Manufacturing, use phase or final disposal: where to focus the efforts to reduce the environmental impact of a food machine?

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\textbf{ABSTRACT}

The end of life of equipment is gaining interest among food companies who want to lower their environmental impacts. However, by considering their life cycle, is it the most impactful phase? To answer the question, a Life Cycle Assessment was carried out by comparing the manufacturing, use and final disposal of a food equipment. Primary data (materials, operations and cleaning consumption) were collected; the end of life was modelled considering European disposal. Eight midpoint indicators were adopted: results demonstrate that the end of life, as well as the raw materials extraction and production, contribute little on many categories. The main impact (95\%) is due to the use phase, primarily in charge of electricity (responsible for 40-70\% of eutrophication, acidification, and global warming potentials). Therefore, food producers aimed at improving their facilities should, firstly, focus on consumption optimization (e.g. using renewable electric energy) and, only later, on the equipment’s final management.

\textbf{1. Introduction}

Today is known that the food industry sector is accountable for negative environmental impacts along the food life cycle, starting from production, processing, distribution, storage and final disposal (Cucurachi et al., 2019; Borghesi et al., 2022). The greenhouse gases emission, land use, deforestation, use of big amounts of water are only a few examples of problems investigated in the available scientific literature (Chukwu, 2009). The impact of agriculture has been recognized to be very high, as well as the impact of the food waste along the supply chain (Agusdei & Coluccia, 2022), however, some impact reductions could be obtained even as far as the manufacturing and packaging phases are concerned. Some studies compared, for example, the impact of different packaging materials (Stefanini et al., 2021), others investigated the food processing (Roibás et al., 2018), stabilization (Vignali et al., 2022) or cooking method (Favi et al., 2018). Furthermore, other prominent themes are resource nexus, policies and legislations, transition challenges and circular premium (Zhang et al., 2022), all related to circular
economy that has become central in tackling global environmental challenges, because it presupposes a cradle-to-cradle approach that disfavours the ‘take-make-dispose’ business logic (Averina et al., 2021). In particular, green-circular premium and sustainability certification represent strategic innovation but also a complex challenge involving widespread change that concerns entrepreneurship, management and industrial policies, as well as stakeholder engagement (Appolloni et al., 2022).

Moreover, following the mentioned circular economy perspective, even the end of life is gaining importance, and in particular the potential of a product or a machine to be recycled and reused is becoming imperative for environmental, economic and social reasons (Rogkas et al., 2021). Recently, several articles have been published evaluating the impact of the components’ end of life on automotive (Ayvaz et al., 2021; Duarte Castro et al., 2021) or packaging and technology applications (Ganesan & Valderrama, 2022; Tamoor et al., 2022), aimed at finding out alternatives to recycle or reuse them. In particular, the manufacturing industries of building materials increased their interest in using waste materials to partially or completely replace the virgin ones (Sandanayake et al., 2022). Furthermore, the production of industrial equipment uses big amounts of virgin materials: it is estimated that in Europe the building and construction sector uses about 10 million tons of plastic every year, 20% of the total, ranking second after the packaging sector (Plastic Europe, 2018). Therefore, once arrived at their end of life, these materials should be managed to reduce their impact on Earth. Moreover, thinking about the food industrial equipment, even the use of steel is very high. In fact, once arrived at the end of the machine’s life, ferrous scraps from old equipment are remelted and allow to obtain benefits in environmental terms: it has been calculated that for every ton of recycled carbon steel scrap, a carbon dioxide saving of 1.4 t CO₂eq is obtained (Federacciai, 2021).

Besides these premises, it is proven that the end of life of food products and equipment is increasingly gaining interest both from an economic and environmental point of view (Stefanini & Vignali, 2022). It is interesting to ask whether, during the entire life cycle of equipment, the end of life is so impactful to justify a rethinking of the machinery or its final management. However, to date, there are no available studies in the scientific literature that analyse the entire life cycle of a food machine. Therefore, to find out the most relevant industrial phases on which act to reduce the environmental impact, the aim of this work is to carry out a life cycle assessment of a food equipment, taking as a reference a case study based on an aseptic filler and capper for beverages. In particular, the raw materials extraction and production for assembling the machine, its use phase by considering the operation consumption and cleaning and sterilizing cycles, and the final disposal after 15 years of life are considered.

To correctly estimate the impact of each phase a Life Cycle Assessment (LCA) approach has been selected. LCA is the methodology, recognized by the European Commission, used to estimate the potential environmental impacts throughout the life cycle of the system (European Commission, 2021).

The work was carried out thanks to an Italian manufacturer of food equipment (GEA Filling & Packaging, 2022), responsible for the collection of primary data.

The following section shows the data collection and the methodology used to assess the environmental impact of the different phases of the food machine. Then, the main results are discussed before drawing the main conclusions of the work.
2. Material and methods

The SimaPro 9.1.1 software was used to carry out the Life Cycle Assessment (LCA), in accordance with the following standards:

- UNI EN ISO 14040 – ‘Environmental management – Life cycle assessment – Principles and reference framework’
- UNI EN ISO 14044 – ‘Environmental management – Life cycle assessment – Requirements and guidelines’.

Some suggestions indicated in the Product Category Rule (PCR) *Machines for filling and packaging of liquid food* have been followed: the functional unit was defined as 1000 approved bottles created by the machine.

The system boundaries of the study are summarized in Figure 1 and include Raw Materials (extraction and production), use phase (production, Cleaning In/Out of Place (CIP/COP), Sterilizing In/Out of Place (SIP/SOP) consumption), and the possible End Of Life (EoL) of the machine.

2.1. Inventory analysis

The beverage system considered in the study is an aseptic blowing-filling system: it consists of an aseptic rotary blow molding machine with an aseptic integrated filler and capper. The principle is to sterilize the preforms with Vaporized Hydrogen Peroxide (VHP) technology, then blow them with sterile air, in a sterile environment, and maintain sterility throughout the filling and capping processes, in which also caps are sterilized with H$_2$O$_2$. The estimated annual productivity is 110 million bottles. The life cycle of the machine is 15 years.

2.1.1. Components and materials

Data collection involved the company’s experts who, based on the technical data sheets and documentation available, analysed the machine components and estimated their weight.

The aseptic blowing filling system is illustrated in Figure 2. The preforms enter in the feeding and dedusting systems, before arriving in the blower. This equipment is composed of a preform oven, a preform sterilizer with VHP technology, a blowing wheel and a chiller. Finally the output group sends the blown bottles to the microbiological isolator. There, bottles are aseptically filled and capped before entering into the sterile exit tunnel. The cap sorting and feeding and the platform that sterilizes caps with VHP are placed above the aseptic capper. Even if they are not represented in the figure, the study also includes the automation panel and the cabinet of the Uninterruptible Power Supply (UPS) which contains 40 lead batteries, as well as the compressors that are usually placed in a separate room because of their noise.

Moreover, all the equipment materials have been identified: steel, plastics, copper, rubbers, glass, aluminium. The category ‘Others’ includes the materials related to the lead acid battery used in the UPS. This classification is in agreement with the Environmental Product Declarations (EPD) of similar filling machines (Ecolean, 2016).
Overall, the total weight of the system resulted as 73,858 kg, mainly due to the great amount of steel (89.31%). Some components are made of aluminium (4.25%), plastics such as Nylon, Polyurethane, Polyethylene, Polyvinylidenchloride (2.77%), copper (1.16%), rubbers (0.72%) and glass (0.39%). Finally, the lead acid batteries appear in a very small percentage (1.50%).

2.1.2. Machine consumption during the use phase
Primary data referred to 500 ml bottle with a validation protocol of internal bottle sterilization for low acid products (Log 6) and external bottle sterilization (Log 5) were provided by the company. The use phase is composed of production, cleaning and sterilizing phases: the following sub-sections describe the consumption related to each phase and illustrate, in italics, the references of the Ecoinvent 3.6 dataset, used to model them with the software SimaPro 9.1.
2.1.2.1. Production phase. During production, the preform is pre-heated using an oven and then is sterilized with a vapor of $\text{H}_2\text{O}_2$ (modelled on the Ecoinvent from Hydrogen peroxide, without water, in 50% solution state [RER]| hydrogen peroxide production, product in 50% solution state + Tap water [Europe without Switzerland]| tap water production, ultrafiltration treatment). The culinary steam used to vaporize $\text{H}_2\text{O}_2$, as well as the process steam needed to produce sterile water, are considered (Steam, in chemical industry [RER]| production). The latter is composed of the steam recovery from condensate and the new steam needed to compensate losses; it also considers the pump energy to return the condensate to the boiler (Electricity, medium voltage [RER]| market group for).

In the next step of the production, the aseptic blower creates the final bottle; then, the aseptic filler and capper end the production phase. Compressed air (Compressed air, 800 kPa gauge [RER]| compressed air production, 800 kPa gauge, >30 kW, average generation) is adopted and, to avoid the overheating of the molds, chilled water is used in a close circuit to reduce consumption (Electricity, medium voltage [RER]| market group for). Treated and city waters are used in the process (i.e. to prepare the sterilizing solutions, in the boiler and the mold) (Tap water [Europe without Switzerland]| tap water production, ultrafiltration treatment). Moreover, Peracetic Acid (PAA) 15% cleans barriers and basement during production: it was modelled with density = 1.14 g/cm$^3$ (Industria Chimica M.a.r, 2022b) and the dataset Acetic acid, without water, in 98% solution state [GLO]| market for + Hydrogen peroxide, without water, in 50% solution state [RER]| market for hydrogen peroxide, without water, in 50% solution state + Peracetic acid + Wastewater, average [Europe without Switzerland]| market for wastewater, average). The Nitrogen gas is used for the headspace between the product and the cap (Nitrogen, liquid [RER]| air separation, cryogenic; density and volume data of (Siad, 2022)). Finally, the $\text{H}_2$
0₂ to sterilize caps and \( \text{H}_2\text{O}_2 \) emissions were considered, as well as the electrical power needed by the bloc, the blower and the compressor (Electricity, medium voltage \{RER\} market group for).

### 2.1.2.2. Cleaning and sterilizing phase.

The cleaning and sterilizing cycles are performed every week, approximately every 162 h. The duration of the cycle is approximately 3 hours. The Cleaning in Place (CIP) is performed with Caustic soda 33% (modelled with Sodium hydroxide, without water, in 50% solution state \{RER\}| chlor-alkali electrolysis, membrane cell + Tap water \{Europe without Switzerland\}| tap water production, ultrafiltration treatment; Density = 1.32 g/cm³ at 20 °C (Industria Chimica M.a.r, 2022b)), followed by rinsing with city water (Tap water \{Europe without Switzerland\}| tap water production, ultrafiltration treatment) and tower water (Electricity, medium voltage \{RER\} market group for).

The Nitric acid 33% cycle (Nitric acid, without water, in 50% solution state \{RER\}| nitric acid production, product in 50% solution state + Tap water \{Europe without Switzerland\}| tap water production, ultrafiltration treatment; density of 1.15 kg/m³ (ACL, 2022)), followed by rising, occurs every 4 weeks.

The Cleaning Out of Place (COP) is performed with Caustic Soda 33% and subsequent rinsing. The Sterilization in Place (SIP) of the filler and tubes is carried out with steam (Steam, in chemical industry \{RER\}| production) and chilled water (Electricity, medium voltage \{RER\} market group for). The Sterilization Out of Place (SOP) uses PAA 15% followed by rinsing. Finally, for the blower and sterilcap SIP and COP, heating and vapour of \( \text{H}_2\text{O}_2 \) are used. In the blower, manual foaming is performed after maintenance and non-standard interventions, approximately every 4 weeks. The foaming time is 10 minutes (98% Foaming agent \{GLO\}| production | Cut-off, S + 2% Tap water \{Europe without Switzerland\}| tap water production, conventional treatment | Cut-off, S), while the rinsing with treated water (Tap water \{Europe without Switzerland\}| tap water production, ultrafiltration treatment) is 20 minutes. Finally, the electrical power for the cleaning and sterilization cycles, as well as the compressed air and nitrogen used to cool the filler, were recreated on Ecoinvent database as illustrated in the production phase.

### 2.1.3. Machine end of life

The construction of food mechanical equipment was considered part of the building & construction sector, where 26% of the plastic waste is subjected to mechanical recycling, which gives plastics a new life through the phases of collection, selection, shredding, separation, washing, granulation (EuRIC AISBL, 2018). Then, 47.5% of plastic waste is used for energy recovery through the waste-to-energy process: after the selection and shredding treatment, alternative fuels to produce thermoelectric energy in industrial processes are obtained (Gestione-rifiuti.it, 2022). Finally, 26.5% goes to landfill (Plastic Europe, 2018).

For the ferrous and non-ferrous materials, considering the Machinery and Equipment product category, the disposal is estimated as 90% recycling and 10% landfills (Schindler, 2019), (BCSA Group of Companies, 2022). The high percentage of recycling is justifiable by the fact that steel is a 100% recyclable material: it can be remelted several times without losing
any intrinsic properties (strength, ductility and formability). In fact, ferrous scrap is the main raw material used for the production of steel: it derives from steel’s waste and products that have finished their life cycle, e.g. the machinery considered in this study (Federacciai, 2021).

As regards glass waste, although the scientific literature is rich in data on the glass packaging disposal (mainly destined for recycling), there is not much information on its disposal from the plant and construction sector. Therefore, it was assumed that glass falls into the category ‘Inorganic materials’ for which landfill is foreseen at a percentage of 100% (Schindler, 2019).

Considering the lead batteries, the European Commission established that their recycling should be as high as possible (EUR-Lex, 2020), since they are dangerous to human and planet health (ECHA, 2020): indeed, Member States declare a recycling rate often higher than 97% and up to 100% (Eionet Portal, 2019; European Commission, 2018). The lead-acid battery recycling process consists of the crushing, smelting and refining phases; to produce one kg of lead from exhausted batteries, it takes just 1/3 of the energy to process the mineral extracted from the Earth. The lead and plastic materials obtained from the recycling process are mostly (60%) reused for new batteries, 15% in the ceramic and chemical industry, 8% in the production of electrical cable coatings and 17% for pellets, weights, building elements and radiological equipment. For example, polypropylene, often present in these batteries, is reused to produce electrical insulators, sanitary and household items, packaging and pipes (Gestione-Rifiuti & Sicurezza Operativa Ambientale, 2022).

Besides these findings, Table 1 resumes the modelled European end of life of the materials involved in this case study.

### 2.2. Impact assessment methods

Data collected in the inventory analysis were elaborated on the software. In particular, the equipment materials were recreated as illustrated in Table 2, specifying the type of waste to be considered on SimaPro. The waste ‘plastics’ was recreated as a mixture of the main plastics used in the equipment: nylon, polyurethane, high density polyethylene, polyvinyl chloride. Lead batteries were recreated in accordance with other studies (Spanosa et al., 2015). The type of waste is classified as ‘other’ since the batteries are composed of different materials, such as polypropylene (Spanosa et al., 2015; Unterreiner et al., 2016), lead, lead oxide and sulfuric acid. However, since lead oxide was not available on Ecoinvent, its percentage has been considered as lead.

### Table 1. End of life of the materials in the building and construction sector.

| Material          | Recycle % | Incineration % | Landfill % | Sources                                                                 |
|-------------------|-----------|----------------|-----------|------------------------------------------------------------------------|
| Plastics          | 26%       | 47.5%          | 26.5%     | (Plastic Europe, 2018; Eionet Portal, 2019)                            |
| Rubbers           |           |                |           |                                                                        |
| Steel             | 90%       | 0%             | 10%       | (Schindler, 2019; BCSA Group of Companies, 2022)                       |
| Copper            |           |                |           |                                                                        |
| Aluminium         |           |                |           |                                                                        |
| Glass             | 0%        | 0%             | 100%      | (Schindler, 2019)                                                     |
| Others (Pb batteries) | 100%     | 0%             | 0%        | (European Commission, 2018; Eionet Portal, 2019; EUR-Lex, 2020; Gestione-Rifiuti & Sicurezza Operativa Ambientale, 2022) |
Then, the 20 components of the machine were modelled using the mentioned materials, with the weight given by the company. The waste scenario on SimaPro was modelled using the Ecoinvent database. Where it was not possible to insert a precise process for the disposal scenario of a waste type, the process as similar as possible was inserted. Moreover, to refer the machine consumption to the functional unit, i.e.1000 bottles as suggested by the Product Category Rules (PCR), the hourly consumption was divided by the bottles produced in one hour and then multiplied by 1000 bottles.

As regards to the start-up cycles, the consumption of the CIP, SIP, COP, SOP, which take place every 162 hours, were divided by the productivity in 162 hours and multiplied by 1000 bottles to find the consumption per functional unit. On the other hand, for the blower’s COP and the cleaning with nitric acid, the consumption was divided by the production of bottles in 4 weeks and then returned to the functional unit.

Data modelled on the software were finally processed to calculate the environmental impact of the machine during the considered phases. Following the suggestion of the Product Category Rule ‘Machines for filling and packaging of liquid food’, the considered environmental impact categories are those used in EPDs of the International EPD Systems (EPD, 2022):

- **Acidification**: the acidification of water, soil and air is due to acidifying substances, such as nitric acid, sulfuric acid, sulfur dioxide, hydrogen chloride, sulfuric acid, hydrogen, phosphoric acid, etc. The unit of measurement for this impact category is the kg SO₂ eq.
- **Eutrophication**: the term indicates the excessive growth of plant organisms that modify the ecological balance of the aquatic environment. The unit is kg PO₄⁻ eq.
- **Global warming (100 years)**: the increase in the Earth’s average temperature due to human activities that release greenhouse gases into the atmosphere, such as CO₂. These gases, remaining trapped in the lowest layer of the atmosphere, act as a barrier to solar radiation reflected from the earth’s surface, whose energy is converted into heat. This causes the rise in the global average temperature. The unit is kg CO₂ eq.
- **Photochemical oxidation**: this phenomenon is due to nitrogen oxides and hydrocarbons, which, due to the effect of the photochemical reactions induced by the sun’s rays, lead to the oxidation of nitrogen monoxide (NO), which becomes...
nitrogen (NO₂), and the formation of ozone (O₃) and other chemical compounds with toxic effects on the ecosystem and human health. The unit of measurement is the kg NMVOC (Non-Methane Volatile Organic Compounds).

- Abiotic depletion, elements: this category refers to the exhaustion of elements, such as metals. The unit of measurement is kg Sb eq.
- Abiotic depletion, fossil fuels: the exhaustion of fossil fuels is measured in MJ.
- Water scarcity, measured in m³ eq.
- Ozone layer depletion: even if this impact category is optional, it was considered in the analysis. The thinning of the ozone layer is measured in kg CFC⁻¹¹ eq.

In the next section several charts illustrate the results. Please remember that the functional unit provided for by the PCR is 1000 bottles, therefore the presented impacts are estimated for 1000 bottles production.

3. Results

3.1. Impact of materials extraction, production and disposal

The aseptic blowing wheel, being also the heaviest component, resulted as the most impactful in all impact categories (up to 30%), except for the abiotic depletion elements where the lead batteries caused the greater impact (almost 60%). The latter result is in line with the literature and regulations (Eionet Portal, 2019), (EUR-Lex, 2020). The impact of the filler is 10% for almost all impact categories, followed by the fluid preparator unit, the compressor and the preform oven; the other components have an impact of less than 5% each.

As regards the materials, the steel resulted highly impacting (70–88%) in all impact categories, except in abiotic depletion elements (20%). In fact, despite the low weight with which these materials are present in the machine, lead batteries of the UPS make up 60% of the impact and aluminium about 17%. The copper, on the other hand, shows its greatest contribution to eutrophication (about 25%) and acidification (20%) potentials (Table 3).

After 15 years, the food equipment is disposed: in Table 4, the environmental impact is reported to the functional unit and is expressed in the different materials categories considering the European incineration, landfill and recycling percentages shown in Table 1. Since the study is based on the EcoInvent allocation cut-off by classification database, the recycling process resulted as an empty process: for example, the lead batteries have no environmental impact in this phase, because they are recycled up to 100% according to regulations (Table 1).

The disposal impacts, if compared to the impact of raw materials production (Table 3), are practically negligible (<1%).

3.2. Impact of the equipment use phase

The electricity is responsible for 40–70% of the impact on eutrophication, acidification, photochemical oxidation and global warming potentials (Table 5). This result is in line with other studies available in the literature (Roibása et al., 2018). The process steam has also an important impact: up to 30% on the ozone layer depletion, abiotic depletion of fossil fuels and global warming. Instead, H₂O₂ emissions have a zero impact on all categories and therefore
Table 3. Environmental impacts of the machine’s constituent materials.

| Impact category                     | Total     | Steel       | Plastics    | Copper    | Rubbers    | Glass       | Aluminium   | Others (Lead battery) |
|-------------------------------------|-----------|-------------|-------------|-----------|------------|-------------|-------------|-----------------------|
| Acidification [kg SO2 eq]           | 1.34E-03  | 9.89E-04    | 2.97E-05    | 2.44E-04  | 3.82E-06   | 1.49E-06    | 5.88E-05    | 8.94E-06              |
| Eutrophication [kg PO4 – eq]       | 4.52E-04  | 3.16E-04    | 6.19E-06    | 1.10E-04  | 1.10E-06   | 1.89E-07    | 1.56E-05    | 2.80E-06              |
| Global warming [kg CO2 eq]          | 1.96E-01  | 1.75E-01    | 7.31E-03    | 2.42E-03  | 7.59E-04   | 1.68E-04    | 1.00E-02    | 4.13E-04              |
| Photochemical oxidation [kg NMVOC]  | 8.25E-04  | 7.07E-04    | 2.35E-05    | 5.37E-05  | 3.57E-06   | 8.38E-07    | 3.39E-05    | 2.26E-06              |
| Abiotic depletion, elements [kg Sb eq] | 3.43E-05  | 6.62E-06    | 4.08E-08    | 1.64E-06  | 2.94E-07   | 4.83E-09    | 5.71E-06    | 2.00E-05              |
| Abiotic depletion, fossil fuels [MJ] | 2.04E+00  | 1.79E+00    | 1.05E-01    | 2.41E-02  | 2.06E-02   | 1.78E-03    | 9.58E-02    | 7.31E-03              |
| Water scarcity [m3 eq]              | 3.31E-02  | 2.41E-02    | 3.61E-03    | 2.04E-03  | 4.70E-04   | 3.54E-05    | 2.55E-03    | 2.64E-04              |
| Ozone layer depletion [kg CFC-11 eq]| 9.22E-09  | 8.41E-09    | 6.69E-11    | 1.31E-10  | 1.51E-10   | 1.65E-11    | 4.10E-10    | 3.44E-11              |

they do not appear in the histogram despite being present in the legend. The use of hydrogen peroxide to sterilize preforms impacts up to 25% on water scarcity and abiotic depletion elements but has a low impact (5–10%) on the other categories (Figure 3).

Figure 4 illustrates that the most important impact contribution in CIP, SIP, COP and SOP processes is given by process steam for 6 impact categories out of 8, except for the abiotic depletion elements (where caustic soda has a contribution of 49%, while it varies from 4% to 26% for the other categories) and water scarcity (where treated water contribute to 60% of the impact). The contribution of the filtered steam is about 20% on average, while is 10% for the electrical power.

3.3. The overall impact of the system

Based on the previously explained impacts, in this paragraph the overall system’s impacts are resumed (Table 4) considering the following life cycle stages:

Table 4. Environmental impact of the materials disposal.

| Impact category                     | Total     | Steel & copper | Plastic & rubber | Aluminium | Glass |
|-------------------------------------|-----------|----------------|------------------|-----------|-------|
| Acidification [kg SO2 eq]           | 7.23E-07  | 1.80E-07       | 5.07E-07         | 2.99E-08  | 6.52E-09 |
| Eutrophication [kg PO4 – eq]       | 2.33E-06  | 3.24E-08       | 2.29E-06         | 3.96E-09  | 1.16E-09 |
| Global warming [kg CO2 eq]          | 1.75E-03  | 2.08E-05       | 1.73E-03         | 2.45E-06  | 7.19E-07  |
| Photochemical oxidation [kg NMVOC]  | 8.07E-07  | 2.23E-07       | 5.52E-07         | 2.42E-08  | 8.56E-09  |
| Abiotic depletion, elements [kg Sb eq] | 7.27E-10  | 1.00E-10       | 5.96E-10         | 2.76E-11  | 2.95E-12  |
| Abiotic depletion, fossil fuels [MJ] | 1.05E-03  | 5.89E-04       | 3.87E-04         | 5.07E-05  | 2.34E-05  |
| Water scarcity [m3 eq]              | 5.19E-05  | 2.71E-05       | 2.44E-05         | 2.96E-07  | 6.75E-08  |
| Ozone layer depletion [kg CFC-11 eq]| 2.05E-11  | 7.03E-12       | 1.26E-11         | 5.81E-13  | 2.95E-13  |
Table 5. Numerical impacts of the consumption during the equipment use phase.

| Impact category                          | Total   | City water | Filtered culinary steam | Process steam (recovery) | Gas nitrogen | H$_2$O$_2$ 35% | Treated water | PAA 15% | Electrical power (Bloc + blower + compressor) | Compressed Air | Chilled water | Pump energy for steam recovery |
|------------------------------------------|---------|------------|--------------------------|--------------------------|--------------|-----------------|---------------|---------|-----------------------------------------------|----------------|---------------|---------------------------------|
| Acidification [kg SO2 eq]                | 4.11E-02| 2.19E-05   | 1.80E-04                 | 7.18E-03                 | 9.62E-04     | 1.85E-03        | 5.96E-05     | 1.63E-04| 2.41E-02                                       | 5.70E-03       | 9.05E-04     | 2.64E-05                        |
| Eutrophication [kg PO4 – eq]             | 2.52E-02| 1.24E-05   | 3.19E-05                 | 1.27E-03                 | 7.02E-04     | 8.81E-04        | 3.37E-05     | 5.74E-05| 1.76E-02                                       | 3.98E-03       | 6.61E-04     | 1.92E-05                        |
| Global warming [kg CO2 eq]               | 9.92E+00| 4.01E-03   | 6.45E-02                 | 2.58E+00                 | 2.06E-01     | 5.34E-01        | 1.09E-02     | 3.63E-02| 5.15E+00                                       | 1.13E+00       | 1.94E-01     | 5.64E-03                        |
| Photochemical oxidation [kg NMVOC]        | 2.12E-02| 1.08E-05   | 1.06E-04                 | 4.26E-03                 | 4.67E-04     | 1.38E-03        | 2.92E-05     | 1.40E-04| 1.17E-02                                       | 2.71E-03       | 4.39E-04     | 1.28E-05                        |
| Abiotic depletion, elements [kg Sb eq]   | 3.95E-05| 4.25E-08   | 3.25E-08                 | 1.30E-06                 | 7.32E-07     | 1.01E-05        | 1.15E-07     | 6.74E-07| 1.61E-05                                       | 9.80E-06       | 6.04E-07     | 1.76E-08                        |
| Abiotic depletion, fossil fuels [MJ]      | 1.21E+02| 4.55E-02   | 9.16E-01                 | 3.66E+01                 | 2.30E+00     | 8.05E+00        | 1.24E-01     | 8.39E-01| 5.77E+01                                       | 1.26E+01       | 2.17E+00     | 6.31E-02                        |
| Water scarcity [m3 eq]                   | 4.29E+00| 3.08E-01   | 5.31E-04                 | 2.12E-02                 | 3.14E-01     | 1.27E+00        | 8.36E-01     | 5.44E-02| 1.17E+00                                       | 2.68E-01       | 4.38E-02     | 1.28E-03                        |
| Ozone layer depletion [kg CFC-11 eq]     | 1.15E-06| 4.60E-10   | 7.88E-09                 | 3.15E-07                 | 2.32E-08     | 6.36E-08        | 1.25E-09     | 6.94E-09| 5.81E-07                                       | 1.27E-07       | 2.18E-08     | 6.36E-10                        |
- Machine’s raw materials extraction and production
- Production consumption during the use phase, considering steam recovery and European electricity
- CIP, SIP, COP, SOP consumption during use phase (every 162 h; manual foaming of the blower every 4 weeks)
Materials end of life according to the European percentage of recycling, landfilling and incineration.

As can be seen from Figure 5, the main impact (95%) in all categories is due to the consumption during the use phase. As mentioned in the introduction, there are no available studies in the scientific literature that analyse a similar topic, however results are in line with works focused on different equipment for cooking (Favi et al., 2018) and with the Environmental Product Declaration of food machines (Ecolean, 2016).

For abiotic depletion, due to the lead acid batteries, 46% of the impact is given by the raw materials extraction and production. In the other categories, despite the large amount of steel making up the machine, the materials have on average an impact of less than 1% of the total.

The same result applies to the impact of cleaning and sterilization consumption.

Now, it is clear where it is necessary to focus the efforts to reduce the overall environmental impact of a similar food machine: the consumption during production must be reduced. Some possible improvements can be implemented, for example, the

Table 6. Overall impact of the machine divided in the four phases.

| Impact category         | Unit          | Total impact | Raw materials extraction and production | Production consumption | CIP SIP COP SOP | Materials end of life |
|-------------------------|---------------|--------------|-----------------------------------------|-------------------------|-----------------|-----------------------|
| Acidification           | kg SO₂ eq     | 4.32E-02     | 1.34E-03                                | 4.11E-02                | 7.55E-04        | 7.23E-07              |
| Eutrophication          | kg PO₄ eq     | 2.60E-02     | 4.52E-04                                | 2.52E-02                | 3.25E-04        | 2.33E-06              |
| Global warming          | kg CO₂ eq     | 1.03E+01     | 1.96E-01                                | 9.92E+00                | 2.15E-01        | 1.75E-03              |
| Photochemical oxidation | kg NMVOC      | 2.24E-02     | 8.25E-04                                | 2.12E-02                | 4.15E-04        | 8.07E-07              |
| Abiotic depletion, elements | kg Sb eq | 7.45E-05     | 3.43E-05                                | 3.95E-05                | 7.13E-07        | 7.27E-10              |
| Abiotic depletion, fossil fuels | MJ | 1.26E+02 | 2.04E+00                                | 1.21E+02                | 2.85E+00        | 1.05E-03              |
| Water scarcity          | m³ eq         | 4.45E+00     | 3.31E-02                                | 4.29E+00                | 1.25E-01        | 5.19E-05              |
| Ozone layer depletion   | kg CFC-11 eq  | 1.19E-06     | 9.22E-09                                | 1.15E-06                | 3.38E-08        | 2.05E-11              |

Figure 5. Environmental impact [%] of the machine during the life cycle.
food industry could recover the steam used in the process. The steam recovery, in this specific case study, allows to reduce the greenhouse gases emission up to 6%, and a similar result could be obtained for the abiotic depletion, photochemical oxidation, ozone layer depletion and acidification potentials. Moreover, as regards the electrical power, a different energy mix that uses renewable resources, such as nuclear or photovoltaic, allows to lower up to 50% the water scarcity and 20% the global warming, photochemical oxidation and acidification potentials.

4. Conclusions

The principles of the circular economy ask companies to focus their attention on the end-of-life of their products, trying to enhance reuse or recycling. In addition, they are also asked to rethink their processes and machines, making them less impacting on the environment and more efficient to reduce waste. However, to date, there are no available studies in the scientific literature that analyse if the disposal phase of a food machine has a high impact in comparison with the others life cycle stages.

On these bases, the present study aimed not only to assess the environmental impact of a mechanical equipment during its life cycle, but also to investigate which is the main hotspot on which act to reduce the overall impacts. An aseptic bottling system, which sterilizes preforms with hydrogen peroxide and then blows and fills bottles with sparkling or still drinks, was chosen as a case study for the analysis. A Life Cycle Assessment was carried out by following the references of the ISO 14,040 series. Primary data were collected, however, as a limitation of the study, it must be noticed that the material’s type and quantity of small components were only estimated, because of the great amount of components and time needed.

Results showed that, for materials’ extraction and production, the large amount of steel present in the machine is the main cause of greenhouse gas emissions, acidification and eutrophication potential, while the lead batteries are the main cause of abiotic depletion elements. In the use phase, the electricity consumption is responsible for up to 70% of the total impacts, followed by the process steam, both during the production and the sterilization or cleaning cycles. Overall, by comparing the impacts of the equipment life cycle phases, the use phase has an impact up to 98% on acidification, eutrophication, global warming, water scarcity and ozone layer depletion potentials. The impact of the end of life, on the other hand, is almost negligible (<1%) when compared with the use phase. Therefore, to reduce the overall impact of a food machine, it is suggested to act mainly on the use phase, optimizing consumption, using renewable sources, or by means of energy recovery systems (e.g. steam condensate recovery). Only as a last resort, it can be useful to act on the materials’ selection and disposal, in order to reduce the overall environmental impact of the machine.

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Data availability

Data used in this article are primary data given by the company. Sensitive data have not been deliberately reported in the article for privacy reasons.

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Authors contribution

All authors contributed to the study. Data collection: Barbara Bricoli; Methodology: Roberta Stefanini; Formal analysis and investigation: Roberta Stefanini; Original draft preparation: Roberta Stefanini; Review and editing: Giuseppe Vignali and Barbara Bricoli; Supervision: Giuseppe Vignali. All authors read and approved the final manuscript.

Ethics approval

The article involves no studies on human or animal subjects.

Consent to participate

The authors consent to participate.

Consent for publication

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