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Transport of Spanish fruit and vegetables in cardboard boxes: A carbon footprint analysis

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Abstract

The increase in international trade due to globalization is evident in southeast Spain, which has become the top exporter of fruit and vegetables. Countries within the European Union, such as Germany and France, emphasize the sustainability and environmental impacts of these products. Hence, a greater understanding of the environmental implications of transporting fruit and vegetables between their origin and their destination might improve the sustainability of this commercial activity.

The concept of a carbon footprint is a recognized environmental indicator that can be used for life cycle analysis. Here, a rigorous carbon footprint assessment was developed to examine the impact of using cardboard box containers to store and transport 1,000 t of fruit and vegetable products by road from their origin in Almería, Spain, to a destination market. The assessment included the fabrication of the cardboard boxes, the service they provide while transporting the products to the distribution center of the destination, and the end-of-life of the boxes for the six main products grown in Almería. The results showed that storing and transporting 1,000 t of product by road emits between 58 t and 130 t of CO_2e depending on the fruit or vegetable type and the destination market. The implications of the end-of-life scenarios with respect to the destination are also discussed. Furthermore, a sensitivity analysis was conducted for the transport distance. Lastly, biogenic CO_2 production was also assessed according to standard carbon footprint assessment method.

Highlights

The carbon footprint of storage and transport of fruit and vegetables was assessed as an environmental indicator

End-of-life scenarios and transport distance were the key aspects affecting the environmental impact

Storing and transporting 1,000 t of fruits from Almería to main European markets emits between 58 t and 130 t of CO_2e

Keywords

Carbon footprint; cardboard boxes; fruit and vegetables; export; Life Cycle Assessment; ISO 14067

Abbreviations

ADEME Agence de l’Environnement et de la Maîtrise de l’Energie
CF Carbon Footprint
EEA European Environment Agency
FEFCO European Federation of Corrugated Board Manufacturers

FEPEX Spanish Federation of Associations of Exporting Producers of Fruits, Vegetables, Flowers and Live Plants
GHG Greenhouse gases
IEA International Energy Agency
IMO International Maritime Organization
INSEE Institut National de la Statistique et des Études Économiques
ISO International Organization for Standardization
LCA Life Cycle Assessment
MAIKWA Manufacturers of machines for cardboard production

1. Introduction

The comprehensive study of the environmental impact of a product or service requires life cycle assessment (LCA); however, given the amount of information required, the complexity of this analysis means that only a few environmental indicators are suitable for this type of assessment. Nevertheless, simplified environmental impact assessments based on a single indicator should only be carried out using a robust methodology (Finkbeiner, 2009; Neusebauer et al., 2015).

The ‘carbon footprint’ (CF) is a widely known environmental impact indicator that quantifies greenhouse gas (GHG) emissions (Borsato et al., 2018; Parajuli et al., 2019; Soode et al., 2015). The environmental impacts of GHG emissions from packaging might be significant, accounting for between 7% and 54% of the total emissions from fresh fruit and vegetable production, depending on the volume and the market (Del Borghi et al., 2014; Payen et al., 2015). Transport emissions, which account for approximately 43% of total emissions, might also be significant where transportation relies on non-renewable energy sources (Payen et al., 2015). Bortolini et al. (2016) proposed a methodology to optimize the distribution of fresh fruit and vegetables produced in Italy that considered costs, time, and the CF.

Parajuli et al. (2019) sought to evaluate environmental costs by conducting a literature review on LCA of fruit and vegetables and some of their derivatives. Their study highlighted the difficulties of making general recommendations as the results are highly dependent on market conditions. LCA has also been used in combination with other tools, such as artificial intelligence, to predict agricultural environmental impacts (Kaab et al., 2019), to optimize CO_2 emissions in the production of certain fruits (Nabavi-Pelesaraei et al., 2014), and to evaluate the energy efficiency of agricultural production (Kouchaki-Penchah et al., 2017). End-of-life phases have also been incorporated into these combined methods (Nabavi-Pelesaraei et al., 2017a; Nabavi-Pelesaraei et al., 2017b).

The production of fruit and vegetable derivatives (e.g., tomato puree and extra virgin olive oil) in the Italian market has also been studied (Manfredi & Vignali, 2014, Pattara et al., 2016). Transport between factories and the retail centers have been shown to have the highest contribution to the overall GHG emissions (45% to 50%) often due to large transport distances. An environmental impact analysis of vegetables produced in Spain was conducted by Pérez Neira et al. (2018) who developed a CF and life cycle approach for tomatoes produced in heated greenhouses. However, their study was restricted to the transport of the products to the regional distribution center, meaning that the transport required for the products to reach the destination markets was disregarded. Other studies have analyzed different agricultural production techniques seeking to reduce GHG emissions including the use of “low-biomass vegetation areas” (Rivera-Méndez et al., 2017), moving production nearer to urban areas (Atallah et al., 2014; Pérez-Neira & Grollmus-Venegas 2018; Sanyé-Mengual et al., 2012), eating seasonal foods (Röös &

Karlsson, 2013), and minimizing emissions during shopping trips (Soode et al., 2015). The influence of the energy efficiency of producers on GHG emissions has also been studied using data envelopment analysis (Nabavi-Pelesaraei, et al., 2014). Other influences on farming efficiency have also been studied including the effects of dam construction (Shabanzadeh-Khoshrody et al., 2016) and the size of orchards (Sabzevari et al., 2015).

The importance of packaging on the environmental impact of transporting fresh fruit and vegetables has already been established via various frameworks (Albrecht et al., 2013, Sim et al., 2007). *Agence de l'Environnement et de la Maîtrise de l'Energie* (ADEME, 2000) developed a LCA (which is not available in English) that focused on the transport of 1,000 kg of apples form a producer to a final distributor. The distribution phase was identified as the main contributor to the environmental impact of the cycle. Other products, such as mangos (Chonhenchob & Singh, 2003), papaya (Chonhenchob & Singh, 2005), and other citrus fruits (Leviet al., 2011) have also studied.

The containers used in the transport of fruit and vegetables have also been assessed from a life cycle perspective (Singh et al., 2006; Levi et al., 2011; Albrecht et al., 2013). These studies have compared different types of containers against a baseline defined for general purposes. For example, Albrecht et al. (2013) assumed an average of 15 kg of fruit or vegetables per box. However, as markets and products seem to be significant factors, fruit and vegetable producers and export companies in Spain might not possess sufficient information on environmental impacts to inform their packaging choices. Therefore, this study focused on the transport of selected fruits and vegetables in cardboard boxes from their production origin in the south of Spain to two reference markets, namely within France (with an average transport distance of 1,500 km) and Germany (with an average transport distance of 2,500 km). The following fruits and vegetables were selected:

- Cantaloupes
- Cucumbers
- Eggplants
- Peppers
- Tomatoes
- Zucchinis

2. Methods

Several organizations have developed regulations for the assessment of CFs including PAS 2050 of the GHG protocol (British Standard Institute, 2008) and ISO 14067 (ISO, 2018). For this study, ISO 14067 was chosen as the reference standard, which requires the following documentation:

- Emissions linked to the main life cycle phases
- Emissions from fossil carbon sources
- Emissions from biogenic carbon sources

It is important to note that biogenic CO_2 was separately accounted for in this assessment, as specified by the standard. The assessment method was developed using SIMAPRO 8.0.1 Software (Pre-sustainability, 2019) and the Ecoinvent 3.01 database (Wernet et al., 2016). Figure 1 shows the overall methodology applied in this study, as based on ISO 14067.

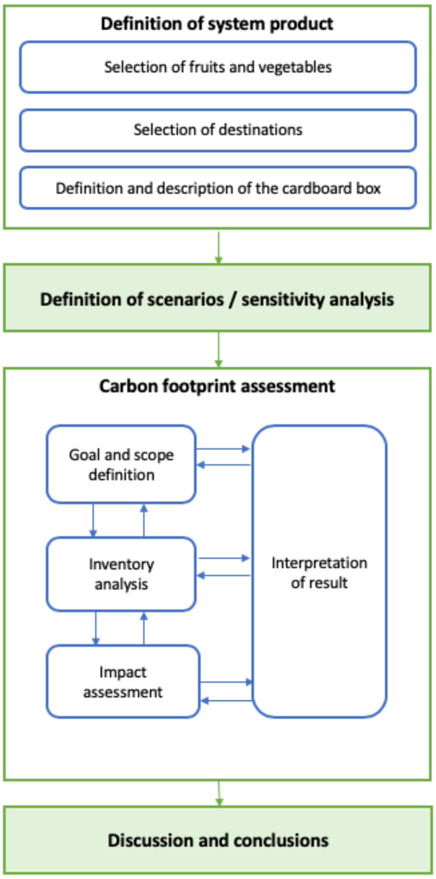

Fig. 1 Methodological framework.

2.1 Definition of system product

Export quotas were used as the basis for choosing the fruits and vegetables for this study. The total amount of each product was set based on the experience of the research group as applied in similar assessments, by considering approximately 25% of exports in monetary terms. The Spanish Federation of Associations of Exporting Producers of Fruits, Vegetables, Flowers and Live Plants (FEPEX) was chosen as a quality data source for this procedure. Table 1 shows the six fruits and vegetables produced in the Almería region of Spain with the highest exports in 2017. Together, these represented 25.78% of the total Spanish export in euros and 24% in terms of weight.

Table 1 Export data for fruit and vegetables (FEPEX, 2018)

Product	Exportation (kiloton)	Exportation (EUR millions)
Tomatoes	810	1,003
Peppers	687	954
Cucumbers	627	566
Cantaloupes	441	287
Zucchinis	320	312
Eggplants	144	152
Total products considered	**3,028**	**3,275**
Total exportation from Spain	**12,617**	**12,704**

For the selected products, France and Germany are the major international markets, with a 51.43% share of annual Spanish fruit and vegetable exports by weight and 54.85% by economic value in 2017 (FEPEX, 2018). The transport distance considered in the assessment was a rounded-up value of the distance between Almería in the Andalusia Region in Spain and the capital city of each country, calculated by weighting the distance to the main cities according to their population (Table 2).

Table 2 Information for key Spanish fruit and vegetable markets

Destination	Distance (km)	Export share (weight) 2017	Export share (monetary) 2017
France	1,500	23.66%	23.95 %
Germany	2,500	27.76%	30.90 %

The products were assumed to be transported from their origin to their destination in corrugated cardboard boxes with different dimensions depending on the product being transported. UNIQ boxes (Fig. 2) were selected as the most widely used on the market according to FEPEX.

Fig 2 A UNIQ box (Group Unique, 2019).

The dimensions for each of the products considered in this study are shown in Table 3. Each product system was codified to simplify the analysis. Tomatoes are transported in two different types of boxes depending on the preference of the farmer, and as the use of each box size is equal, both were considered in this study. The dimensions of the boxes given in Table 3 are both for when they are in use (i.e., open) and when they are empty (i.e., folded).

Table 3. Product system description

Code	Vegetable or Fruit	Cardboard box dimensions			
		Open / in use (mm^3)	Folded / empty (mm)	Weight (kg)	Maximum capacity (kg)
CA-400	Cantaloupe	400×300×145	7.0	0.316	5
CU-400	Cucumber	400×300×145	7.0	0.316	5
EP-400	Eggplant	400×300×145	7.0	0.316	5
PE-600	Pepper	600×400×200	7.0	0.810	15
TO-400	Tomato	400×300×145	7.0	0.319	6
TO-600	Tomato	600×400×90	7.0	0.478	7
ZU-400	Zucchini	400×300×145	7.0	0.316	5

Definition of the scenarios and the sensitivity analysis

Separate scenarios were configured for France and Germany (see Table 2). Therefore, two different scenarios were assessed for each product system. Distance and waste treatment procedures at the end-of-life were identified as sensitive parameters. For this reason, the Netherlands was included as a third country for the sensitivity analysis, with an average transport distance of 2,300 km. The waste treatment procedures for each country are outlined in Section 2.4.3, which describes the end-of-life stage. The sensitivity analysis was developed for the product system that was most representative of the entire sample. Therefore, TO-600 (tomato) was selected as it had the highest proportion (approximately 30 %) of the traded amount among all of the products (Pérez Neira et al., 2018).

2.2 Carbon footprint assessment

2.2.1 Goal and scope definition

The goal of the assessment was to quantify the CF of cardboard boxes used to export refrigerated fruit and vegetables. The CF was assessed with the objective of visualizing the potential contribution of each of the product systems to climate change.

A *functional unit* was defined as the container system used to store and transport 1,000 t of product by road from its origin, located in Almería, southeast Spain, to the destination market. The function included the fabrication of the cardboard boxes, the service they provide in the transportation of the fruit or vegetable to the distribution center within the destination country, and the end-of-life treatment of the box. Table 4 describes the *reference flows* defined for each product system.

Table 4 Reference flows for the functional unit

Code	Vegetable or Fruit	Maximum capacity (kg)	Actual load (kg)*	Number of boxes
CA-400	Cantaloupe	5	5	200,000
CU-400	Cucumber	5	5	200,000
EP-400	Eggplant	5	3	333,334
PE-600	Pepper	15	10	100,000
TO-400	Tomato	6	6	166,667
TO-600	Tomato	7	7	142,858
ZU-400	Zucchini	5	5	200,000

*Data provided by the export companies

System boundaries were defined as ‘cradle-to-grave’ boundaries while applying a closed loop for cardboard recycling following FEFCO (2015); FEFCO states that during the recycling process in both countries (Germany and France), a closed loop from cradle-to-grave can be assumed even when the recycling product does not feed into the same life cycle. Figure 3 illustrates the full life cycle that was assessed. Furthermore, each unit process was described. For this, the FEFCO database (2015) was used to build each unit process, flow-by-flow, based on the corresponding allocation.

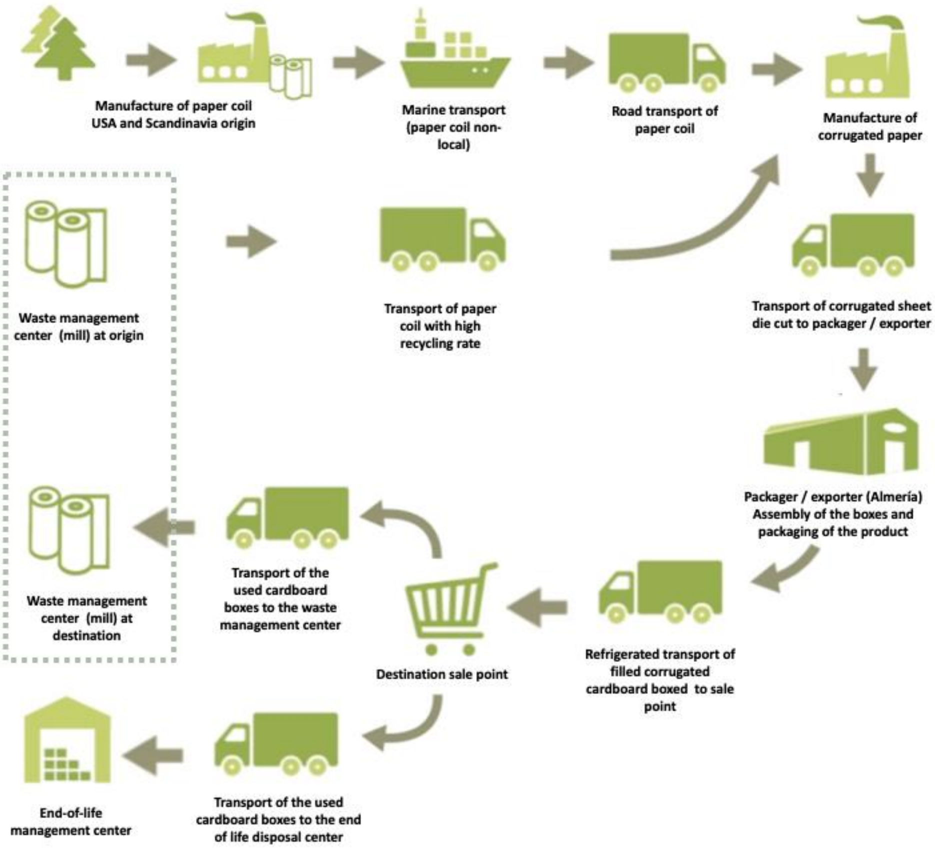

Fig. 3 Life cycle: Definition of system boundaries.

According to ISO 14044 (ISO, 2016), cut-off rules were applied to the inventory analysis by excluding those individual inputs that represented less than 5% of the total inputs of the system (on a mass or energy basis). The inputs affected by the cut-off were: pallets, low-density polyethylene film used for strapping and palletization of the boxes, sieving, cleaning treatments, and packing conducted at the entrance of the warehouse and during transport of the fruit and vegetables. Infrastructure was also excluded from the scope of this study.

Direct quantification was considered desirable to ensure data quality. Government organizations and recognized institutions, technical fact sheets, and the relevant literature were also considered as valid data sources when the desirable source was not viable. The quality index of data (DQR) suggested by the European Commission (2010) was chosen, which includes representativeness and completeness factors as well as uncertainty, as required by ISO 14067. DQR was assessed using Eq 1:

$$\boldsymbol{DQR} = \frac{\boldsymbol{TeR+GR+TiR+C+P+M+X_w*4}}{\boldsymbol{i+4}} \quad \text{[Eq. 1]}$$

where TeR is the technical representativeness; GR is the geographical representativeness; TiR is the temporal representativeness; C is the completeness; P is the precision/uncertainty; M is the methodology and consistency; X_w is the most adverse level of all indicators; and *i* is the total of all the indicators.

The indicators were assigned a number from 0 to 5, whereby: 0 represented “not applicable”; 1 accounted for a representativeness greater than 95%; 2 indicated a representativeness of between 85% and 95%; 3 indicated a representativeness of between 75% and 85%; 4 indicated a low representativeness of between 50% and 75%; and 5 indicated a very low representativeness of less than 50%.

Data with DQR values of 1.6 or less were classified as high quality (HQ); data with DQR values between 1.6 and 3.0 were classified as basic quality (BQ); and data with DQR values above 3.0 were considered as estimates (E). Table 5 shows the quality assessment of the inputs and flows that were used in the assessment. The analysis of each parameter was undertaken by the authors and was approved by an independent expert panel after critical review. The FEFCO, box manufacturers, and export companies were sources of the main parameters to ensure data quality.

Table 5 Data quality analysis

Input / flow	TeR	GR	TiR	C	P	M	Source	DQR	
Dimensions, maximum capacities, weight, and box composition	0	1	1	2	2	2	Box manufacturers	1.78	BQ
Environmental data of raw materials for box manufacture	2	1	1	1	2	1	FEFCO, 2015	1.60	HQ
Actual load of the boxes for each fruit or vegetable	0	2	2	2	2	1	Export companies	1.89	BQ
Internal transport	3	3	2	2	3	2	Export companies	2.70	BQ
Electrical supply model	0	2	2	1	2	2	OECD/IEA, 2015	1.89	BQ
Fuel for internal transport	0	3	3	2	2	2	Ecoinvent 3.01 database	2.67	BQ
Manufacturing and die-cut process of cardboard	2	1	1	2	2	2	FEFCO, 2015; MAIKWA, 2017	1.8	BQ
Trucks and ships for raw materials and cardboard box transport	2	2	2	2	2	2	Ecoinvent 3.01 database	2	BQ
Emission factors for the modeling of road transport	0	2	1	1	2	2	EMEP/EEA, 2014	1.78	BQ
Emission factors for the modeling of maritime transport	0	2	1	1	2	2	IMO	1,78	BQ
Distance to the destination market	0	2	1	2	3	2	Statistics Netherlands May 2016, INSEE, 2015 Federal Statistical Office, 2013 Vía Michelín, 2017	2.44	BQ
Distribution of the waste management treatments of plastic packaging	0	1	1	1	2	2	Eurostat, 2017	1.67	BQ
End-of-life treatment	3	3	3	3	3	3	Ecoinvent 3.01	3	BQ

The oldest data sources applied in the assessment were from 2014 and the most recent data were from 2017. This period was considered the *data time limit* for which the results of the assessment are most meaningful.

The limitations of the study were defined by the underlying assumptions and some additional considerations (Fig. 4):

- Transport of raw materials: Paper rolls were transported to the box manufacturer in non-refrigerated trucks with a 40 t maximum authorized weight and a tare of 16 t.

- Transport from the box manufacturer to the producer/packer was via non-refrigerated trucks with a 40 t maximum authorized weight and a tare of 16 t.
- Transport of the loaded cardboard boxed from the producer/packer to the destination market was via refrigerated trucks with a 40 t maximum authorized weight and a tare of 16 t.
- Transport of the used cardboard boxes to the waste management centers was via non-refrigerated trucks with a 16 t maximum authorized weight and a tare of 6.5 t.

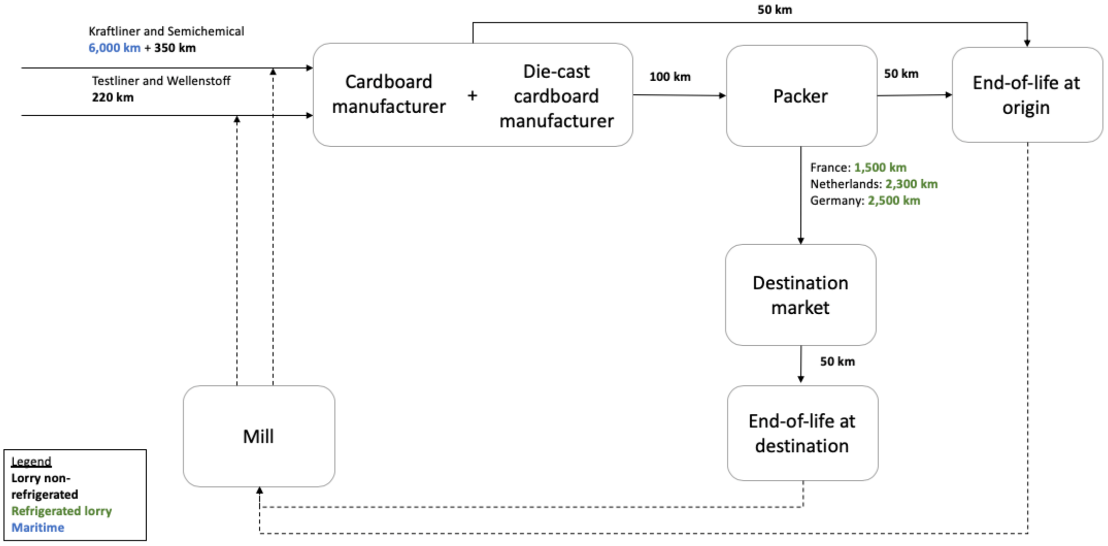

Fig. 4 Transport stages, distances, and types of trucks.

The fuel consumption for each type of truck is shown in Table 6 with respect to the load being transported. It should be noted that the consumption of compressors in refrigerated trucks was also related to the load being transported.

Table 6 Information for transport by truck

Type of truck	Ecoinvent 3.01 database reference	Load transported (t)	Fuel consumption (l/100 km)
Non-refrigerated truck, 16 t	Transport, freight, lorry 7.5–16 metric ton, EURO5 RER	9.5	24
Non-refrigerated truck, 40 t	Transport, freight, lorry >32 metric ton, EURO5 RER	23–20	33
		19–15	32
		14–10	31
		9–8	30
Refrigerated truck, 40 t	Transport, freight, lorry >32 metric ton, EURO5 RER	23–20	36
		19–15	35
		14–10	34
		9–8	33

Diesel and electric forklifts were considered for the internal transport assuming a proportional use of 33% and 67%, respectively. The forklifts had a load of 1,500 kg and a movement time of 60 s. The power consumption for diesel forklifts working at full load was 2.3 l/h (Wernet et al., 2016) and for electrical forklifts was 4.1 kWh/h (IEA, 2015).

Additional assumptions were made regarding the end-of-life of the cardboard boxes. Specifically, it was assumed that once used, all boxes were managed at the waste treatment plants of the destination country with the exception of 0.1% of the boxes, which were assumed to break during their assembly at the packing site (the breakage rate). In the case of broken boxes, these were assumed to be managed at the waste treatment plant of the exporting country.

Since the recycling process was allocated proportionally, the associated GHG emissions were shared among more than one product system (ISO, 2018). Following ISO 14044 (ISO, 2016), the allocation of shared unit processes was based on a closed cycle when considering the raw materials. Closed cycles are applicable when the recycled materials are recovered during the end-of-life stage and reused in the same system. In this case, the allocation was avoided as the recovered fibers replaced the use of virgin fibers. The allocation of other emissions linked to the flows of each unit process was defined according to the FEFCO (2015) database.

The emissions produced during the recycling process were accounted for under the end-of-life stage, considered as credit on the manufacturing stage of the cardboard boxes. GHG emissions from fossil and biogenic CO_2 were also included in the assessment, being accounted for separately, according to ISO 14067:2018 (ISO, 2018).

The limitations of the study therefore affected the quantification of the CF and are included in the results dissemination (ISO, 2018). The two main limitations of this study were the focus on climate change as the only impact category (as defined by the CF) and the inherent limitations of the methodology described.

This study was subjected to an independent critical review following the suggestions of ISO 14044. The review was undertaken by three external, internationally recognized experts who developed a detailed report that acknowledged the adequate development of the study and the correct application of the regulations. This article summarized the information once the critical reviewers had validated the study and its results.

2.3 Inventory analysis

2.3.1 Cardboard box manufacturing

Cardboard box manufacturing includes the manufacture of paper coils, the transport of the coils (via marine and road routes), and the manufacture and die-cutting of the corrugated paper. This manufacturing process includes white coils and coils with a high recycling rate (Fig. 3). Cardboard box manufacturing requires four types of paper: (1) Kraftliner, (2) semi-chemical fluting, (3) Testliner, and (4) Wellenstoff. The environmental data for these materials was obtained from the European Database for Corrugated Board Life Cycle Studies (FEFCO, 2015), which includes raw materials, additives, the energy required, emissions, water waste, waste, and associated transport. The paper rolls were transported to the manufacturing sites of the cardboard boxes. Krafliner paper rolls with 0% and 20% recycled fibers required trans-oceanic transport (6,000 km) and additional road transport via a 40 t truck (350 km). Maritime transport was modeled using emission factors provided by the International Maritime Organization (IMO, 2015). Testliner and Wellnstoff paper rolls with 100% recycled fibers were transported 220 km with a 40 t truck by road. The composition of each UNIQ cardboard box for each product system is described in Table 7. The unit process is shown in Fig. 5.

Table 7. Composition of cardboard boxes

Product system	Layer 1 (external)	Layer 2	Layer 3	Layer 4	Layer 5 (internal)
TO-600	Testliner, 100% recycled fibers Paper grade: 195 g/m^2	Wellenstoff, 100% recycled fibers Paper grade: 170 g/m^2 Channel B, coef. 1.33	Wellenstoff, 100% recycled fibers Paper grade: 170 g/m^2	Wellenstoff, 100% recycled fibers Paper grade: 190 g/m^2 Channel C, coef. 1.43	Testliner, 100% recycled fibers Paper grade: 250 g/m^2
TO-400	Kraftliner, 20% recycled fibers Paper grade: 135 g/ m^2	Wellenstoff, 100% recycled fibers Paper grade: 150 g/m^2 Channel B, coef. 1.33	Wellenstoff, 100% recycled fibers Paper grade: 170 g/m^2	Wellenstoff, 100% recycled fibers Paper grade: 190 g/m^2 Channel C, Coef. 1.43	Kraftliner, 20% recycled fibers Paper grade: 170 g/ m^2
CA-400 **CU-400** **EP-400** **ZU-400**	Kraftliner, 20% recycled fibers Paper grade: 135 g/ m^2	Wellenstoff, 100% recycled fibers Paper grade: 150 g/m^2 Channel B, coef. 1.33	Wellenstoff, 100% recycled fibers Paper grade: 120 g/m^2	Wellenstoff, 100% recycled fibers Paper grade: 150 g/m^2 Channel C, Coef. 1.43	Kraftliner, 20% recycled fibers Paper grade: 170 g/ m^2
PE-600	Testliner, 100% recycled fibers Paper grade: 170 g/m^2	Wellenstoff, 100% recycled fibers Paper grade: 150 g/m^2 Channel E, coef. 1.33	Wellenstoff, 100% recycled fibers Paper grade: 120 g/m^2	Wellenstoff, 100% recycled fibers Paper grade: 150 g/m^2 Channel B, Coef. 1.43	Testliner, 100% recycled fibers Paper grade: 170 g/m^2

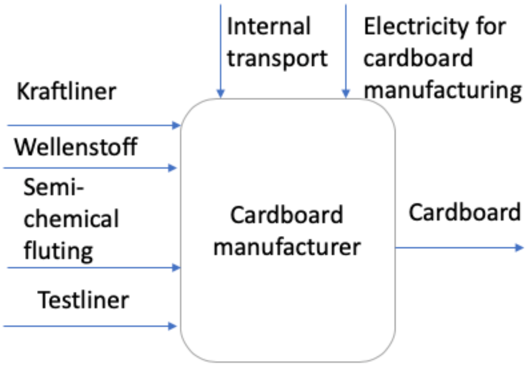

Fig. 5. Cardboard manufacturing process (see Fig. 3 for further details).

The die-cutting and manufacturing of the cardboard boxes were considered with a 10% loss of material due to the cutting of the cardboard sheets. For this, FEFCO (2015) and MAIKWA (2017) provided the required data. The unit process is shown in Fig. 6.

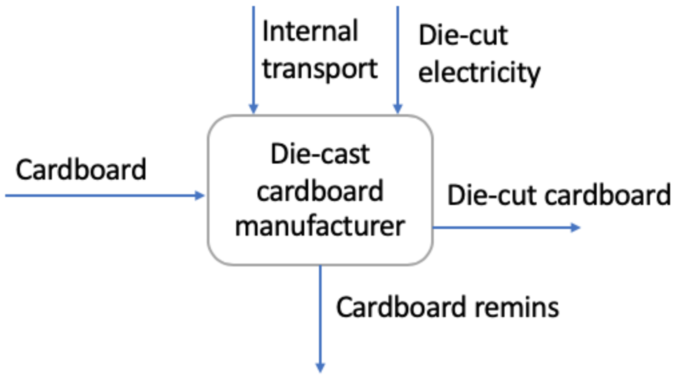

Fig. 6. Cardboard box manufacturing process and die-casting (see Fig. 3 for further details).

Table 8 shows the information relating to the transport of the cardboard boxes to the producer/packer of the vegetables and fruits. The average transport distance was 100 km via a 40 t non-refrigerated truck. The percentage of cardboard boxes that were damaged during the manufacturing was managed as waste in Spain. The unit process scheme is shown in Fig. 7.

Table 8. Transport of cardboard boxes to the packer

Product system	Cardboard sheets per truck	Sheets required to transport 1,000 t of fruit or vegetables	Percentage of losses	Total sheets required per functional unit
CA-400	29,500	200,000	0.1%	200,200
CU-400	29,500	200,000	0.1%	200,200
EP-400	29,500	333,334	0.1%	333,667
PE-600	14,750	100,000	0.1%	100,100
TO-400	29,500	166,667	0.1%	166,834
TO-600	14,750	142,858	0.1%	143,001
ZU-400	29,500	200,000	0.1%	200,200

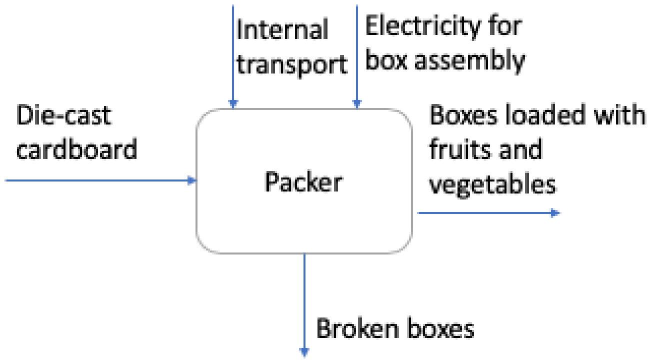

Fig 7. Packing process (see Fig. 3 for further details).

Table 9 shows the weights considered for the internal transport inside the packing facilities.

Table 9. Weight for internal transport consideration

Product system	Weight of cardboard sheet (kg)	Weight of die-cut cardboard sheet (kg)
CA-400	0.35111	0.316
CU-400	0.35111	0.316
EP-400	0.35111	0.316
PE-600	0.70222	0.632
TO-400	0.35444	0.319
TO-600	0.53111	0.478
ZU-400	0.35111	0.361

2.3.2 Transport of loaded boxes

Once the cardboard boxes were loaded with the corresponding fruit or vegetables they were transported to the destination market in 40 t refrigerated trucks. Table 10 shows the information related to the capacity of this transport pathway.

Table 10 Transport of cardboard boxes loaded with fruit and vegetables.

Product system	Rows of boxes by pallet	Boxes by row	Pallets per truck	Actual load per box (kg)	Boxes by truck	Boxes to transport per functional unit	Total load to transport per truck (t)	Number of trips to transport 1,000 t (functional unit)
CA-400	14	8	33	5	3,696	200,000	19.65	54.11
CU-400	14	8	33	5	3,696	200,000	19.65	54.11
EP-400	14	8	33	3	3,696	222,224	12.26	90.19
PE-600	10	4	33	10	1,320	100,000	14.03	75.76
TO-400	14	8	33	6	3,696	166,667	23.36	45.09
TO-600	22	4	33	7	2,904	142,858	21.72	49.19
ZU-400	14	8	33	5	3,696	200,000	19.65	54.11

According to the Spanish law (Royal Decree 888/1988 https://www.boe.es/eli/es/rd/1988/07/29/888), these types of boxes can only be used once. Therefore, no cleaning or other related processes were involved. Thus, a cardboard box ends its service life once the transport is complete.

2.3.3 End-of-life of the boxes

Two processes were considered at this stage: (1) transport to the waste treatment center and (2) the waste treatment processing (Fig. 8). After use, all boxes were managed at the destination. However, a small percentage (0.1%) usually break during the assembly, which was managed in Spain.

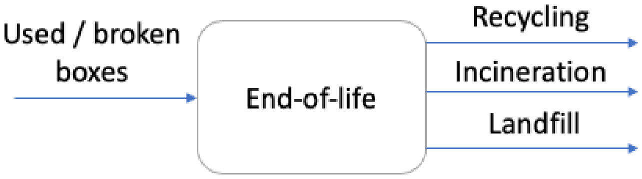

Fig. 8 Waste treatment process (see Fig. 3 for further details).

Table 11 shows the data collected for all of the end-of-life processes for each country involved. Eurostat (2017) was chosen as the most reliable data source; although information is available for 2014, the database used in this study was for July 2017.

Table11 Distribution of processes applied for cardboard waste treatment by country (Eurostat, 2017)

Country	Incineration / energy recovery	Recovery, except energy recovery	Incineration with energy recovery at waste incinerators	Material recycling	Other recycling including compost
FRANCE	0.00%	0.00%	5.15%	94.43%	0.42%
GERMANY	12.28%	0.00%	0.03%	87.33%	0.36%
NETHERLANDS(1)	0.00%	0.00%	24.59%	75.41%	0.00%
SPAIN	0.00%	0.00%	5.38%	94.62%	0.00%

(1) Only for the sensitivity analysis

The end-of-life stage closes the life cycle loop with the unit process of recycling cardboard, as previously described (Fig. 9).

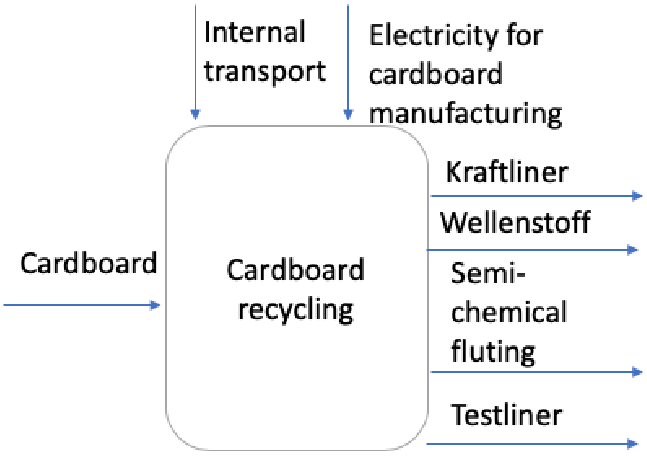

Fig. 9 Cardboard recycling process (see Fig. 3 for further details).

2.4 Impact assessment

The impact assessment was conducted following the methodology described in Section 2 using SimaPro software (Pre-sustainability, 2019). Version 1.02 of Intergovernmental Panel on Climate Change (IPCC) 2007 GWP 100a method was chosen for the assessment. For this, the characterization factors were based on the IPCC 4th assessment report (Foster et al., 2007).

The results of the impact assessment are shown for each product system in Table 12. The assessment compared both destinations, considered a 0.1% damage rate, and the different box dimensions as previously described.

Table 12 CF results by product system

Destination:	**France (1,500 km)**				**Germany (2,500 km)**			
	Carbon Footprint (tCO$_2$e)							
Product system	Cardboard box manuf.	Transport of loaded boxes	End-of-life of boxes	**Total**	Cardboard box manuf.	Transport of loaded boxes	End-of-life of boxes	**Total**
CA-400	61.87	6.26	1.42	**69.55**	61.87	10.43	2.37	**74.67**
CU-400	61.87	6.26	1.42	**69.55**	61.87	10.43	2.37	**74.67**
EP-400	103.12	13.78	2.37	**119.27**	103.12	22.97	3.95	**130.04**
PE-600	64.39	8.27	1.42	**74.09**	64.39	13.78	2.37	**80.54**
TO-400	52.24	4.31	1.20	**57.75**	52.24	7.18	1.99	**61.41**
TO-600	69.77	5.53	1.53	**76.84**	69.77	9.22	2.56	**81.55**
ZU-400	61.87	6.26	1.42	**69.55**	61.87	10.43	2.37	**74.67**

3. Results and Discussion

It is evident that the physical properties of each fruit and vegetable, such as their dimensions and weight, have a direct influence on the container system used to store and transport 1,000 t of product by road from its origin to the destination market. Figure 10 and Fig. 11 show a comparison of the CF of each product system for the same destination.

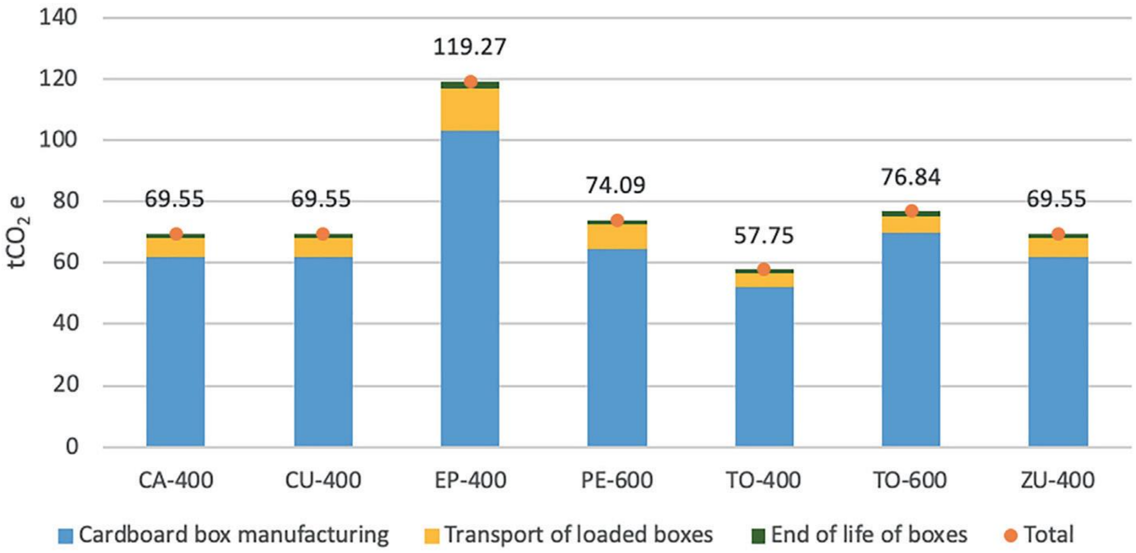

Fig. 10 CF results for all product systems destined for France (1,500 km)

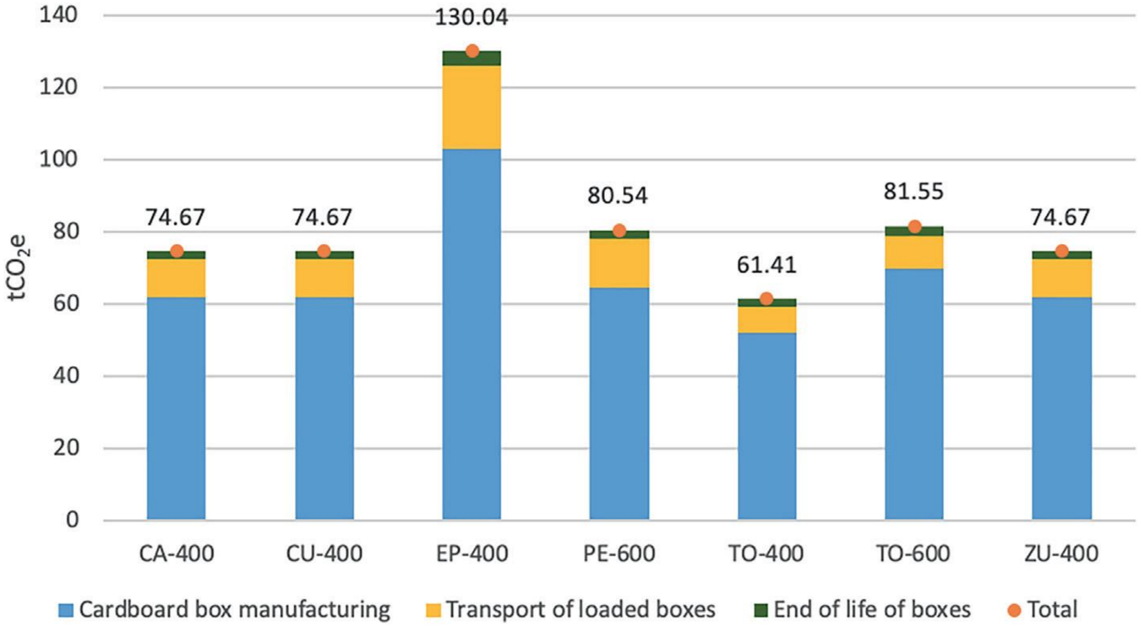

Fig. 11 CF results for all product systems destined for Germany (2,500 km)

The results highlight that, for both the destination markets, a higher impact for eggplants, at 56% over the average impact for France and increasing up to 58% over the average impact for Germany. A difference of more than 60 tCO_2e between eggplants, which had the highest impact, and tomatoes, which had the lowest impact, when transported in 400 mm boxes to both markets. Cantaloupes, cucumbers, and zucchinis had the same level of impact for both markets as the characteristics of their transport and packaging were the same.

The key parameter in this comparison and the main difference between each product system was the actual load of the cardboard boxes (see Table 4). Eggplants and peppers had a 0.40% and 0.33% difference between the maximum capacity and the actual load, respectively. However, as peppers were transported in larger boxes (600 × 400 × 200 mm^3) compared to eggplants, 233,334 extra boxes were required to transport 1,000 t of product, reducing the CF of peppers in both scenarios.

The results showed that storing and transporting 1,000 t of product by road from Almería to the destination markets emits an estimated 58 t to 130 t of CO_2e depending on the fruit or vegetable and the destination market. The end-of-life stage contributed under 4% of the total emissions for all the scenarios while the contribution of transporting loaded boxes varied between 7% and 17%. Predictably, scenarios with Germany as the destination had a greater CF.

It is important to note that the system boundaries of the analysis did not include the production of the transported vegetables and fruits. Nevertheless, previous studies have assessed the CF of this phase. For example, Pérez Neira et al. (2018) calculated an average CF of 136 t CO_2e per 1000 t for the production of tomatoes in the south of Spain on conventional farms. Considering this, the container system used to store and transport 1,000 t of product by road to France and Germany accounted for 36% and 37% of the total CF, respectively, for tomatoes transported in 600 × 400 × 90 mm^3 boxes. A comparison between the same life cycle phases in other studies was not possible as the functional units and scope of the existing studies cited in the introduction are different, i.e., oranges were the products transported and the destination was to local markets instead of exports.

Biogenic CO_2 was considered separately, as established following ISO 14067:2018. Although it is not mandatory, CO_2 emissions were also included due to land transformation and absorption. Figure 12 shows CO_2 emissions due to each source.

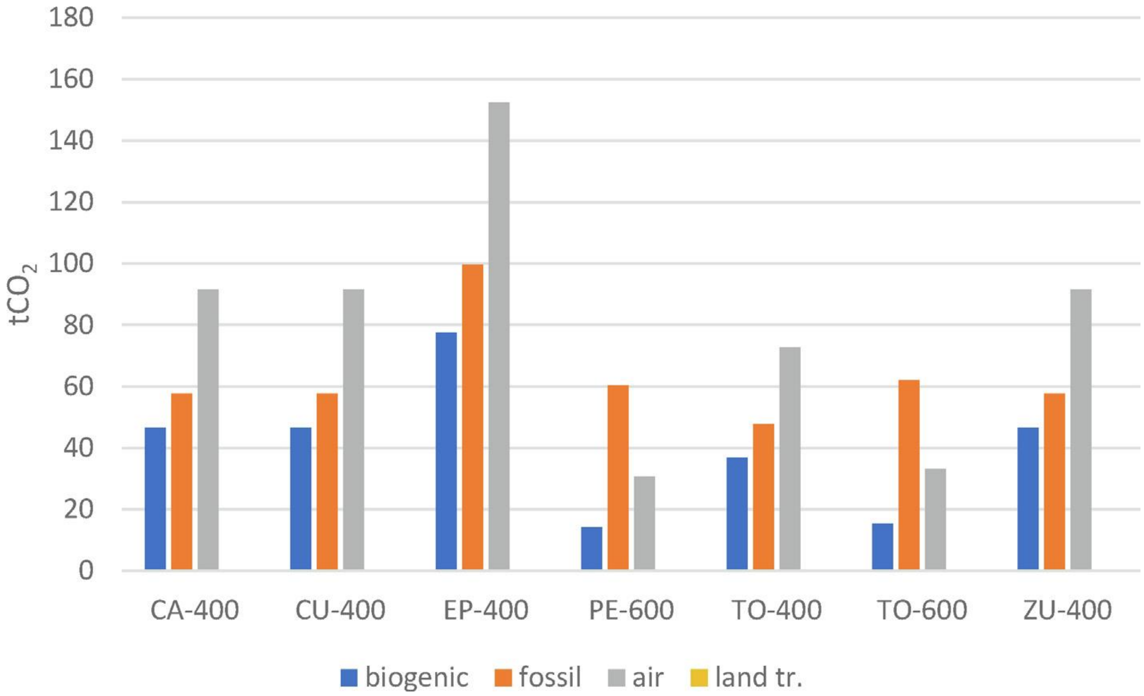

Fig. 12 a. CO_2 emissions by origin for product systems destined for France (1,500 km).

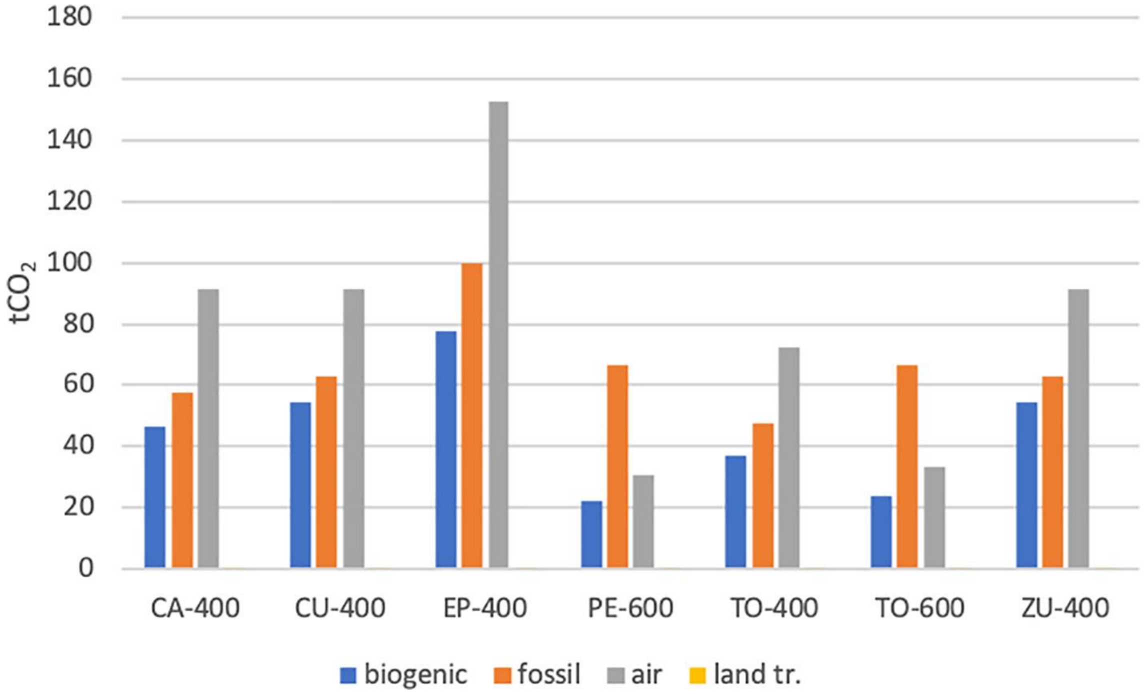

Fig. 12 b. CO_2 emissions by origin for product systems destined for Germany (2,500 km)

Emissions due to biogenic CO_2 were present in all the stages of the life cycle. Figure 13 shows the distribution of emissions by life cycle stage. A major proportion of the biogenic CO_2 emissions was from the manufacturing stage due to the raw materials used and the paper fibers.

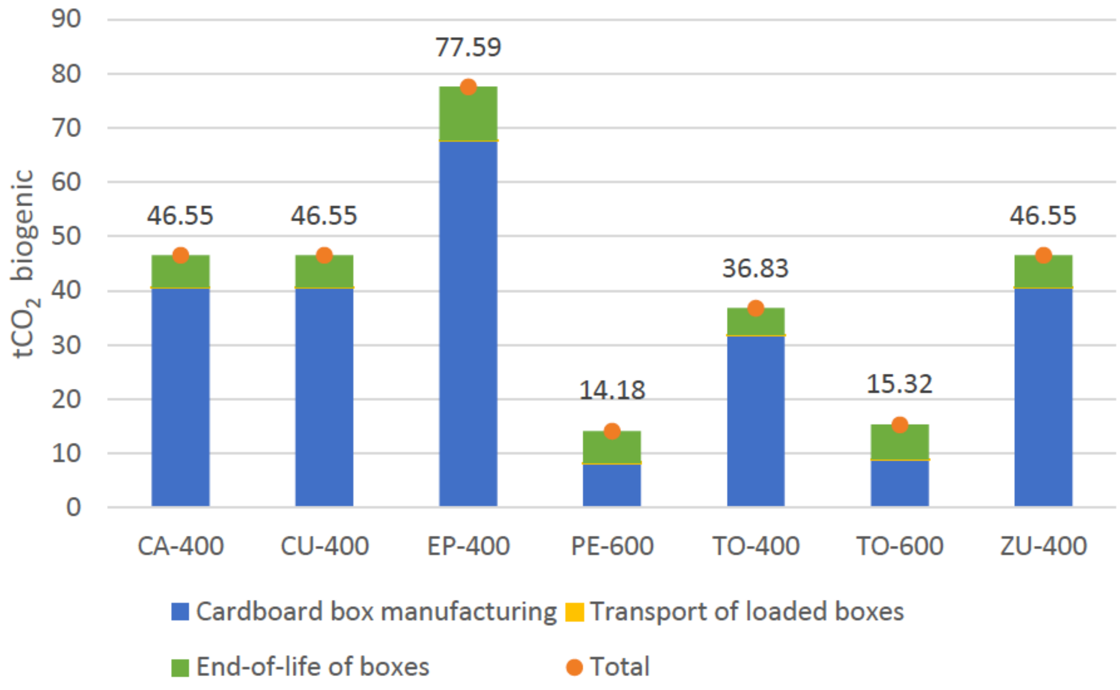

Fig. 13a. Biogenic CO_2 for product systems destined for France (1,500 km).

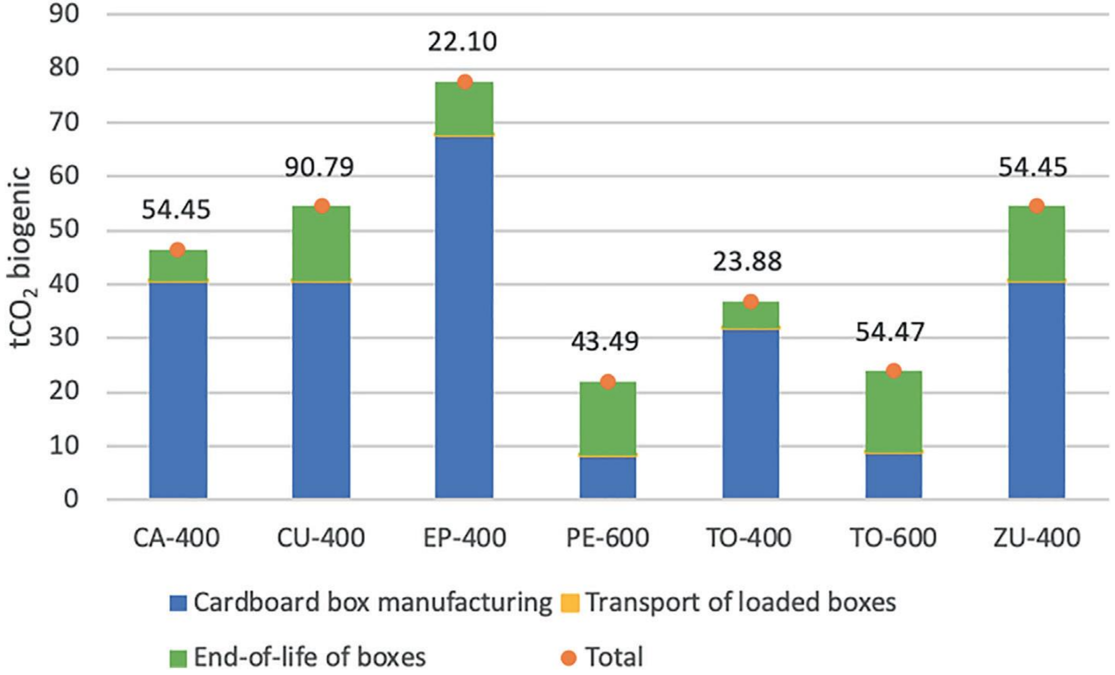

Fig. 13b. Biogenic CO_2 for product systems destined for Germany (2,500 km).

Figure 14 shows the results of the sensitivity analysis of the distance for tomatoes transported in 600 × 400 × 90 mm^3 boxes, the main product exported to these markets. For this analysis, the Netherlands was considered as a third destination. The results show a positive but non-linear relationship between distance and the CF.

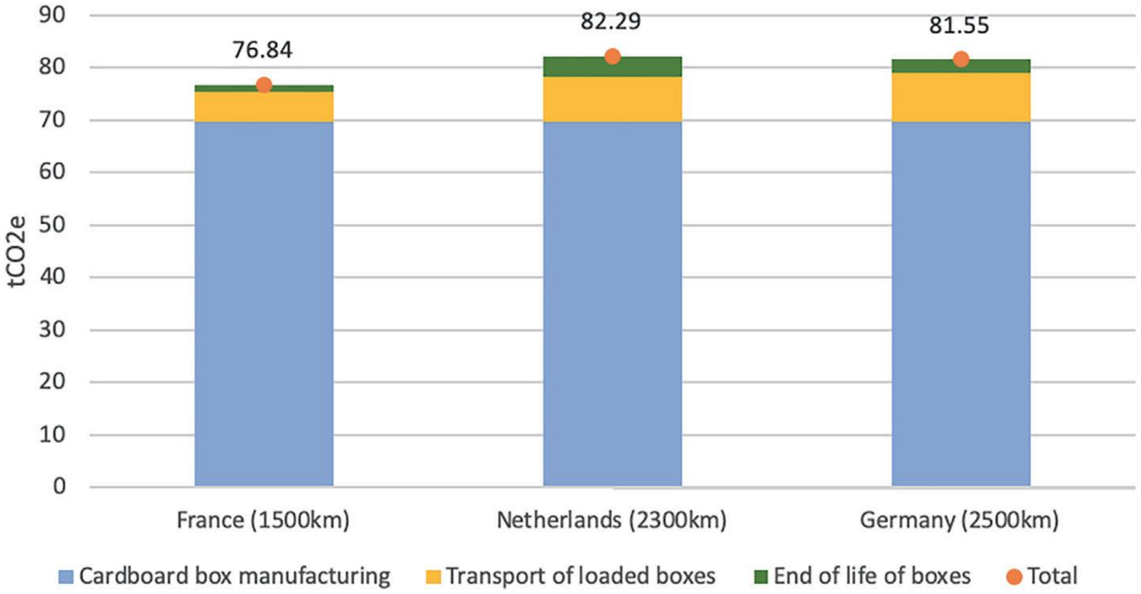

Fig. 14 Sensitivity analysis for the CF of product system TO-600 considering France (1,500 km), the Netherlands (2,300 km), and Germany (2,500 km).

Although distance had a significant influence on the CF, the end-of-life phase can also lead to a large volume of emissions. The waste treatment processes, which defers from one country to another, also influenced the CF with respect to distance. Following the methodology and inventory analysis described, material recycling was assigned as a benefit for the manufacturing stage. However, incineration with energy recovery and landfill generated a direct contribution to the emissions during the end-of-life stage. The share of incineration for the Netherlands (24.59%) was significantly higher than for France (5.15%) and Germany (0.03%) (see Table 11).

4. Conclusions

The CF was found to be a useful environmental indicator to assess the impact of the target functional unit, defined as the container system to store and transport 1,000 t of product by road from the south of Spain to the dominant export markets of France and Germany.

Although all phases of the life cycle influenced the CF, the transport distance and the end-of-life scenario—which depends on the destination country—were the key factors affecting emissions.

The further study of other types of fruit and vegetables such as citrus fruits and leafy vegetables could provide further information, particularly as their containers may be different owing to the characteristics of each product (i.e., more resistant and different shapes). Other destination markets with different end-of-life scenarios could also be considered to improve the available information on CFs.

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