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Life Cycle Assessment of reusable plastic containers throughout the fruit and vegetables supply chain

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Abstract: In the food packaging industry, waste, resource utilisation, and transport are critical issues that significantly influence the food supply chain footprint. Several studies evaluated the Life Cycle Assessment (LCA) of food packaging systems by comparing alternative materials and sizes, such as plastic, cardboard, and wood. This study illustrates the results of a LCA conducted on a novel reusable plastic container (RPC) for fresh products travelling within a logistic network made of growers, retailers, package manufacturers, and RPC poolers. It is based on an Italian country-wide distribution system of fruit and vegetables. The novel contributions of this research deal with the utilisation of primary data and the development of a multi-scenario analysis considering different packaging solutions, production recipes, and energy mix at the production plant.

Keywords: Life Cycle Assessment, Food packaging systems, logistic network, reusable plastic containers, digital twin

1. INTRODUCTION AND LITERATURE REVIEW

Global warming and climate change are critical challenges of our times. Urgent solutions must be found to address these issues, especially in the most impactful areas. Many food system activities produce greenhouse gases (GHGs) (Vermeulen et al., 2012). The food industry significantly contributes to climate change, considering production and distribution activities (Campbell et al., 2018). The packaging solution (PS) plays a crucial role. PS is a source of waste with a considerable environmental impact.

Recently, the European Directive (UE) 2019/904 aimed to prevent and reduce the impact of plastic products on the environment, notably by limiting the placement of single-use plastic products on the market. Introducing reusable plastic PSs can significantly reduce waste compared to single-use plastic (Greenwood et al., 2021).

However, the spread of such systems is limited due to the awareness and willingness of consumers and their doubts about the environmental impact (Ertz et al., 2017). For this reason, it is essential to conduct research studies focusing on measuring and comparing the environmental impacts of alternative packaging and distribution systems.

Previous studies proposed a comparison of the environmental impacts of alternative packaging solutions in the retailer food supply chain (FSC). In particular, some research contributions evaluated the environmental sustainability of reusable plastic containers (RPCs) compared to single-use recyclable systems. Singh et al. (2006) and Albrecht et al. (2013) demonstrated that RPCs are generally preferable to Corrugated Cardboard Boxes (CCBs).

Accorsi et al. (2014) studied fresh fruit and vegetable distribution throughout a food catering system. They compared a reusable packaging system to traditional single-use (e.g., wooden boxes, disposable plastic crates and cardboard boxes) and quantified the economic returns and environmental impacts. Levi et al. (2011) studied the environmental impacts of alternative PSs in the transportation phase of fresh fruits and vegetables. They demonstrated that RPCs are preferable at travel distances less than 1200 km. Similarly, Abejón et al. (2020) evaluated the environmental impact of fruit and vegetables distribution in Spain using RPCs and CCBs. A sensitivity analysis revealed a robust preference for plastic crates compared to cardboard boxes, even in alternative scenarios.

Accorsi et al. (2022) compared the environmental impacts of three alternative packaging solutions and distribution systems, including reusable polypropylene polymer (PP) plastic crates, corrugated cardboard boxes, and disposable/recyclable PP plastic crates networks. They demonstrated that after 10 years, the environmental impacts of the single-use containers are higher than those of the RPCs in all the impact categories evaluated, such as Global Warming Potential (GWP) 20 years, acidification, and human toxicity.

The study illustrated in this paper evaluates the environmental impact of a new RPC adopted to distribute fresh products from growers to retailers over a time span of 10 years. Figure 1 shows the new RPC object of this study, named "Redea F6412".

Figure 1. Redea F6412 RPC

The logistic network is inspired by a case study of a country-wide fruit and vegetable retailer supply chain in Italy.

Figure 2 illustrates the logistic network of this RPC. This figure has two dimensions: the nodes (represented by the

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facilities in Fig. 2) and the connections (represented by the arrows in Fig. 2). The nodes describe the actors responsible for production, washing, and End-of-Life (EoL), named Processes. The connections describe the physical Distribution flows of virgin materials and empty/full containers within the network. Each dimension produces environmental emissions.
The raw material production facility supplies virgin materials according to the selected recipe. The package production facility produces reusable containers merging virgin, secondary, and auxiliary materials. After the production stage, the PS starts the utilisation phase and enters the FSC. The retailer distribution center is the intermediate node of the network between growers and shops. The grower fills the empty container with fruits and vegetables, and the distribution center delivers fully loaded pallets to the retailer shop. The last actor involved is the pooler, which collects and washes empty containers. The generic RPC is washed after two rotations (i.e., delivering food and returning it to the retailer). The RPC performs about ten rotations per year in a life cycle of 10 years. At the EoL, the pooler sends the PS to the grinding and printing facility (i.e., package production facility) to produce the recycled materials reused in a new container recipe.

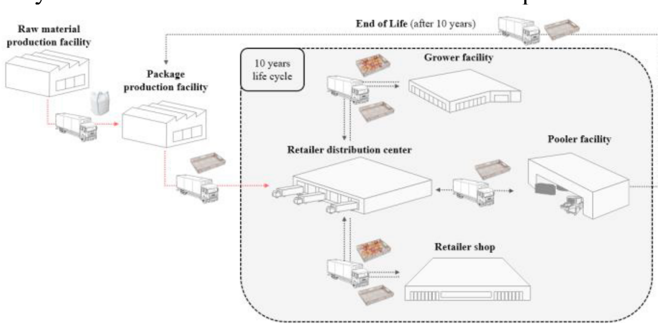

Figure 2. Logistic network of RPCs

The proposed LCA examines products and processes along the whole life cycle from a “cradle to grave” perspective and is based on the analysis of materials and energy flows at each phase of the cycle, starting with the extraction of raw material, passing through manufacturing, distribution, washing and finishing with end-of-life processes and activities (Accorsi et al., 2014).
Recently, Vidergar et al. (2021) showed the added value of high-quality primary data to conduct an accurate life cycle assessment, highlighting the need to overcome measurement difficulties in evaluating real-world scenarios.
For these reasons, this study conducts a LCA on a RPC thanks to collecting and analysing primary data from a real and significant case study. In particular, this study gathers primary data on the production, washing and EoL by on-field monitoring and data collection. It uses primary data on travel distances and flows collected throughout the logistics network to model real-world systems with bottlenecks and unbalanced infrastructural networks. The virtualisation of all Distribution flows between the network nodes is supported by a supply chain digital twin with the same approach introduced by Accorsi et al.(2022).
The novel contributions of this study lie in the utilisation of primary data (1) for the LCA of the new RPCs and the development of a multi-scenario analysis (2) varying PS, RCP recipe, and energy mix.

The remainder of this paper is organised as follows. Section 2 examines the proposed methodology. Section 3 presents the result of the LCA and the multi-scenario analysis. Finally, section 4 illustrates the conclusion and suggestions for future research.

2. METHODOLOGY

This study presents the results of the LCA conducted on RPC (reusable plastic containers) for the distribution of fresh fruits and vegetables over a time span of 10 years.
Most of the studies in the literature compare different containers under variant materials, sizes, and weights. The original contribution of this study complies with the comparison of alternative PSs, including variant recipes and energy mixes at the production plant.
Figure 3 illustrates the proposed methodology based on a Life Cycle Assessment (LCA). It is a comparative and competitive multi-scenario methodology. In particular, the scenarios depend on three features, each with two possible options:

- the packaging solution. This study analyses two alternative RPCs named 6410 and F6412. The F6412 is a new version of the 6410; they differ in size, weight, and volume. The features and performance of each PS are presented in Table 1;
- the production recipe. It mainly involves the mix of plastic materials used. This study investigates two combinations of raw and recycled materials: 70% raw – 30% recycled (“30” in Fig. 3) and 30% raw – 70% recycled (“70” in Fig. 3);
- the energy mix. It refers to the energy consumed to produce the RPC. This mix depends on the typology of the production facility selected. This study considers two alternative production facilities in Italy, one located in Salerno (“P1” in Fig. 3) and the other in Verona (“P2” in Fig. 3).

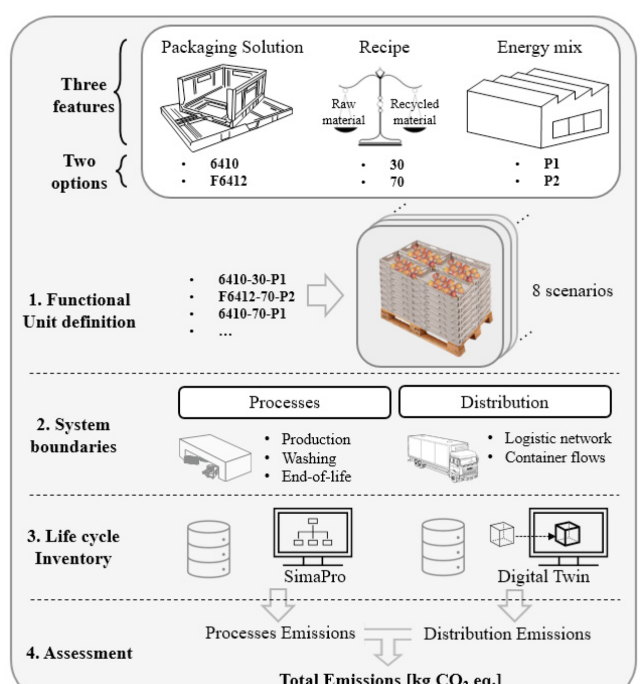

Figure 3. Multi-scenario Life Cycle Assessment Methodology

The proposed methodology consists of a four-step analysis: (1) functional unit definition, (2) system boundaries, (3) life cycle inventory, and (4) assessment. Each step is described in detail in the following subsections.

2.1 Functional Unit definition

The Functional Unit (FU) of the proposed LCA deals with the amount of food contained in a palletised unit load (UL) of F6412 RPCs, which travels within a grower-retailer FSC over a time span of 10 years. This FU transports 1737.60 dm^3 of fresh fruits and vegetables. The UL includes a wood pallet EPAL 800 x 1200 x 144 mm (22.3 kg), holding 80 open containers 600 x 400 x 115 mm (1.38 kg). Table 1 shows the features of the container object of the FU (i.e., the F6412 RPC) and the alternative RPC analysed in the multi-scenario analysis (i.e., the 6410 RPC).

The combination of PS, recipe, and energy mix generates 8 different scenarios (Step 1 in Fig. 3). To compare different RPCs, it is necessary to perform a normalisation process according to Accorsi et al. (2022), because of the variation in the sizes of RPCs, containers per pallet and the number of unit loads travelling through the FSC. These features bring a different number of necessary RPCs to provide the same amount of fresh products to the retailer shops. The number of ULs is scaled accordingly. Table 2 presents the differences in the PS stackability, which is the number of open/closed RPCs per UL and loading performance (i.e., the food volume capacity). In particular, the normalised volume is equal to 1 for the 6410 RPC and 0.9087 for the new F6412 RPC.

2.2 System Boundaries

The system boundaries include the life cycle of a palletised UL serving countrywide retailers over 10 years. The flow includes the materials, processes, and resources needed to produce, handle, and dispose of PSs. Two transportation phases are excluded from this analysis: the connection between the raw material production facility and the package production facility and the connection between the package production facility and the retailer distribution centers. These flows are represented by the red arrows in Figure 2.

There are two contributions to the global life cycle emissions (Step 2 in Fig. 3), as anticipated in Figure 1: the Processes and Distribution emissions. The first concerns the emissions to produce, wash, and manage the EoL of the RPC. The second regards the emissions of the Distribution phase over the country-wide logistic network in 10 years.

The proposed multi-scenario methodology was applied to a case study of fruit and vegetables distribution of an important Italian retailer. The raw material production facility is located in Antwerp (Belgium). This facility is responsible for the supply of virgin material according to two different recipes. There are two alternative package production facilities, one in Salerno (Italy) and the other in Verona (Italy). They differ in the types of systems installed in the RPC production lines and, consequently, in the energy consumption. The logistic network counts over 100 growers distributed over the country and five retailer distribution centers.

2.3 Life cycle inventory

The life cycle inventory (LCI) foresees the collection of the data and the modelling of the system object of the study. The data consists of all the inputs and outputs related to the Processes and Distribution flows (see Figure 2) in the life cycle (Step 3 in Fig. 3). There are primary and secondary data. Primary data are collected on-field via direct observations at each system facility (i.e., nodes responsible for production and distribution in Figure 2).

The data involving production, washing, grinding, and recycling information are processed using the SimaPro 7.3 software platform. This tool provides the total emissions of Processes (i.e., production, washing, and EoL).

The logistic flows of empty and full containers are virtualised using a SC digital twin incorporating a geographic information system (GIS) and routing features. This tool provides the total emissions of transportation (Distribution in Figure 3).

This data-driven approach overcomes the limitations of conventional general-purpose secondary (GPS) data collection commonly used in LCA analyses. The remaining secondary data were gathered from renowned LCI databases.

2.4 Assessment

The final step aims to evaluate the environmental impact of Processes and Distribution (Step 4 in Fig. 3). This carbon footprint impact is quantified using the Global Warming Potential 20 years (GWP_{20} indicator).

SimaPro 7.3 provides the environmental impact to produce, wash, and dispose of a FU. Furthermore, considering the total number of 6410 RPC distributed in the FSC logistic network in 1 year (7,295,912 containers), the digital twin performs the Distribution phase in 10 years and provides the total environmental impact.

The following section presents the results of the proposed methodology under variant packaging solutions, recipes, and energy mixes.

3. RESULTS AND MULTI-SCENARIO ANALYSIS

The selected case study involves a logistic network in Italy. The logistic network comprises more than 100 growers and retailer shops (see Fig. 2), and five retailer distribution centers located in Catania, Forli, Reggio Emilia, Rutigliano, and San Vito al Tagliamento. The package production facilities are located in Verona and Salerno. There are about 20 pooler facilities, and 4 of them are responsible for washing the containers before reuse.

Table 3 shows the results of the LCA analysis of scenario F6412-P1-70, where the PS is the novel F6412 RPC, the recipe contains 70% raw material and 30% recycled material, and the production facility is located in Salerno.

Table 1. Reusable plastic containers (RPC) features

Type	Material	Weight [kg]	Outer size (closed RPC) [mm]	Outer size (open RPC) [mm]	Inner size [mm]	Inner volume [dm^3]
F6412	PP reusable	1.38	600 x 400 x 30	600 x 400 x 115	570 x 370 x 103	21.72
6410	PP reusable	1.47	600 x 400 x 35	600 x 400 x 119	570 x 370 x 104	21.93

Table 2. Unit Load (UL) features

Type	Material	Open containers per UL	Closed containers per UL	Food volume capacity [dm^3]	Normalised volume	UL weight (open RPC) [kg]	UL weight (closed RPC) [kg]
F6412	PP reusable	80	288	1737.60	0.9087	110.40	397.44
6410	PP reusable	72	240	1578.96	1	105.84	352.80

Table 3. Results of scenario with F6412 RPC produced in P1 (Salerno) with a recipe 70 (70% raw - 30% recycled materials)

	Processes [kg CO_2 eq./FU]				Processes [kg CO_2 eq.] (10 years)	Distribution [kg CO_2 eq.] (10 years)	Total [kg CO_2 eq.] (10 years)
Type	Production	Washing	End of Life	Total Processes	Processes	Distribution	Processes + Distribution
F6412	253.453	135.078	25.441	413.973	3,775,412	1,578,243	5,353,655

The LCA analysis performed with SimaPro provides the environmental emissions to produce (253.453 kg CO_2 eq.), wash (135.078 kg CO_2 eq.), and dispose of (25.441 kg CO_2 eq.) a FU. The total Processes emissions of a FU is 413.973 kg CO_2 eq.

Each retailer distribution center provides primary data on the annual flows of containers. The digital twin manages these flows and measures the total (i.e., Processes and Distribution) emissions over a time span of 10 years.

In particular, the annual flows allow to evaluate:

- the number of containers and palletised ULs necessary to perform all the movements required, considering that the generic RPC rotates ten times per year;
- the number of trucks involved in the Distribution phase and the travelled distances.

In this scenario (i.e., F6412-P1-30), the Processes emission (i.e., production, washing, and EoL) is 3,775,412 kg CO_2 eq., and the emission of the Distribution phase is 1,578,243 kg CO_2 eq. Both contributions are quantified over 10 years. The total emissions (i.e., Processes and Distribution) generated by the F6412 RPCs to move the amount of food products of this case study is 5,353,655 kg CO_2 eq. over 10 years.

Table 4 shows the results of the multi-scenario analysis. Due to its size and production system, the selected PS has different food volume capacity, stackability and production phase emissions. The recipe of the container varies according to the percentage of raw/recycled materials. The energy mix depends on the selected production facility.

The combination of packaging solution, recipe, and energy mix generates different Processes impacts:

- a UL containing RPC with a higher percentage of recycled materials has lower emissions in the production phase than ULs containing more raw materials. Significant examples are the scenario 6410-P1-70 (70% raw-30% recycled) and the scenario 6410-P1-30 (30% raw-70% recycled);
- a UL containing RPC produced in Salerno (P1 in Tab. 4) has lower emissions in the production phase than ULs produced in Verona (P2 in Tab. 4). Significant examples are the scenario 6410-P1-70 (Salerno) and the scenario 6410-P2-70 (Verona);
- a UL containing F6412 RPCs has higher emissions in the production phase than ULs containing 6410 RPCs. Two examples are scenarios 6410-P1-70 and F6412-P1-70. However, since a UL of F6412 contains more RPCs than a UL of 6410 (see Tab. 3), the production emissions of a UL of F6412 RPC (3.168 kg CO_2 eq.) are lower than the production emissions of a UL of 6410 RPCs (3.392 kg CO_2 eq.);
- a UL containing F6412 RPCs has lower emissions in the washing phase than ULs containing 6410 RPCs. Two examples are the scenario 6410-P1-70 and the scenario F6412-P1-70;
- a UL containing F6412 RPCs has lower emissions in the EoL phase than ULs containing 6410 RPCs. Two examples are scenarios 6410-P1-70 and F6412-P1-70.

These results refer to one UL that combines multiple full RPCs. Considering the number of containers necessary to perform the material flows in the considered time span, it is possible to evaluate the emissions of Processes and Distribution for the necessary containers travelling within the network in 10 years.

Regarding the processing emissions, the total number of containers depends on the previously introduced features (see Tables 1 and 2). The novel F6412 RPC has a lower food volume capacity (21.73 dm3), but the smaller size allows the transport of more containers in a UL (80 open containers and 288 closed containers). In the Italian case study, the annual flows of the 6410 RPC are 7,295,912 (flows/year) and 159,999,350 dm^3 of fresh food. To transport the same amount of food, it is necessary to perform 7,366,453 flows/year of the F6412 RPC.

Considering these flows, it is possible to evaluate the necessary number of RPCs per PS and measure the total Processes emissions in 10 years for the 8 scenarios.

The F6412 RPC produced in Salerno with a recipe containing 30% raw-70% recycled materials generated the lowest Processes emissions equal to 2,917,242 kg CO_2 eq.

Table 4. Results of the multi-scenario analysis

Scenario	6410 P1 70	F6412 P1 70	6410 P2 70	F6412 P2 70	6410 P1 30	F6412 P1 30	6410 P2 30	F6412 P2 30
Production	244.227	253.453	255.554	263.647	148.874	159.354	160.200	169.548
Washing	150.087	135.078	150.087	135.078	150.087	135.078	150.087	135.078
End of Life	23.902	25.441	23.902	25.441	23.902	25.441	23.902	25.441
Total Processes [kg CO_2 eq./FU]	418.217	413.973	429.544	424.167	322.864	319.875	334.190	330.069
Total Processes [kg CO_2 eq.] (10 years)	4,237,791	3,775,412	4,352,685	3,868,378	3,271,667	**2,917,242**	3,386,441	3,010,208
Distribution [kg CO_2 eq./FU] (10 years)	1,936,040	1,736,812	1,936,040	1,736,812	1,936,040	1,736,812	1,936,040	1,736,812
Normalised volume	1	0.9087	1	0.9087	1	0.9087	1	0.9087
Distribution normalised [kg CO_2 eq./FU] (10 years)	1,936,040	**1,578,243**	1,936,040	**1,578,243**	1,936,040	**1,578,243**	1,936,040	**1,578,243**
Total emissions [kg CO_2 eq./FU] (10 years)	6,173,831	5,353,655	6,288,725	5,446,621	5,207,707	**4,495,485**	5,322,481	4,588,451
Difference with the best scenario	+37.33%	+19.09%	+39.89%	+21.16%	+15.84%	**-**	+18.40%	+2.07%

The packaging solution features, such as stackability, affect the number of travels and the total Distribution emissions. The scenarios with the F6412 RPC have lower Distribution emissions equal to 1,736,812 kg CO_2 eq. In addition, the emissions of scenarios with F6412 RPCs must be normalised according to the food volume capacity of a UL, as shown in Table 2.
Now, it is possible to aggregate the Processes and Distribution emissions to quantify the total emissions in 10 years for each scenario.
The F6412 RPC produced in Salerno with a recipe of 30% raw-70% recycled materials generates the lowest total emissions equal to 4,495,485 kg CO_2 eq.
The best scenario using the 6410 RPC is scenario 6410-P1-30, where the PS is produced in Salerno with a 30% raw-70% recycled materials recipe, generating 5,207,507 kg CO_2 eq in 10 years.
Figure 4 illustrates the results of the multi-scenario analysis conducted on other important environmental impact categories. For each indicator, the scenario with the higher impact value is at the 100% level, and the other scenarios are scaled consequently. This comparative analysis shows that scenario F6412-P1-30 (represented in yellow in Figure 4) generates lower overall environmental impacts.

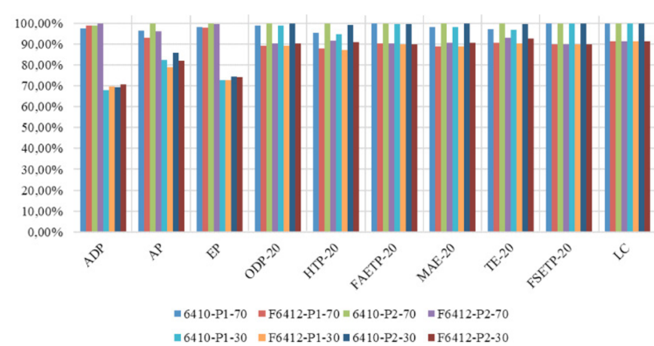

Figure 4. Multi-scenario impact categories. (Legend: ADP: Abiotic Resource Depletion Potential; AP: Acidification Potential; EP: Eutrophication Potential; ODP: Ozone Depletion Potential 20y; HTP: Human toxicity potential 20y; FAETP: Freshwater aquatic ecotoxicity.

4. CONCLUSIONS

The food supply chain overall environmental impact is greatly affected by the packaging industry's waste, resource utilisation, and transportation issues. Previous studies evaluated the Life Cycle Assessment of reusable plastic containers (RPCs) in food supply chain networks, promoting their use compared to recyclable paper and plastic containers. This study introduces a multi-scenario methodology to perform LCA analyses of different RPCs distributed in a logistic network of an Italian fresh food distribution from growers to retailers over a time span of 10 years (see Fig. 2). One of the novel contributions of the proposed methodology lies in the utilisation of primary data, which is necessary to make accurate analyses. Furthermore, this study proposes a multi-scenario assessment comparing different packaging solutions, RPC recipes, and energy mixes at the production facilities.

The functional unit is a palletised unit load of a new RPC, named F6412, capable of handling 1737.60 dm^3 of fresh fruits and vegetables. The logistic network is inspired by a case study of an Italian retailer that involves over a hundred growers and five retailer distribution centers.
The LCA analysis conducted with primary data allows to evaluate the total emissions (Processes + Distribution) of a F6412 RPC realised in the Salerno production facility with a recipe of 70% raw-30% recycled materials. This scenario generates 5,353,655 kg CO_2 eq.
In addition, the multi-scenario analysis allows for finding the best combination of RPC recipe, energy mix, and packaging solution that minimises global emissions. This is the scenario F6412-P1-30 corresponding to 4,495,485 kg CO_2 eq. over 10 years.
Future research is expected on new applications of the proposed methodology to support decision-making on the best configuration of the production/distribution/End-of-Life network. For example, it is important to optimise the location of crucial facilities (e.g., packaging production facilities, retailer distribution centers, and pooler facilities) to reduce Processes and Distribution emissions.

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