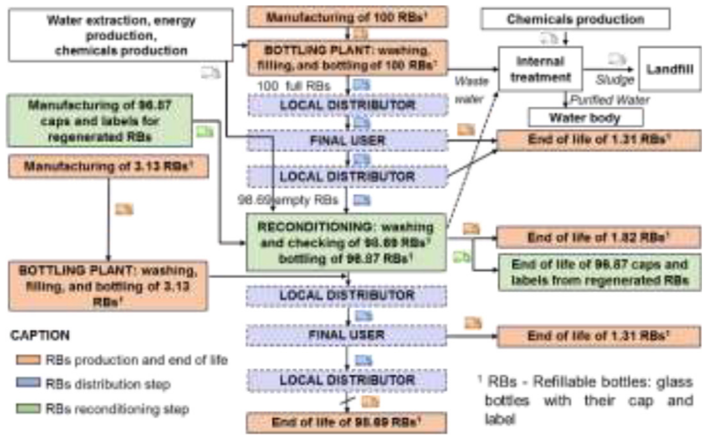

Fig. 1. Analyzed system with the relative system boundary.

Table 1
Main characteristics of the packaging under study.

Component of RBs	Material	Amount (*g/bottle*)
Bottle (refillable)	Glass	452
screw	aluminum (body)	1.4
cap	Plastic (seal and liner)	0.4
label (single-use)	Paper	1.0

2. Material and methods

The environmental assessment was performed according to the LCA methodology based on the ISO 14,040 (ISO 2006) and ISO 14,044 (ISO 2018) standards and the Product Environmental Footprint (PEF) Guide (Zampori and Pant, 2019). The SimaPro software (version 9.0) supported the data processing. According to such mentioned documents, the LCA is composed of four main steps: goal and scope definition (Sections 2.1 and 2.2), inventory analysis (Section 2.3), impact assessment and interpretation (Section 3).

2.1. Goal definition

The main objectives of the study are:

- to assess the impacts of the RBs system as a function of the number of deliveries (from now on indicated as *n*) for the distribution of mineral water in Italy;
- to identify the impact contribution of the main stages (RBs production and end of life, RBs reconditioning, and RBs distribution) in order to provide companies with indications for a more sustainable management;
- to understand if and under which conditions the RBs system performs better than an alternative system based on Single-use glass Bottles (SBs) of the same capacity. This comparison is reported in Section 3.2.

2.2. Scope definition

2.2.1. System description

Four Italian bottled water companies agreed to be surveyed in order to understand the general operation of the RBs system and to gather primary data about the packaging components (i.e., mass and material, way of manufacturing, end of life treatment), the layout and mass balance of the regeneration, and the way of distribution (i.e., covered distance and type of vehicles). The RBs system is based on glass bottles with a screw cap and an informative label (Table 1). Bottles are available in different sizes, but the 1-liter bottle, being clearly dominating, it was taken as the reference.

In the RBs system (Fig. 1), the components of the refillable packaging are manufactured in dedicated plants and then transported to a bottling facility. Here, bottles are subjected to the following steps: washing with hot water and chemicals (detergent, release agent for label, acid product, and disinfectant), filling with water, capping, labeling, and packaging for the distribution. Full bottles are then transported to a local distributor, which delivers them to the final users, simultaneously withdrawing the empty ones. The average refund rate of empty bottles is 98.69% (primary data provided by the surveyed companies). The losses in the distribution stage (1.31% at each delivery) are supposed to be disposed with the separated collection of glass and sent to recycling.

In the regeneration process, after the removal of caps, all the returned bottles are washed in the same way described for the first washing. Then they are checked manually and by electronic inspection to verify the absence of damages. In this stage, about 1.85% of the washed bottles are discarded. Regenerated bottles and the new ones replacing the losses of the distribution and of the regeneration are filled, capped, and labelled with new caps and labels, and then packaged for the delivery.

The bottling facility generates wastewater and solid waste composed of discarded caps, labels, and damaged bottles. Wastewater is treated in an internal plant based on a chemical-physical treatment in order to adjust the pH and to reduce the concentration of surfactants. The purified wastewater is discharged into a receiving water body, while the process sludge is periodically sent to landfill after dehydration. Solid wastes are sent to a dedicated plant of sorting and recycling.

According to collected primary data, a maximum number of 30 deliveries was assumed. This average re-use rate of glass bottles is also recommended in the PEF guide (Zampori and Pant, 2019).

2.2.2. Functional unit

The function of the analyzed system is to provide a certain volume of mineral water to the final user by using 1-liter glass bottles. Then, the Functional Unit (FU) is assumed as *100 liters of mineral water* (*corresponding to 100 bottles*) at each delivery. The number of deliveries (*n*) is included between 1 and 30. For *n* equal to 1, refillable bottles are used only once and then discarded. Thus, the reference flow is 100 new bottles. For *n* equal to 2, refillable bottles, after the first use, are returned to the bottling plant. There, 3.13 bottles are discarded (1.31 lost during the distribution and 1.82 discarded in the reconditioning process), while the others 96.87 are made available for the second delivery. Thus, the reference flow is 103.13 new bottles. In general terms, the reference flow is (100 + 3.13 (*n*-1)) new bottles, as shown in Fig. 2.

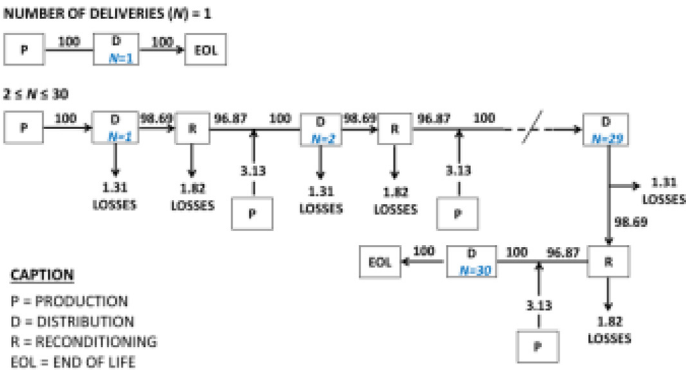

Fig. 2. Simplified chart of the life cycle of 100 RBs as the number of deliveries changes.

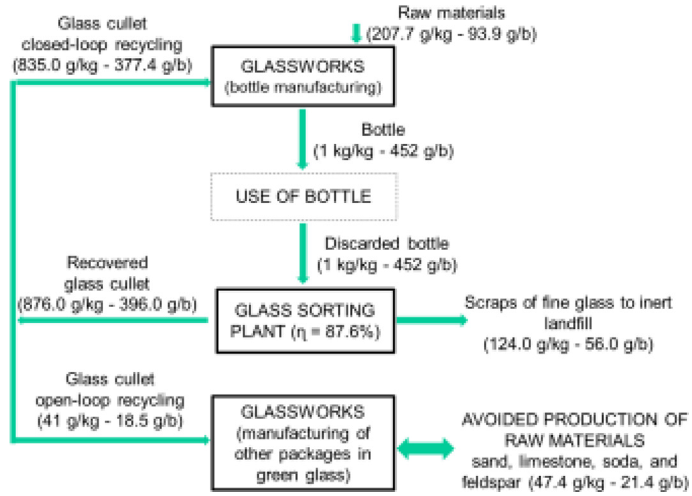

Fig. 3. Mass balance related to the production of a green glass bottle according to a process of closed-loop recycling. g/b = g/bottle.

2.2.3. System boundary

The system boundary (Fig. 1) includes:

- the manufacturing of the RBs components and the relative transportation to the bottling plant (100 new RBs and those replacing losses);
- the first washing, filling, capping, and labeling of RBs (energy, water and chemicals consumption, wastewater treatment including the management of the sludge);
- the distribution of RBs (transportation from the bottling plant to the local distributor and then to the final user);
- the reconditioning process of RBs (energy, water and chemicals consumption, wastewater treatment and caps/labels replacement);
- the end of life of the RBs components, i.e. the transportation and the waste treatment in dedicated facilities (RBs after *n* uses and RBs discarded at every use). In this stage, cases of multi-functionality related to the avoided primary productions due to the recovery of energy and materials were solved by expanding the system boundary (Finnveden et al., 2009).

2.2.4. Data quality

The study refers to the average operation of 4 bottling companies located in northern Italy, that distribute water within the whole national territory. Data refer to the year 2017.

The foreground system was mainly described with primary data gathered from the companies (distribution, first bottling, and reconditioning) and from the operators of waste treatment plants in the northern Italy (end of life of the RBs components and of the sludge). For the processes of the background system (such as chemicals production), data from the ecoinvent 3.5 database (*allocation cut-off by classification* approach) were generally used (Ecoinvent 2018).

2.2.5. Selected indicators

For the assessment, 14 impact categories from the Environmental Footprint Life Cycle Impact Assessment Method, version 2.0 (Fazio et al., 2018) were selected: climate change (CC), ozone depletion (OD), photochemical ozone formation (POF), particulate matter (PM), human toxicity, non-cancer effects (HT_{NC}), human toxicity, cancer effects (HT_C), acidification (A), aquatic freshwater eutrophication (FE), aquatic marine eutrophication (ME), terrestrial eutrophication (TE), freshwater ecotoxicity (FEC), water scarcity (WS), resource use - energy carriers (RU_{EC}), resource use - minerals and metals (RU_{MM}).

2.3. Inventory

This section reports the primary data used to model the processes included in the system boundary.

2.3.1. Packaging production and end of life

The manufacturing of a green glass bottle was modelled according to the average European composition at the furnace reported in the ecoinvent database (Ecoinvent 2018) and confirmed for the Italian context. The bottle is produced by the melting of glass cullet (835 g/kg bottle) and virgin raw materials, i.e. sand, soda, limestone, and feldspar (208 g/kg bottle). As shown in Fig. 3, the glass cullet comes directly from RBs at their end of life, after a sorting process (efficiency of 87.6%; consumption of electricity, Italian mix equal to 19 Wh/kg bottle). Part of the recovered glass cullet (835 g/kg) is used to produce new RBs (closed-loop recycling), while the remaining amount (41 g/kg bottle) is destined for the production of other green glass packages (open-loop recycling) in replacement of virgin raw materials according to a substitution ratio equal to 1:1.15 by mass (Ecoinvent 2018).

The steps of melting in the furnace, as well as forming, cooling, testing, and packing (air emissions, fuel consumption, residues treatment, and glasswork manufacturing and maintenance) were modelled with average European data of actual consumption and emission levels in the manufacture of container glass (Scalet et al., 2013). The transportation of the produced glass bottles from the glasswork to the bottling plant is performed by large-size trucks ($>$ 32 t) along an average distance of 200 km.

The aluminum body of the cap is produced by deep drawing of thin foils, 8011 alloy (98.5% primary aluminum, 0.8% cast iron, and 0.7% silicon of metallurgical grade; (AZoM 2013)). The liner and the seal were manufactured by extrusion of plastic granules, a mixture of polyethylene and polyvinylidene chloride. According to primary data, the cap is generally produced in Spain and so its manufacturing was modelled according to the electricity mix of this country. The transportation to the bottling plant in Italy (1100 km on the average) was supposed to be performed by small truck, freight train and container ship at a similar rate.

After use, the cap is sent to a metal sorting facility where the aluminum body is separated from the plastic elements and then crushed and pressed (electricity, Italian mix: 25 Wh/kg input waste; diesel: 236 kJ/kg input waste). The plastic waste is supposed to be incinerated in a municipal solid waste incinerator, with the recovery of electricity and thermal energy (1.5 kWh and 3.2 MJ per kg of input waste). The aluminum scraps are sent to a smelter where they are used in substitution of primary pure aluminum (aluminum 99.7%) with a substitution ratio equal to 1:0.7 by mass, based on an economic evaluation (Koffler and Florin, 2013).

Table 2
Inventory of the operations in the bottling facility for refillable bottles based on collected primary data. Data refer to one bottle entering the facility.

Input	Amount per bottle
Electricity according to the Italian mix	44 Wh
Water for washing (well water)	0.67 l
Heating of water (natural gas, conventional boiler)	459 kJ
Detergent (solution of caustic soda)	0.24 g
Disinfectant (based on peracetic acid)	1.15 g
Release agent for label	
Type A (based on EDTA)	0.12 mg
Type B (based on sodium cumene sulfonate)	0.24 mg
Acid product - removal of the mineral residue	
Type A (based on sulfuric acid)	65 mg
Type B (based on lactic acid)	65 mg
Transport of chemicals to the bottling plant	1.52 g × 200 km
Caps substitution in the regenerated bottles (production + end of life) [1]	1.77 g
Labels substitution in the regenerated bottles (production + end of life) [1]	0.98 g
Output	Amount per bottle
Wastewater to the internal treatment	0.67 l

[1] The substitution is not performed in the first washing.

The paper label is produced by uncoated, wood-containing paper and then transported to the bottling plant by small trucks (120 km on the average).

The end of life process of the label depends on the place where it is discarded. When discarded in the bottling plant, the label is sent to a paper sorting plant (electricity, Italian mix: 58 Wh/kg of input waste; diesel: 428 kJ/kg of input waste) and then to a paper mill. In absence of primary data, the recycling in the paper mill was modelled according to the BREF document related to the production of pulp, paper, and board (Suhr et al., 2015). In this step, no credits associated to the recovery of the material and so to the avoided production of virgin paper were considered, as the paper of label has a low quality and should be mixed with a lot amount of other paper in order to be recycled. When discarded by the users (due to bottle break or leak), the label is supposed to be collected with the bottle (separated collection of glass) and sent to a glass sorting plant. Here, it is separated from the glass cullet by aspiration of light bodies and sent to incineration with the recovery of electricity and thermal energy (0.7 kWh and 1.4 MJ per kg of input waste).

2.3.2. First washing and bottling/Reconditioning process

The complete inventory of the operations in the bottling facility is reported in Table 2, based on the collected primary data. In case of first washing and bottling, the replacement of the label and cap is not performed. The generated wastewater is sent to a physical-chemical treatment plant (located within the bottling facility). The treatment of 1 m^3 requires electricity (already included in the overall consumption of the bottling plant; see Table 2) and 3.69 kg of sulfuric acid. The process generates 1 m^3 of purified water and 0.54 kg of process sludge. The purified water is discharged into a water receiving body with the emission of: 27 g/m^3 BOD_5, 54 g/m^3 COD, 3 g/m^3 of total nitrogen, 0.3 g/m^3 of total phosphorus, 55 g/m^3 of sulfate, 13 g/m^3 of chloride, and 10 g/m^3 of total suspended solids. The process sludge (at 5% of dry matter) is subjected to a conditioning and dewatering treatment (consumption of: 7.5 g of ferric chloride solution, 9.25 g of lime, and 3.1 Wh of electricity per kg of input wet sludge). The output flows are dewatered sludge (178 g/kg of input sludge, 35% of dry matter) sent to a neighboring landfill and the supernatant (0.84 l/kg of input sludge) sent to a municipal wastewater treatment plant.

2.3.3. Distribution

The distribution of RBs includes the transportation from the bottling plant to the local distributor and the delivery trip to the final user. Inventory data are reported in Table 3.

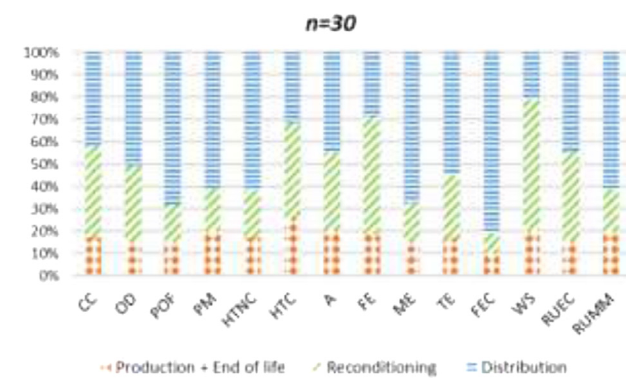

Fig. 4. Percentage contribution of the stages “production + end of life”, “reconditioning”, and “distribution” to the value of the indicator for $n = 30$.

3. Results and discussion

3.1. Impact assessment

The impacts related to the system of 100 RBs ready for the n^{th} delivery include the environmental loads of:

- the production and end of life of [100 + 3.13 (n-1)] RBs;
- the reconditioning of 98.69 × (n-1) RBs;
- the distribution of 100 × (n + 1) RBs.

By increasing the number of deliveries, the contribution of the stage “production + end of life” decreases gradually, remaining below 30% in all the indicators for $n = 30$ (Fig. 4).

On the contrary, the contribution of the reconditioning and distribution stages increases with the number of uses. In particular, when $n = 30$ (Fig. 4), the contribution of the distribution is generally higher than 50% and reaches 80% in the impact category *freshwater ecotoxicity*. The contribution of the reconditioning process is more modest, always lower than 45%, with the exception of the impact categories *freshwater eutrophication* (53%) and *water scarcity* (59%).

Depending on the indicators, the main burdens of the reconditioning process are associated to the electricity consumption, the heating of the washing water (use of a gas conventional boiler), the replacement of the caps in the regenerated bottles (production of primary aluminum), and the water consumption. The consumption of chemicals, the wastewater treatment, and the replacement of labels show a negligible contribution instead. From an energy point

Table 3
Inventory of the distribution stage.

Step	Truck type	Transported mass (*kg/bottle*)	Transportation distance
Transport to the local distributor	Large-size lorries (> 32 t) Euro 3: 84% Euro 4: 7% Euro 5: 6% Euro 6: 3% (Automobile Club d'Italia 2018)	Outward journey: 1.7 [1] Return trip: 0.7 [1]	200 km (Sensitivity analysis Section 3.3)
Transport to the final user	Small-size lorries (< 7.5 t) Euro 3: 84% Euro 4: 7% Euro 5: 7% Euro 6: 2% (Automobile Club d'Italia 2018)	Outward journey: 1.65 [2] Return trip: 0.65 [2]	15 km

[1] Transportation of full/empty bottles with caps and labels and associated plastic crates and wooden pallet.
[2] Transportation of full/empty bottles with caps and labels and associated plastic crates.

of view, the reconditioning process can be optimized by reducing the consumptions and/or by promoting the use of alternative, more efficient sources (e.g., a combined heat and power boiler). As regards the production of the caps, it is not directly under the control of the bottling companies, except for the selection of the supplier (currently caps are purchased in Spain). Finding alternatives to aluminum or reducing the weight of the cap should be considered in the design phase.

In the distribution stage, most of the impact is due to the transportation to the local distributor. In the baseline scenario, an average transportation distance of 200 km is considered, but the influence of this parameter was investigated in a sensitivity analysis (Section 3.3). The burdens of transportation could be reduced by promoting the use of vehicles with a Euro class 5 or 6 motor, instead of a class 3 (See Table 3).

3.2. Reconditioning vs. single-use

In this section, the RBs system is compared to an alternative Single-use glass Bottles one (SBs system). In this case, the reference flow that fulfills the FU is $100 \times n \times$ SBs. According to primary data, single-use bottles have the same capacity and the same weight of the refillable bottles. Their production and end of life were modeled as previously described in Section 2.3.1 for the refillable bottles. The only difference is that all the bottles are discarded by the user in the glass separated collection, without being returned to the company. In the distribution stage, the transportation to the final user was modelled differently with respect to the RBs system. Single-use bottles are in fact generally sold at the large-scale retail trade. According to the Product Category Rules for mineral water bottles (The International EPD System 2017), the transportation from the retailer to the user was modelled with a roundtrip of 4 km performed by private car, with the bottle being part of a 20 articles purchase.

By comparing the two alternatives, the RBs system, under the average operating conditions, shows better environmental performances starting from two deliveries. When $n = 2$, depending on the indicators, the ratio between the impact in the RBs system and in the SBs system ranges from 44% to 74%. For the maximum number of deliveries ($n = 30$), the same ratio decreases up to 17%–37% (see Fig. 5 for the impact category *climate change* reported as an example).

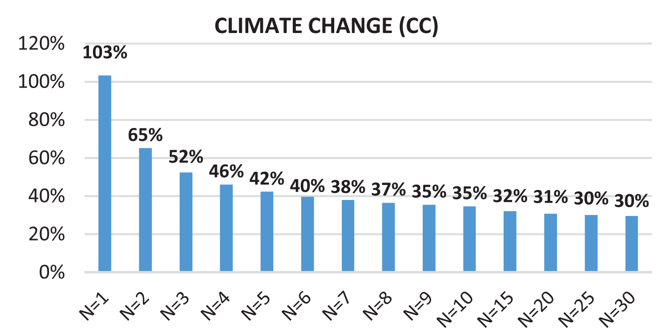

Fig. 5. Ratio between the value of the indicator *climate change* in the RBs and SBs system, for each number of deliveries.

3.3. Sensitivity analysis

Some sensitivity analyses on the most important parameters in the RBs system (bottle weight and maximum number of uses, average refund rate and travelled distance in the distribution) were performed in order to check their influence on the results. The travelled distance between the bottling plant and the RBs distributor (progressively incremented up to 1000 km) resulted the only parameter affecting the comparison between the SBs and RBs systems. For a 400 km distance, at least 4 deliveries are required to achieve better environmental performances than the single-use distribution, while for 800 km or more, the RBs system is not convenient also when $n = 30$ (Fig. 6).

4. Conclusions and recommendations

In this study, the environmental performances of the refillable glass bottles system for the distribution of mineral water in Italy were assessed, as a function of the number of uses.

Results show that the impacts of the RBs system are mainly associated to the distribution stage, in particular to the transportation of the bottles from the bottling plant to the local distributor (200 km distance on the average). For the maximum number of uses ($n = 30$), the impact contribution of the distribution can reach 80% of the overall indicator. The environmental loads of the reconditioning process are more modest, generally below 45%, even for the maximum number of uses. Most of the burdens are associated to the energy consumption and to the caps production composed of primary aluminum.

When compared to the single-use bottles system, for a local market (within 200 km) the use of refillable bottles is by far preferable just starting from two deliveries. However, the distance between the bottling plant and the local distributor in the RBs distribution plays a key role in the impact evaluation. For a 400 km distance, at least 4 uses of the refillable bottles are required to achieve better environmental performances, while for 800 km or more, the RBs system is not convenient also for 30 uses.

This study is part of a wider research activity related to an environmental assessment of the re-use practice in Italy. New LCAs

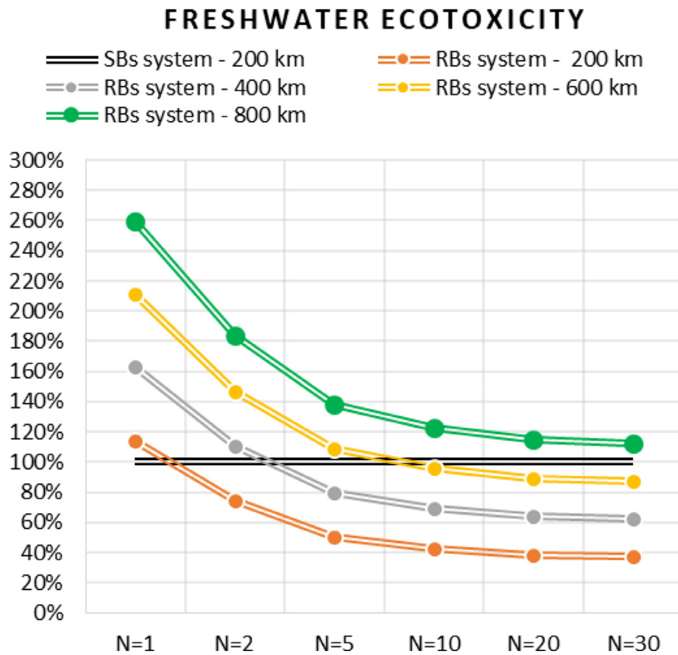

Fig. 6. Comparison between the value of the indicator in the RBs and SBs system (the value of the indicator in the SBs system is put at 100%), for each number of deliveries and for different values of transportation distance in the RBs system. The category *freshwater ecotoxicity* is taken as reference because it is the most influenced by the distance.

on other reusable packages will be soon implemented by applying the same modeling approach.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Camilla Tua: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Data curation, Writing - original draft. **Mario Grosso:** Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Lucia Rigamonti:** Conceptualization, Methodology, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition.

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