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Multiuse Polystyrene Plates for Phasing Out Single-Use Plastics: Chemical Performances and Environmental Impact Assessment Through a Life Cycle Approach

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European governments are addressing plastic pollution by implementing the Directive EU 2019/904 that bans single-use items like cutlery, plates, straws, and beverage stirrers. One strategy proposed by several industries to continue their production is the conversion of single-use items into multiuse items. Herein, the focus is on the production of polystyrene reusable plates and the suitability of this product for microwave and dishwasher use is assessed: in proper conditions, the structure is preserved without cuts or visible deformations, and the chemical stability is guaranteed. To get a full picture of the benefits and impacts of this new product, a life cycle assessment methodology is applied to compare the performances of one reusable plate with 20 single-use plates. Results indicate that proper use is crucial: a reusable plate disposed after one use is more impactful than a single-use plate. In contrast, the reuse of plates for 20 times allows to reduce carbon footprint and acidification potential. Eutrophication and ozone layer depletion, on the other hand, increase due to the washing phase. The solutions that can mitigate these issues and enhance the sustainability of the reusable plates include the improvement of the detergent compositions and the use of electricity from renewable sources.

1. Introduction

Plastics are widely employed as packaging materials in numerous sectors like pharmaceutical, food, and detergent, owing to their well-established benefits like safety, ease of processing, lightweight, storage convenience, and cost-effectiveness.[1] Nevertheless, there are numerous concerns regarding their usage and disposal. The main issues include the accumulation of waste in landfills and natural habitats, adverse effects on organisms due to ingestion or entanglement with micro and macroplastics,[2,3] and the release of low-molecular-weight compounds, such as additives, residual monomers, and oligomers.[1,4] To address the challenges associated with plastic materials, the European Union (EU) is actively promoting sustainable alternatives. In 2019, the EU approved a Directive aimed at prohibiting certain single-use plastics. In particular, the Directive regards the most common plastics found in the marine litter[5–7]: plates, cutlery, straws, cotton buds, balloon sticks, drink stirrers, food and beverage containers made of expanded polystyrene (PS), oxo-degradable plastic products. Numerous single-use plastic items, including plastic bottles and their caps, plastic bags, cigarette butts, wet wipes, and sanitary products, lack viable alternatives, making unfeasible a complete ban. Instead, the Directive seeks to reduce their usage by implementing a proper waste management and promoting awareness of the environmental impacts caused.

The Directive EU 2019/904 bans both single-use petroleum-based plastics and bioplastic products. Bioplastics include 1) polymers derived from microorganisms such as

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polyhydroxyalkanoates; 2) biodegradable polymers that can derive from fossil resources as well as renewable resources such as polylactic acid (PLA), polycaprolactone (PCL), poly(butylene succinate) (PBS); and 3) bio-based polyolefins such as bio-poly (ethylene terephthalate) (bioPET) and bio-polyethylene (bioPE), which are non-biodegradable bioplastics that have the same end of life of their non-renewable counterparts. The European Directive treats "bioplastics" in the same way as conventional plastics because "there are no widely agreed technical standards available to certify that a specific plastic product is properly biodegradable in the marine environment in a short time span and without causing harm to the environment".[8] While the toxicity aspects of bioplastics on living organisms are not yet sufficiently studied, there is a wealth of literature on their environmental impacts, typically assessed through Life Cycle Assessment (LCA) studies. The LCA is a useful tool for assessing the environmental performances and impacts of production processes or activities throughout the entire life cycle, comprising extraction of raw materials, production, distribution, use, end of life.[9–12] LCA has been successfully applied for studying the impacts of several materials such as food products, lignocellulosic materials, glass and plastic.[13–16] Razza et al.[17] used LCA to compare the environmental impacts of biodegradable, compostable and pure plastic cutlery. Bioplastic cutlery, if disposed with organic waste and then composted, has a lower impact than the general-purpose polystyrene (GPPS) cutlery sent in landfill or incinerated with the food waste. Another LCA report considered plates made of GPPS, poly-coated paperboard, molded bleached pulp and PLA.[18] PLA has the lowest carbon footprint, but the highest energy requirement, followed by pulp, LDPE paperboard (heavy-duty), GPPS (heavy-duty), LDPE paperboard (lightweight) and GPPS (lightweight). PLA plates have significant greenhouse gas emissions (GHG) due to the nitrous oxide emissions associated with the use of fertilizers, the highest water use and in terms of weight, GPPS products are low density and are lighter than PLA products. In a study[19] commissioned by Pro. Mo (an Italian industry association), four disposable dishes in polypropylene (PP), PS, PLA, and cellulose were compared with reusable porcelain flat dishes (the porcelain dishes were assumed to be used for maximum 1000 uses before disposal in landfill). Reusable porcelain dishes have lower impact compared to single-use dishes except for water resource use. An intermediate situation between porcelain dishes and single-use plastic products is represented by reusable plastics. The environmental footprints of two kinds of trays, one of reusable PP and the other one of compostable bagasse were compared in terms of greenhouse gas contribution, energy consumption, material waste, and water consumption.[20] The single use of 15 compostable trays results in a greater environmental impact in terms of GHG emissions, energy consumption, and material waste, compared to the reuse of a PP tray 15 times. The water consumption for the PP trays is higher compared to the compostable trays because of the washing phase. The replacement of single-use items with reusable plastics is presently the most common approach used by several industries to continue their production and reduce plastic pollution. Currently, plastic reusable products are mainly made in PP that has a recycling rate higher than other plastic alternatives. As public awareness of the importance of recycling rises, demand for PP is expected to grow accordingly and several packaging manufacturers are currently deselecting certain materials like PS and polyvinyl chloride (PVC). However, for certain applications, PS has a better rheological behavior than PP, and numerous changes in the industrial plants are needed for the conversion from PS to PP or other non-fossil-based materials. In this transition phase, we believe that PS reusable plates can be a good alternative, and companies can have more time and funds to convert their plants. The reusability of PS plates is a first step to adhere to the principles advocated by the waste management perspective, i.e., the five Rs "reduce, reuse and recycle, recovery and redesign".[4] Since multiuse helps reduce the petrochemical sources and waste production, in this work, we optimized the conditions of use (microwave and dishwasher suitability) and estimated the environmental impacts of reusable PS flat dishes. After identifying the optimal conditions of use, we tested mechanical properties and chemical composition of the plates. The mechanical properties were measured through a dynamometer Instron. The chemical composition was evaluated through nuclear magnetic resonance (NMR), Fourier-transform infrared spectroscopy (FTIR) with attenuated total reflection (ATR) and gas chromatography with flame-ionization detection (GC-FID). FTIR and GC-FID were mainly used to verify the migration of the monomer styrene or the inorganic layer embedded in the polymeric blend. The control of the chemical migration and the surface aspect are necessary to keep consumer health safe. Once verified the chemical stability, we carried out a life cycle assessment study (LCA) to assess the environmental impact of this new product and compare the results with the former single-use products. The steps for the environmental impact assessment are outlined in the graphical abstract presented in **Figure 1**. The reference flows are 1 PS plate reusable for 20 times and 20 single-use PS plates. The environmental impact categories chosen are global warming, acidification, eutrophication, and ozone layer depletion.

2. Results and Discussion

2.1. Optimization for Microwave Heating and Dishwasher

Initially, reusable plates were subjected to 20 uses in a microwave oven (with lasagna as food, according to the test methods described in AR/2013/067/B Chapter 1 and UNI EN 15 284:2008[21]) and 20 uses in dishwasher. The food was heated for 2 min and with a power of 750 W. The plates were washed with 25 mL of a commercial surfactant with an intensive program that includes a temperature of 65 °C, a duration of 2 h and fifty minutes, the use of 16 L of water per cycle and a consumption of 1.60 kWh per cycle. The plates start to deform mechanically at the first use in microwave; after several uses and washings, the deformations become more relevant with several cuts, spots of sauce, and cancellation of the dotted structure of the plate as it can be seen in **Figure 2**a. The conditions of use were optimized by changing dishwasher and microwave oven settings. To avoid mechanical degradation, microwave was used just once at lower powers: 300 W for 2 min, 450 W for 1 min, or 600 W for 30 s. In addition to lasagna, we explored the microwave compatibility of the plates with other foods, namely vegetables

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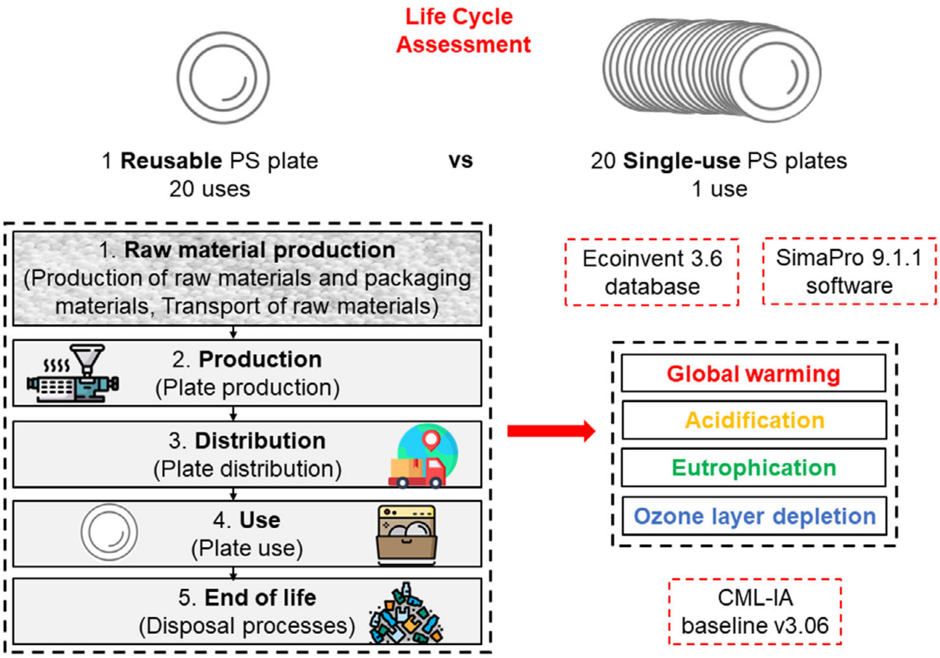

Figure 1. Graphical abstract with the key components of the LCA study.

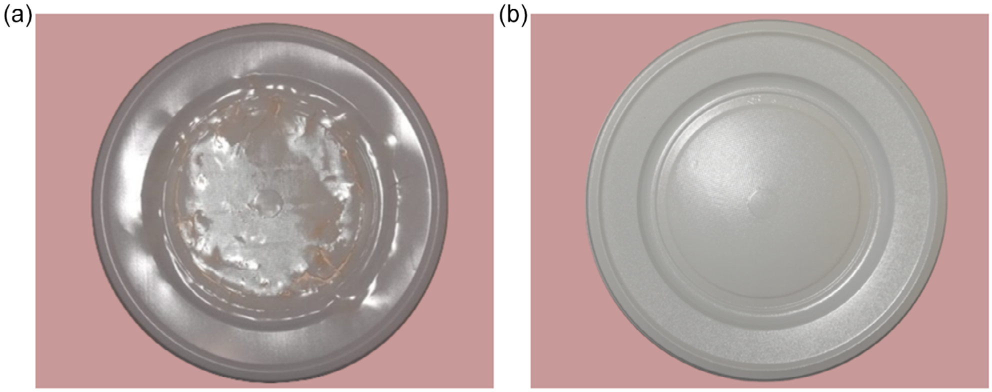

Figure 2. Picture of a reusable PS plate after: a) 20 uses in a microwave oven (heating lasagna at 750 W for 2 min) and 20 uses in dishwasher; b) 1 use in a microwave oven (heating lasagna at 600 W for 30 s) and 20 uses in dishwasher.

and pizza, broadening the scope of our study. The kind of food was varied based on the temperature ranges achieved during warming, heating, and/or cooking as indicated in ref. [22]. Based on temperature range, lasagna is classified as category 4, temperature 170–220 °F (77–104 °C); vegetables such as broccoli and cauliflower are category 2 and have a temperature range of 130–180 °F (54–82 °C); and pizza is included in category 3 and has a temperature range 160–205 °F (71–96 °C).

The plates were then subjected to 20 uses in dishwasher with 25 mL of a commercial surfactant and a normal program that includes a temperature of 50 °C, a duration of 1 h and 30 min, implying the use of 13 L of water and a consumption of 1.15 kWh per cycle. The plates maintain their appearance without cuts or noticeable deformations when tested with various foods at low power settings (Figure S1–S3, Supporting Information, for the appearance of the plates before and after the food contact, respectively, for lasagna, vegetables, and pizza) and after cleaning. Therefore, the ideal and reproducible conditions revealed from our experiments are: one use with microwave heating at low-power levels (300, 450, or 600 W) and 20 normal washing cycles. Subsequently, plates were analyzed mechanically to notice the different behavior according to the number of uses. The plates are made of high-impact polystyrene (HIPS) and GPPS. HIPS is an immiscible polymer blend comprising polybutadiene rubber particles embedded in a PS matrix. PS homopolymer is inherently stiff but brittle, and the presence of rubber particles yields a tough material with a good stiffness. When subjected to stress, the rubber inclusions induce plastic deformations in the matrix, absorb energy through the formation of crazes or shear bands, each of which extends to an adjacent

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rubber particle before terminating. **Figure 3** reports the stress–strain curves for the plates at different conditions of use (a rectangular piece of plate was cut for each measurement). The shape of the stress–strain curves is typical of HIPS. **Table 1** resumes the elastic modulus, the yield strength, and the elongation at break for the plate at time 0 and the plates after use. The main difference is related to the elongation at break that is reduced after the microwave oven and to a less extent after the use of dishwasher.

2.2. Concentration of Styrene Monomer and Global Migration

Plates after 20 uses in microwave and dishwasher were analyzed chemically to calculate the concentration of styrene monomer. According to the GC measurements (chromatogram shown in Figure S4, Supporting Information), the concentration of styrene monomer is almost the same at time 0 and after 20 uses (styrene concentration expressed as the amount of monomer released from plate is [styrene] $= 0.11 \pm 0.01\ \mathrm{mg\,g^{-1}}$ of plate). This concentration is lower than the amount of styrene monomer in PS containers found in the samples described in ref. [1] ([styrene] $= 0.230\ \mathrm{mg\,g^{-1}}$) and ref. [23] ([styrene] $= 0.224\ \mathrm{mg\,g^{-1}}$). Our results show that the microwave and dishwasher for the time used are not responsible for the chemical degradation of PS into the corresponding monomer and the main deformations are mechanical. We also investigated the global migration of the inorganic charge with simulant B, acetic acid 3% w/v, commonly used to extract hydrophilic substances especially inorganic salts from food contact materials (UNI EN 1186-1[24]). After 20 uses in dishwasher, the plates were filled with 200 mL of simulant B and left in a drying oven for 2 h at 70 °C. The simulant was then left evaporated, and the amount of powder remained was weighted and divided by the area of contact. The amount of inorganic charge is higher compared to the original plate: the deformed plate has an average global migration of $3\ \mathrm{mg\,dm^{-2}}$, while the initial plate has a global migration below the quantification limit of $1.3\ \mathrm{mg\,dm^{-2}}$; however, both the values are below the legal limit of $10\ \mathrm{mg\,dm^{-2}}$.[25] Although the slight difference of migration, most of the inorganic filler remains in the second layer as demonstrated from the ATR-FTIR measurements: the peaks of the inorganic charge are only visible if the top layer of PS is dissolved with few drops of methylene chloride (**Figure** 4b), while the ATR-FTIR spectrum of a deformed plate only shows the peaks related to PS (Figure 4a) and resumed in **Table 2** (the assignments are based on refs. [26,27]).

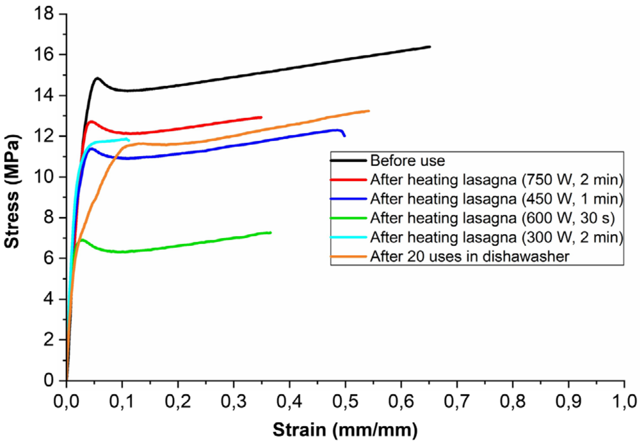

Figure 3. Stress–strain curves for reusable PS plates. (-) Plate before use. (-) Plate after heating lasagna at 750 W 2 min. (-) Plate after heating lasagna at 450 W 1 min. (-) Plate after heating lasagna at 600 W 30 s. (-) Plate after heating lasagna at 300 W 2 min. (-) Plate after 20 uses in dishwasher.

Table 1. Mechanical properties of the reusable PS plates.

Sample	Elastic modulus [MPa]	Yield strength [MPa]	Elongation at break [%]
Plate before use	390	14.8	65
Plate with lasagna at 750 W 2 min	366	12.7	35
Plate with lasagna at 600 W 30 s	403	6.90	37
Plate with lasagna at 450 W 1 min	596	11.4	45
Plate with lasagna at 300 W 2 min	514	7.5	43
Plate after 20 uses in dishwasher	394	11.6	54

2.3. Life Cycle Impact Assessment (LCIA)

The potential impacts have been calculated for the functional unit (i.e., the use of a PS plate for 20 meals). Four environmental indicators have been selected: global warming (GWP), acidification potential (AP), eutrophication potential (EP) and ozone depletion potential (ODP). Regarding uncertainty, a 5% margin is deemed acceptable for the four categories, as established in a prior LCA study focused on single-use PS plates.[19] The results obtained highlight a reduced impact for the reusable plates, $0.867\ \mathrm{kg\ CO_2eq}$, compared to the single-use option, $1.499\ \mathrm{kg\ CO_2eq}$ (**Figure** 5a). For the reusable plate the hotspot of process regards the washing of the plate that represents the 89% of the emissions. In the single-use plate, the production phase is the most impactful factor (63%), followed by the end of life (19%). The reusable plate allows to reduce by 93% the consumption of the raw materials (plastic and additives) and consequently the production of waste and the end of life. Although the reusable plates allow the reduction of the raw materials, the phase use can give non negligible environmental impacts. It is worth considering that the actions to reduce the emissions during the use are more viable than the replacement of the raw materials. For example, the use of electric energy from renewable sources could allow to reduce the emissions by almost 70%: the category GWP has been calculated using a residual mix energy (dataset for Italian residual mix available from ecoinvent database) and compared with the electric energy produced from solar panels in Italy. The GWP for residual mix energy is 0.867 kg of $\mathrm{CO_2eq}$ compared to 0.279 kg of $\mathrm{CO_2eq}$ for the electric energy produced from solar panels, the relative difference between the two electric sources is $\Delta = 68\%$.

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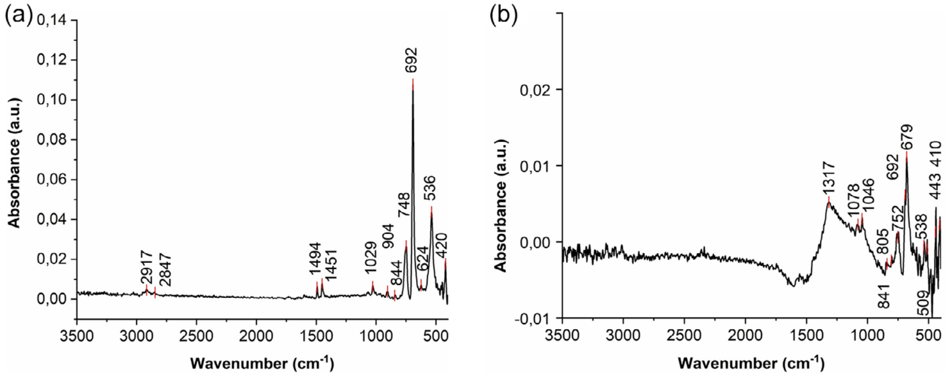

Figure 4. a) ATR-FTIR spectrum of a reusable PS plate after 20 uses in dishwasher, b) ATR-FTIR spectrum of a reusable PS plate slightly dissolved in methylene chloride.

Table 2. Main absorption bands of a polystyrene plate after 20 uses.

Absorption bands [cm^{-1}]	Assignment
2917	C–H stretch
2847	C–H stretch
1494	Aromatic ring stretch
1451	CH_2 bend
1029	C–C deformation in linear alkanes
904	C–C deformation in linear alkanes
844	C–H deformation out of plane
748	C–H deformation out of plane
692	Aromatic C–H out of plane bend
624	C–H deformation out of plane
536	Aromatic ring out of plane bend and C–C in alkane skeletal linear

Different results are due to the different sensibility to the process inputs. The GWP and AP indicators clearly demonstrate that the reusable alternative is less impacting compared to the single use: the relative difference is 42% for GWP and 20% for AP (Figure 5a,b). The hotspots of the process regard the phase of use for the reusable plate and the use of raw materials for the single-use plate. The EP and ODP highlight a different trend with the single-use less impacting than the reusable plate (Figure 5c,d). The relative difference between the two alternatives is 88% for EP and 51% for ODP. In both cases, the high impact derives from the use (washing) responsible for 99% and 97% on the total emissions. **Figure 6** shows the details of the use phase and the percentage contribute of each variable. Most of the emissions is due to the electric energy; only for EP the soap used is the factor that gives the greatest impact (the details of the soap composition are reported in the Table S1, Supporting Information). The EP is related to the fertilizers necessary for the cultivation of palm and coconut from which the surfactants of formulations are extracted. Eco-friendly detergents with minimal or no palm oil content could serve as a solution to minimize EP.

In order to mitigate the disadvantages of reusable plates, two alternatives were explored: reducing the functional unit and modifying the washing program. The results obtained from the decrease of functional unit from 20 to 10 uses are detailed in the supporting information (Figure S5–S7, Supporting Information). All the four impact categories are reduced with a minor number of uses; however, EP and ODP are still high compared to the single-use plates. The use of an eco-program for the cleaning of the plates leads to a reduction of all impact categories (the variation is 13.7%, 15.4%, 3.56%, and 17.1%, respectively, for global warming, acidification, eutrophication, and ozone layer depletion), due to a minor consumption of electric energy and water for the same amount of soap. Although GWP and AP indicators decrease, EP and ODP remain elevated in comparison to the single-use products. The results for all the scenarios are summarized in **Table 3**.

The proper use of reusable plates is necessary to effectively reduce resource appropriation along the life cycle of the product. If the reusable plates were employed as single-use items, the GWP value would be even greater. **Figure 7** shows the results of the comparison between 1 reusable plate used 20 times, 20 reusable plates used once (which is the least desirable option), and 20 single-use plates. Reusable plates not properly employed lead to an increase of the 50% of the environmental impacts compared to the scenario of the correct use and an increase of 20% compared to 20 single-use plates. The major impacts are due to a major use of nonrenewable raw materials, an increase in the production of waste and the emissions for the end of life.

3. Conclusion

Reusable plates in PS can represent a valid option for the industries after the ban of single-use plastics in the EU countries. The reusable option is interesting from the industrial standpoint, since it enables to “gain time” before the development of new technologies and the transition towards proper renewable sources. The ideal use of the plates tested is one heating with microwave at 300 W for 2 min, 450 W for 1 min, or 600 W for 30 s and maximum 20 washes. In these conditions, the plates slightly deform mechanically (as demonstrated from the stress–strain curves) without presenting scratches or cuts. The plates are chemically stable, and the concentration of monomer styrene does not change after the uses and the migration of the inorganic

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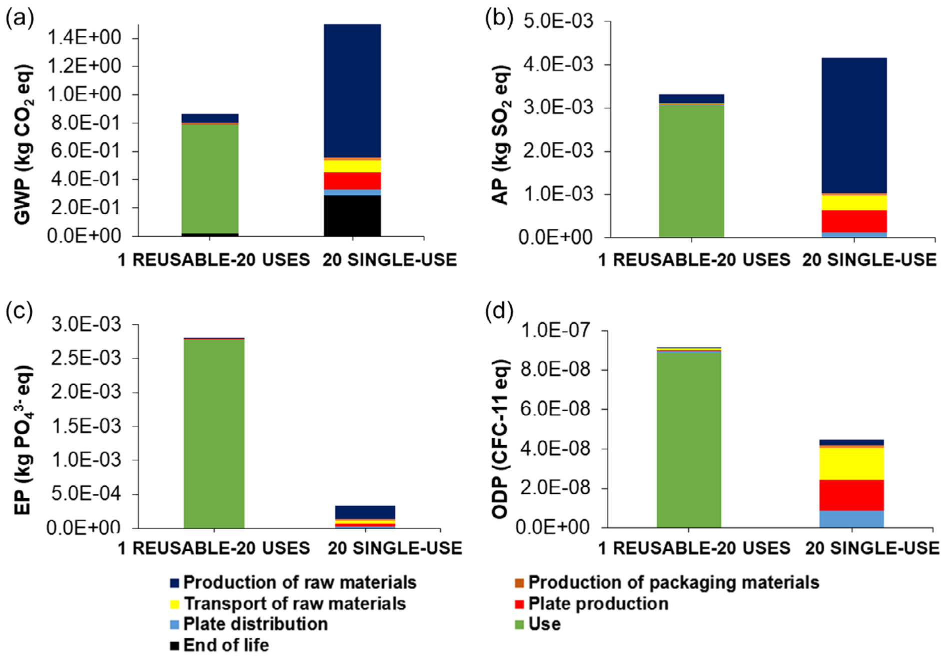

Figure 5. LCA results and comparison between two scenarios:1 reusable plate-20 uses and 20 single-use plates. The impact categories considered include a) global warming, b) acidification, c) eutrophication, and d) ozone layer depletion. The stages that contribute to the impact categories are production of raw materials, production of packaging materials, transport of raw materials, plate production, plate distribution, use, and end of life.

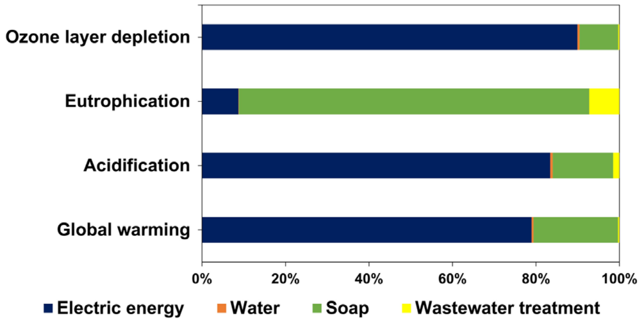

Figure 6. Percentage contribution of electric energy, water, soap, and wastewater treatment to the impact categories selected (use stage for 1 reusable plate after 20 uses).

charge are slightly superior for the reusable plate but below the legal limit of migration. The LCA study demonstrates that the reusable plates are less impacting than single use for two

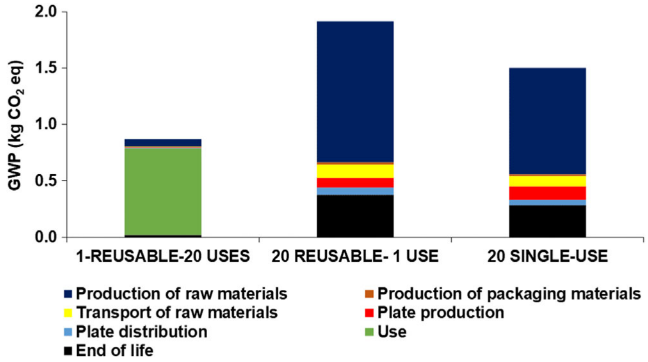

Figure 7. Comparison of global warming potential among 1 reusable plate (after 20 uses), 20 reusable plates (20 reusable plates discarded after 1 use), and 20 plates single use (traditional plates discarded after 1 use). The life cycle stages analyzed are production of raw materials, production of packaging materials, transport of raw materials, plate production, plate distribution, use, and end of life.

Table 3. Results of the four indicators.

	Global Warming (GWP) [kg CO_2eq]	Acidification (AP) [kg SO_2eq]	Eutrophication (EP) [kg PO_4^{3-}eq]	Ozone layer depletion (ODP) [kg CFC-11eq]
Reusable plate (20 uses with dishwasher normal program)	0.867	3.32×10^{-3}	2.81×10^{-3}	9.14×10^{-8}
Reusable plate (10 uses with dishwasher normal program)	0.482	1.79×10^{-3}	1.41×10^{-3}	4.69×10^{-8}
Reusable plate (20 uses with dishwasher eco program)	0.748	2.81×10^{-3}	2.71×10^{-3}	7.58×10^{-8}
Single-use plate	1.50	4.17×10^{-3}	3.38×10^{-4}	4.48×10^{-8}

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categories: GHG and acidification. The emissions produced during the use of the reusable plates are the hotspots of the process and are mainly due to the electric energy consumption and soap for the dishwasher. The use of renewable sources for the electric energy could reduce the GWP indicator in this phase. Reusable plates allow a reduction of nonrenewable raw materials (PS and additives), even if the washing gives more emissions compared to the single use when the comparison regards other impact categories (EP, ODP). The proper use is a crucial factor to effectively gain an advantage in terms of resources and reduction of energetic consumptions during the use.

4. Experimental Section

Materials: PS plates were produced by the industry Aristea SpA (Battipaglia, SA, Italy). The plates were thermoformed and had a three-layer structure with the intermediate layer that includes a mineral filler. The plates with different kinds of foods were heated with a microwave oven Whirlpool MW 204 and washed with a Whirlpool WRIC 3C26PF dishwasher. Styrene monomer used as a standard for the calibration curves was purchased from Merck. The food simulant solution was prepared with acetic acid (Carlo Erba Reagents). Hexane (Carlo Erba Reagents) and methylene chloride (Carlo Erba Reagents) were used for the chemical analysis.

Gas Chromatography-Flame Ionization Detection (GC-FID): PS plates were cut and about 7 g were dissolved with methylene chloride, under stirring. Hexane was added in excess to the solution to enhance the precipitation of the polymer. The precipitated polymer was removed from the solution, and the clear supernatant was collected to measure the amount of styrene.[1] Styrene analyses were performed using an Agilent 7820A gas chromatograph equipped with a flame ionization detector. 1 μL of sample was injected in split mode with a split flow of 1.5 mL min^{-1}, and the separation was performed using a column DB Heavywax (30 m × 0.32 mm × 0.25 μm).[28] The GC oven temperature program was 40 °C (0.5 min), the ramp was 5 °C min^{-1} to 200 °C (hold time 4 min) for a runtime of 25.5 min and a post run of 2 min. The quantification was calculated from a calibration curve with model styrene at various concentrations.

Instron: Rectangular pieces, approximately 0.4 mm thick, 10 mm wide, and 50 mm long, were cut from the plates. These specimens underwent a tensile test at a strain rate of 5 mm min^{-1}. To mitigate potential damages at the gripping points, the ends of each specimen were covered with sandpaper and securely held in place using serrated chucks. The distance, l_0, between the two metal rods was 20 mm.

Attenuated Total Reflection-Fourier Transform Infrared: Plates were cut into rectangular shapes and analyzed with a Bruker Vertex 70 spectrometer equipped with a cell Specac's Gateway ATR Accessory Kit that contains a multireflection horizontal ZnSe accessory. The spectra were recorded in absorbance mode with a resolution of 2 cm^{-1} in the range of 400–4000 cm^{-1}.[29]

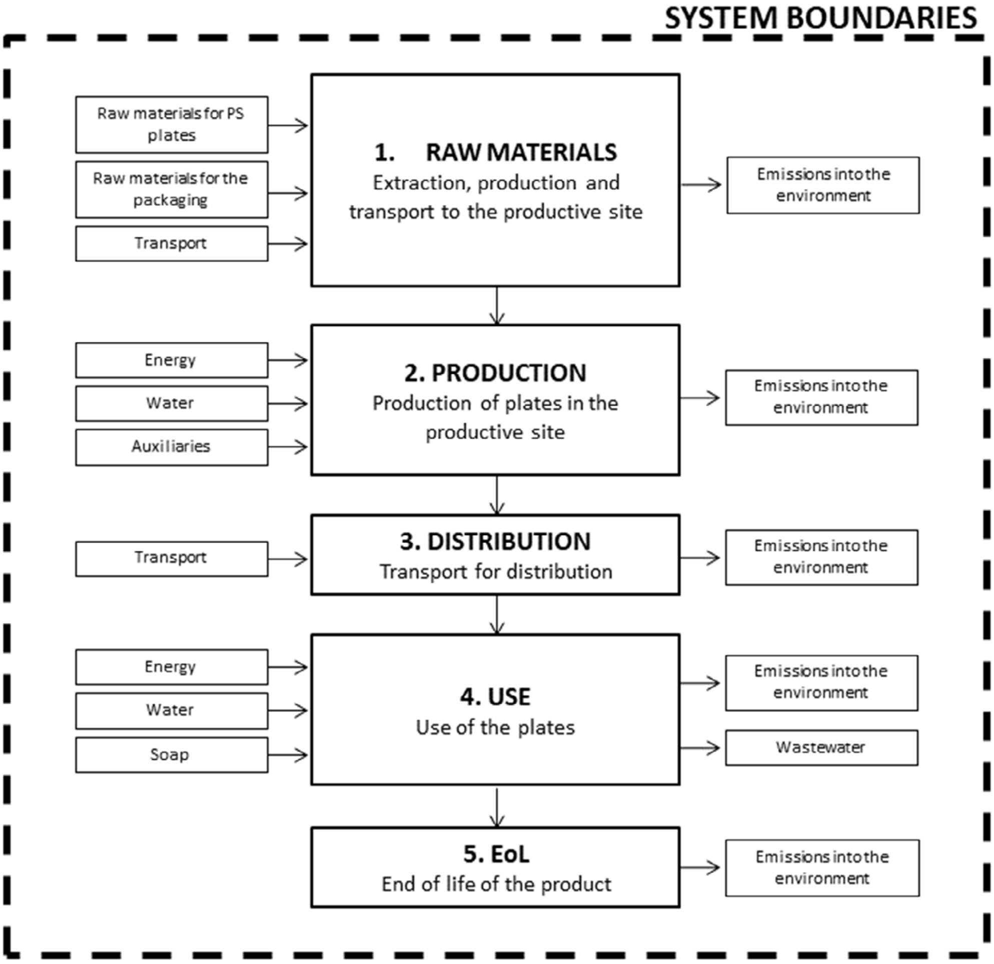

Figure 8. Boundaries of the system and phases of the process.

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Life Cycle Assessment: The study has been conducted using the database ecoinvent 3.6 to support the inventory analysis.[30,31] The model was developed with the software LCA SimaPro 9.1.1.[32] The calculation method, CML-IA baseline v3.06,[33] was used to estimate the four main categories required for communicative purposes of an Environmental Product Declaration (International EPD System, according to the ISO 14 025[34]): 1) the global warming potential (GWP, 100 year period); 2) the AP; 3) the EP; and 4) the ODP. The GWP or carbon footprint gives information about the emissions of climate-altering gases, and it is expressed in terms of tons of CO_2eq (carbon dioxide equivalent). The AP refers to the phenomenon by which the atmospheric precipitations have pH values lower than usual with harmful effects on the ecosystems (e.g., forests and vegetable crops, aquatic ecosystems) and products; the indicator is expressed in kg SO_2eq. The EP includes the impacts due to the high release of macronutrients in water, air and soils, and is expressed in kg PO_4^{3-}eq. The ODP is used to evaluate the effects associated with the reduction of the protective ozone layer in the stratosphere resulting from the release of ozone-depleting substances, including chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), and halons; this parameter is expressed in kg CFC-11 eq. These four categories, recommended by the ILCD Handbook as being of a more mature methodological level,[35] are the most common and internationally recognized and the most effective for the communication of the environmental profile of a product.

The LCA study was carried out following the four LCA phases[12,34]: 1) goal and scope definition; 2) life cycle inventory; 3) life cycle impact assessment; and 4) results interpretation. The first two phases are reported in this subsection, while the last two phases are discussed in Section 2. The scope is to compare the potential environmental impacts generated from the use of reusable PS plates compared to single-use PS plates. The functional unit of reference is the use of a PS plate for 20 meals; thus, the two reference flows are defined as: 1 plate in PS reusable for 20 times and 20 plates in PS single-use (the supporting information reports the results for a different functional unit: 1 plate in PS reusable for 10 times and 10 plates in PS single-use). The flowchart describes the boundaries of the system and the main phases of the process analyzed. The procedure adopted is “from cradle to grave” and includes the upstream processes to produce the raw materials and all the resources used until the end life of the product (EoL-end of life). The process analyzed has been divided into five main stages: 1) Production and transport of the raw materials regarding the product, the primary and secondary packaging. The PS plates are composed of more layers of different materials: GPPS, high molecular weight crystal PS; a middle layer of calcium carbonate; HIPS, high impact PS made of PS and polybutadiene; a white masterbatch, made of PS, titanium dioxide and pigments. The calcium carbonate and the masterbatch come from an Italian supplier. GPPS and HIPS, used in Aristea SpA, have different origins: 10% India, 10% China, 40% Germany, and 40% Italy. The origin of the packaging materials has not been considered because it is not relevant for the study; 2) Production of plates. This part includes the consumption of electric energy, water, and lubricants in the plant. The scraps represent almost the 25% of the material, which are recovered and remelted. The plates are packed in sets of 25 and 70 pieces (for reusable and single-use products, respectively) and then in cardboards for the delivery. The data of the electric energy consumption derive from inner controls and are referred to the amounts in output from the productive process; 3) Distribution including transport of the product from the plant to the customers. The scenario considers the transport of the product in Italy for 400 km; 4) Use (for the reusable plate), including the washing phase in a domestic dishwasher, for simplicity the use in a microwave oven was not considered; and 5) End of life including the disposal processes of the product at the end of its life. The end-of-life scenario has been prepared from the statistics related to the plastic disposal at national level.[36] **Figure 8** shows the system boundaries that include the activities with e nvironmental implications.

The waste produced during the productive process has not been considered because it is not relevant for this study. This form of LCA is useful and efficient to define solutions to optimize the integrated supply chain and the formulation of better choices in decision-making.

Considering all the processes within the boundaries of the system, quantitative data have been collected and related to the input to and output from every specific unit process. The LCA has been performed through the collection of primary data, modes of transport, distribution, and disposal scenarios. These data were provided from the business managers of the firm, literature, technical documents, and chemical analysis reported in this work. A Cut-off model was used to compare the potential environmental impacts generated from the use of reusable PS plates compared to single-use PS plates. In this model, wastes are under the producer's

Table 4. Materials and dataset used for the cycle inventory.

Material	Details	Dataset Ecoinvent v3.6
GPPS	High molecular weight crystal polystyrene	Polystyrene, general purpose {RER}| production | Cut-off, U
Calcium carbonate	Inorganic filler	Calcium carbonate, precipitated {GLO}| market for calcium carbonate, precipitated | Cut-off, U
HIPS	Blend of polystyrene and polybutadiene	Polystyrene, high impact {RER}| production | Cut-off, U
Masterbatch white	Polystyrene with titanium dioxide and pigments	Polystyrene, general purpose {RER}| production | Cut-off, U

Table 5. LCI for 1 plate in reusable PS and 20 PS single-use plates.

			Reusable plate	Single-use plate
Production of raw materials	Reference flux	g	18.5	280.00
	GPPS	g	1.50	22.76
	Calcium carbonate	g	2.01	30.35
	HIPS	g	14.04	212.42
	Masterbatch white	g	1.00	15.17
Production of the primary and secondary packaging	LDPE film	g	0.22	2.00
	Core board	g	0.71	11.81
Transport of the raw materials	Transport by boat	kgkm	35.74	540.92
	Transport by truck	kgkm	13.63	206.35
Production of the item	Energy	kWh	0.01	0.28
	Water	g	8.14×10^{-4}	1.23×10^{-2}
	Lubricants	g	3.43×10^{-6}	5.19×10^{-5}
Distribution of the finished product	Transport by truck	kgkm	7.79	117.80
Use of the product for 20 times	Electric energy	kWh	1.44	–
	Water	L	16.25	–
	Soap	g	31.25	–
End of life	Landfill	g	2.42	36.62
	Recycling	g	10.20	154.38
	Energy recovery	g	5.88	89.00

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responsibility (“polluter pays”), and recyclable products are available burden free. In this way, all the burdens are attributed to the user, and no benefits (from recycling of the PS plates) are attributed. **Table 4** reports the generic datasets selected for the various materials (the database ecoinvent does not contain the specific processes).

The inventory data elaborated in line with the choice of the functional unit are described in **Table 5**. The two kinds of plates (reusable and single use) are produced from the same industry, with the same raw materials and the same percentage weight composition. The main difference between the plates regards the total weight: the reusable plate is heavier than the single use (18.5 g vs 14 g). During production, electricity consumption per kg of disposable plate produced is higher because the machinery makes more moulds for the same weight of product (71 molds for single-use plates vs 54 molds for reusable plates).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Keywords

food contact materials, life cycle assessment, polystyrene, recycling, single-use plastics

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