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Greenhouse gas emissions and energy consumption during the post-harvest life of apples as affected by storage type, packaging and transport

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A B S T R A C T

In this study, the life cycle assessment (LCA) has been applied to analyze the greenhouse gas (GHG) emissions and energy requirements in the post-harvest life of apples from the Trentino-South Tyrol region (Northern Italy). Data were collected over four years from two commercial apple packinghouses. The key processes in the supply chain were identified based on direct observation, and different scenarios for conservation, packaging, and transport, as well as the source of electricity were analyzed.

The results showed that the packaging was the main contributor to both the global warming potential (GWP, from 68 to 98 gCO_{2eq} per kg of apples) and to the cumulative energy demand (from 1.3 to 1.9 MJ/kg). The cooling process (i.e., initial refrigeration and maintaining the cool temperature) that the fruit undergoes before being stored was the second largest contributor to the environmental effects produced during the apple post-harvest. The use of renewable energy is an attractive option to drastically reduce the GWP of this phase. If long transportation distances need to be covered (for example for export, or distances exceeding 300 km), using rail transport or shipping could cut down substantially the environmental costs. The most favorable environmental performances during the post-harvest of the apple include the storage by controlled atmosphere (CA), the delivering of fruits in large reusable plastic bins and their transport over short distances.

1. Introduction

Agricultural practices contribute to environmental problems (Notarnicola et al., 2017) including the depletion of resources, the emission of greenhouse gases (GHGs) (Tilman et al., 2001) and a significant segment of consumers is becoming increasingly aware and concerned about environmental sustainability (McLaren et al., 2010; Moser and Raffaelli, 2012).

Life cycle assessment (LCA) is an important tool for assessing the environmental sustainability associated with agri-food systems and represents a reference method to analyze the global environmental performance of produces (Longo et al., 2017; Sala et al., 2017). The LCA principles, framework, and requirements are defined by Guinee (2002) and by two international technical standards (ISO, 2006a, 2006b). The results of LCA can be used by different stakeholder groups as a supporting tool for decision-making (Cellura et al., 2012; Notarnicola et al., 2017; Pennington et al., 2007).

Italy is the second-largest apple producer in Europe, and approximately 70% of Italian apples are produced in the Trentino-Alto Adige region in Northern Italy (Provincia Autonoma di Bolzano, 2015). Several LCA studies (Akdemir et al., 2012; Alaphilippe et al., 2013; Blanke, 2013; Cerutti et al., 2015, 2013; Milà i Canals et al., 2006; Mouron et al., 2006) assessed the environmental effects of apple production in the so called ‘cradle to farm gate’ phase. Once apples have been harvested, they undergo the so-called ‘*post-harvest*’ phase that includes cooling, cleaning, sorting,

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and packing operations (Rees et al., 2012). After a storage period (from a few days to 12 months), apples are transported from the packinghouse to regional, national, or international markets. Some LCA studies have expanded the boundaries of their analysis to the post-harvest phase and the transportation of fruit to the retailers (Canals et al., 2007; Frater, 2010; Keyes et al., 2015; Longo et al., 2017; Sessa et al., 2014; Stoessel et al., 2012; Zanotelli et al., 2014), or to the final consumers (Blanke and Burdick, 2005; Jones, 2002; McLaren et al., 2010). Although a body of literature exists on this topic, most studies provide only vague data on or insufficient explanations of the technology, materials, and energy used in the post-harvest period. For example, only few of them provide information or data on the technology of the cooling systems for the conservation of the produce and relatively few studies (Fakouri et al., 2008; Frater, 2010; Longo et al., 2017; Milà i Canals et al., 2007) mentioned which conservation technology had been modeled. Moreover, no or only scant information is provided on the type of packaging (Blanke and Burdick, 2005; Keyes et al., 2015; McLaren et al., 2010), and usually only one type of packaging was analyzed (Cerutti et al., 2011a; Fakouri et al., 2008; Frater, 2010; Longo et al., 2017; Milà i Canals et al., 2007; Sessa et al., 2014). Furthermore, aggregated results are normally given (Keyes et al., 2015; McLaren et al., 2010, Longo et al., 2017, Cerutti et al., 2011b), a fact that does not allow to distinguish the contribution of the individual steps. Specific data and the modeling description of each life cycle phase are essential to make fair and meaningful comparisons among reports and to understand which technology offers a superior environmental eco-profile. Accordingly, as emphasized by Notarnicola et al. (2017), undetailed and incomplete data and different LCA modeling choices, "could potentially lead to misrepresentation of products in the marketplace if comparisons are made between alternative food products on the basis of … biased data."

Against this background, this study aims at: 1) elaborating a consistent and up-to-date life cycle inventory of the post-harvest cycle of apples in the most important Italian apple-producing district; 2) determining the global warming potential (GWP) and the energy required (expressed as cumulative energy demand [CED]) associated with the post-harvest life of apples; and 3) illustrating and discussing the alternatives available for standard operations that could bring about a decrease in GHG emissions and in the energy use during the post-harvest cycle.

To reach these objectives, a comprehensive LCA of the post-harvest chain of apples was conducted, using data collected in actual operating packinghouses in the Trentino-Alto Adige region of Italy. Different conservation technologies, packaging methods, energy sources and transport solutions were investigated.

2. Materials and methods

The LCA conducted in this study, performed according to ISO standards 14040:2006 (ISO, 2006a) and ISO-14044:2006 (ISO, 2006b). The software SimaPro PhD 8.0.3.14, developed by PRé Consultants (PRé Consultants bv, Amersfoort, the Netherlands) was used to model the system and to set up the balances.

2.1. LCA goal and scope definitions

The primary goal of this study was to provide an evaluation of the effects of the post-harvest cycle of apples in relation to climate change and energy requirements. We carried out the LCA to find answers to the following questions, namely, i) what are the effects generated by the post-harvest cycle; ii) which processes require more energy, resulting in higher GHG emissions; and iii) which solutions and technologies could lead to environmental savings?

2.2. System boundaries and functional unit

The boundaries of the system range from the moment the apples arrive from the orchards to the packinghouse (warehouse in Fig. 1) to their final transport to the retailers (Fig. 1). Accordingly, the reference stakeholders are all the players in the post-harvest chain.

Additional storage, transportation and waste of apples that could occur after the apples have reached the retailers were excluded in the assessment (Longo et al., 2017).

The functional unit (FU) we used was 1 kg of fresh apples. A mass-based FU is appropriate when the study refers to a single product or when different management options for the same product are compared (Cerutti et al., 2015). The mass-based FU is used widely in the LCA studies on the fruit sector; therefore, our results can be compared easily with those of other studies.

We assumed that all the apples that enter the packinghouse will also leave it eventually, although we are aware that small losses (up to 2%, according to local data) could occur because of post-harvest diseases or disorders. The energy consumption and the GHG emissions were attributed fully to the total amounts of apples stored in the packinghouse, which were considered the only output of the system, without any grade distinction.

Indeed, the LCA carried out in this study is of the attributional type, that means that all the input (resources, energy, etc.) and the outputs (i.e. GHG emissions and energy consumption) are attributed to the delivery of a specified amount of the functional unit (Thomassen et al., 2008). Since our system does not imply co-products (apple is the only product going out in this study) there is no need for allocation. Our data also refer to the average apple (AA) of the two analyzed packinghouses, using the Italian electricity grid mix (ItMix, see section 2.6.3), which draw a realistic picture of the Italian apple conservation sector. To calculate the effects per kilogram of average apples (kg_{AA}), the following equation was used:

$$I_{AA}=I_{FU}*\text{Weight}(\%),$$

where I_{AA} is the effect per average apple, I_{FU} is the effect per functional unit, and Weight (%) is the proportion of apples managed in each of the supply chain step shown in Fig. 1.

2.3. System description and modeling

The post-harvest system modeled in this study emulated the procedures employed in two packinghouses of similar size located in the Non Valley, in the Province of Trento (Italy). The first one, situated in the lower part of the valley, receives apples from 574 ha, managed by 375 producers, and has an average storing capacity of approximately 34.000 ton apples. The second packinghouse, located in the upper part of the Non Valley, receives on average approximately 36.000 tons of apples from 630 ha, managed by 305 farmers. The main cultivars in the area are Golden (>60%) and Red Delicious (15%), followed by others such us Renetta del Canada, Gala, Fuji, Evelina and Morgenduft. In this study the entire post-harvest cycle of the apples has been divided into the following processes:

1) The handling of the apple bins (approximately 300 kg each), which considers the handling of the bins from the tractors delivering the produce to the refrigeration storage cells. This includes all the handling of the bins occurring during the other steps of the post-harvest production chain, such as pre-calibration, packaging and storage in the picking-room.

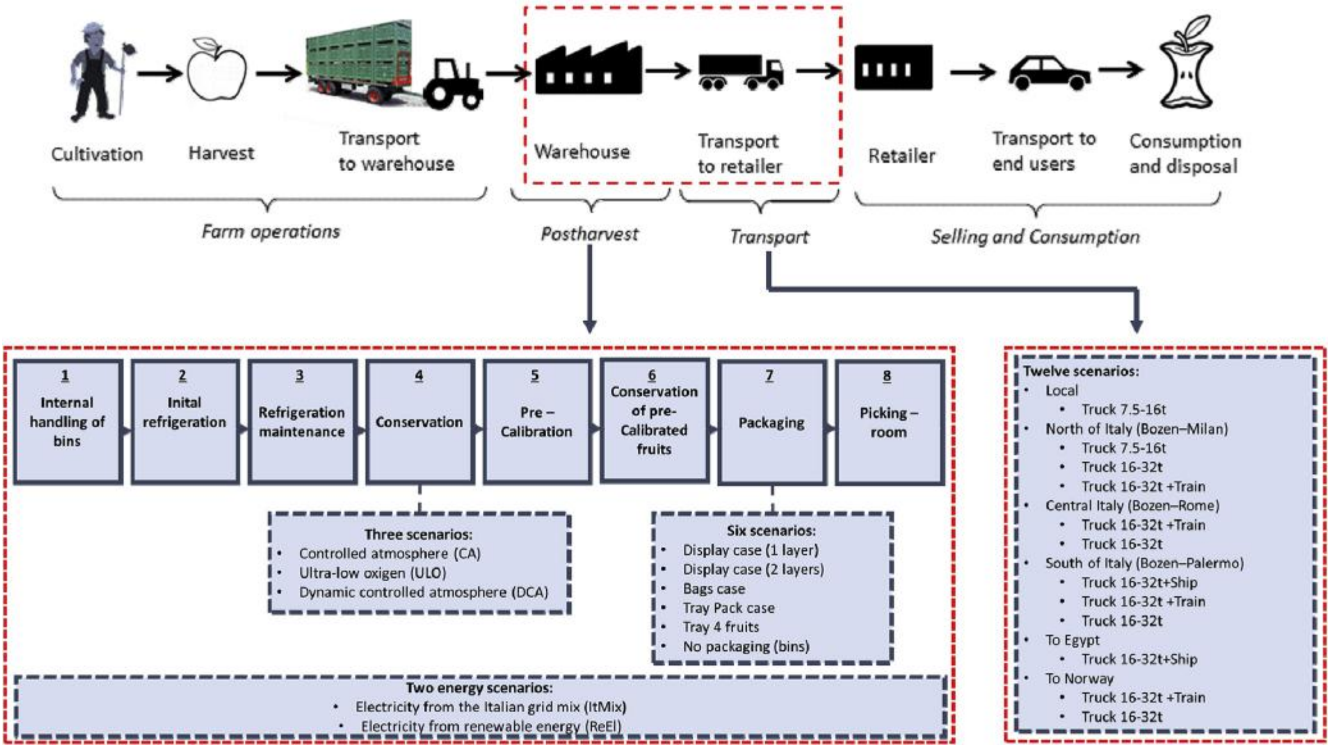

Fig. 1. System boundaries of the analyzed production cycle. The upper part shows the entire apple supply system. The lower part shows a detailed scheme of the modeled post-harvest process. The dotted-line frame shows the system boundaries of this study.

2) Initial refrigeration or pre-cooling of the fruit through forced-air cooling technology, which implies the use of a screw compressor to generate ammonia. This process starts directly after the fruit is loaded into the storage cells.
3) Maintaining the refrigeration in storage cells (refrigeration maintenance process), which includes glycol recirculation to keep the storage cells at a reference temperature of 4 °C.
4) Conservation. After approximately 5–6 days from the initial cooling phase (see point 3), the fruit is subjected to a controlled atmosphere aimed at reducing the rate of metabolism of the stored apples. The internal air is washed by a continuous flux of N_2 produced by a compressor, until the O_2 concentration is below 4%. Subsequently, the metabolic respiration of the apples causes an increase in CO_2 and a further decrease of the O_2 concentration, which is controlled by activated carbon filters. The concentration values of these two key molecules are managed during the whole conservation period according to three different technologies. These are the controlled atmosphere (AC), the ultra-low oxygen (ULO), and the dynamic controlled atmosphere (DCA). A detailed description of these technologies is provided in section 2.6.1. An average storage period (from the initial cooling to the storage of the pre-calibrated fruits) of five months has been assumed in this study.
5) Pre-calibration. When the storage cells are unloaded, the apples undergo selection and pre-calibration phases, the bins are emptied into water conduits that deliver the apples to a scanner that separates them based on their size.
6) Storage of the pre-calibrated fruits. Approximately 50% of the apples are divided according to their size and quality, and are re-allocated to conditioned rooms, where they are stored in a refrigerated environment for a maximum of one month. The remaining 50% of the apples are sent directly to packaging.
7) Packaging. We analyzed separately the main packaging methods used by the two packinghouses. A description of the different scenarios is given in section 2.6.2 and Table 2.
8) Picking-room, where the apples are stored for a brief time after packaging in a conditioned room, before being loaded onto the trucks and dispatched to the markets.
9) Transport to large-scale retail outlets. Most apples (78%) are sold in Italy, the rest is sent abroad, mainly in North Africa (Egypt in particular) and northern Europe (especially Norway) (Provincia Autonoma di Bolzano, 2015). The transport scenarios investigated are described in detail in section 2.6.4.

2.4. Data collection and life cycle inventory (LCI)

Only the *direct inputs* of energy and materials used in the packinghouse were included in the assessment, i.e., only the direct consumables were included (such as the direct consumption of electricity, fuels, materials, and compounds for the operation of machinery). The raw materials and energy used for the construction, maintenance, and disposal of the buildings and the post-harvest facilities are outside the system boundaries of our analysis and were not considered.

The materials and energy used to assemble the different packages have been included, whereas the effects deriving from their disposal were excluded, because out of the boundaries of our system.

The inventory data on the materials and the energy consumption related to all the phases of the post-harvest were collected on site through surveys, direct measurements, and interviews with the managers and operators of the two packinghouses. The collected data refer to the average figures obtained for four operating years (2011–2014), whereas the data on the background processes were obtained from the Ecoinvent Database v3 (Wernet et al., 2016). All the direct inputs required in the post-harvest chain are presented in Table 1 and the inputs related to packaging are presented in Table 2.

As regards transport, only the direct expenditure for the operation and maintenance of the carriers (such as diesel or fuel used during the transport, lubricating oil, battery, and the like) is included in the analysis in order to stay within the system boundaries. We modeled the most frequent transport options occurring at the two packinghouses, as reported by the experts during the interviews. The foreground and background data related to the transport processes were obtained from the Ecoinvent Database v3 (Wernet et al., 2016). We disregarded the backhaul journeys in all the transportation options, as we assumed that these were used for hauling other cargo, in agreement with the practices of modern logistics providers. The fuel consumption for transportation is presented in Table A2 in the Appendixes.

The latest data on the energy sources that comprise the Italian electricity grid mix were obtained from the International Energy Agency (IEA, 2016), relevant to 2015. For each type of fuel, we considered the phases of extraction, transport, refining, storage, conversion to electricity, and waste disposal, as reported in the database (Wernet et al., 2016). The data on the types of renewable energy we investigated (such as hydropower in alpine areas and photovoltaic power) were obtained from the Ecoinvent Database v3 (Wernet et al., 2016).

2.5. Life cycle impact assessment (LCIA)

We focused our assessment on the global warming potential (GWP) and the cumulative energy demand (CED) only, as their reduction is a priority in the EU agricultural policy (Caffrey and Veal, 2013; Cerutti et al., 2015; EC, 2013). The GWP is an index for estimating the relative global warming contribution attributable to the atmospheric emission of greenhouse gases (GHG) (Albritton and Meira-Filho, 2001) and the effects on climate change. To calculate the GWP we used the method suggested by the Intergovernmental Panel on Climate Change (IPCC, 2007).

We chose the CED method (CED v1.8, Hischier et al., 2010) to assess the primary energy used along the whole apple post-harvest chain. This method calculates the direct and indirect energy used throughout the life cycle of a product and differentiates among renewable and non-renewable energy sources (Huijbregts et al., 2006), allowing to calculate the environmental effects related not only to the emissions but also to the consumption of energy (Girgenti et al., 2013). In our study, the CED was calculated by including both non-renewable (from fossil fuels, nuclear, and non-renewable biomass) and renewable (from wind, solar, geothermal, and water) energy sources.

2.6. Sensitivity analysis and scenario modeling

Considering the uncertainty and variability in LCA studies, it is crucial to determine both the validity of the collected data (Beccali et al., 2010; Cerutti et al., 2015) and the reliability and robustness of the final results (Cellura et al., 2011; ISO, 2006a, 2006b; Notarnicola et al., 2017). As explained by Huijbregts (1998), the different types of uncertainties can be distinguished in: parameter uncertainties, model uncertainty and uncertainty linked with choices. The robustness of our parameters and modeling should be considered very high since we based our analysis on real measured data, while the model represents real functioning warehouses. We focus on analyzing uncertainties due to choices. We applied the sensitivity analysis, a procedure to determine how changes in data and methodological choices affect the results of the study (Cellura et al., 2011; Huijbregts, 1998). In our study, sensitivity analysis was performed by adopting the 'scenario analysis' method (ISO, 2006b), where the values of selected parameters are changed at a single time. We modeled different scenarios for conservation, packaging, transport, and electricity production, which represent the actual and real options available in the post-harvest sector.

2.6.1. Storage scenarios

The purpose of storage is maintaining the organoleptic and aesthetic characteristics of the fruit over time. The conditioning of the atmosphere, associated with refrigeration, evolved over time and, currently, allows the maintenance of the fruit quality characteristics and the shelf life requirements for extended periods (up to ten months after harvesting).

The following three main storage technologies have been applied in our analysis (Table 1):

- Controlled atmosphere (CA) is the most traditional storage system and approximately 10% of apples are stored in this way. A typical atmospheric composition under this regime includes oxygen (O_2) and CO_2 at approximately 3% and N_2 at approximately 94%.
- Ultra-low oxygen (ULO) is the evolution of CA, where the O_2 level is reduced to between 1.0 and 1.3%, CO_2 usually does not exceed 2.5%, and the N_2 concentration is approximately 97%. Approximately 75% of the apples are stored according to the ULO system.
- Dynamic controlled atmosphere (DCA) represents the last step in the evolution of storage technologies. The technology reduces the incidence of apple loss caused by physiological disorders. The oxygen is brought down to extremely low levels ($O_2 < 0.6\%$ and $CO_2 < 1.2\%$), and a parallel assessment of the physiological behavior of the apples is carried out. The restoration of gaseous formulas to less-restrictive respiratory conditions is done

Table 1
Direct inputs of the post-harvesting processes. Inputs are given per FU (1 kg of apples).

Processes		Electricity inputs (kWh)	Other inputs (g)	
1	Internal handling	0.0003	–	
2	Initial refrigeration	0.0391	ammonia	0.13
			ethylene glycol	5
			lubricating oil	0.02
3	Refrigeration-maintenance	0.056	–	
4	Conservation:			
CA		0.0142	lubricating oil	0.0003
ULO		0.0162	lubricating oil	0.0003
DCA		0.022	lubricating oil	0.0003
5	Pre-calibration	0.0189	–	
6	Conservation of the pre-calibrated fruit	0.056	–	
8	Picking-room	0.0018	–	

Table 2
The materials and energy needed to assemble different types of packaging, including data regarding the wooden pallets used for their transport. (PP = polypropylene, PS = polystyrene, PET = polyethylene terephthalate, LDPE = low-density polyethylene, HDPE = high-density polyethylene).

Packaging section	Material	Packaging scenarios					
		Display case (1 layer)	Display case (2 layers)	Bags case	Tray pack case	Tray 4 fruit	Bin
Packaging		weight (g)					
Case/box	Corrugated board	314	472	900	1271	900	
Celled-tray	PP	15	32				
Celled-tray	Cellulose pulp				350		
Tray	PS					5.6	
Plastic film	PET	2.7	2.7			3.8	
Plastic bag	PET			75.5	13		
Bubble wrap	LDPE				10		
Bin	HDPE						37000
Total material (kg)		0.33	0.51	0.98	1.64	0.91	37
Electricity to pack one piece (Wh)		6	6	9	manual	9	–
Weight of apples contained per package (kg)		4	8	20	18	19	300
Pallet		weight (kg)					
Pallet	Wood	10					–
Staples	Steal	0.01					–
Straps	HDPE	0.1					–
Angular border	Corrugated board	1.87					–
Number of packages piled in one pallet		176	104	35	49	35	–

according to the appearance of objective stress signals, commonly detected by measuring alternatively the chlorophyll fluorescence and the respiratory quotient, or by analyzing the metabolites (Zanella and Stürz, 2015). This conservation method is applied to approximately 15% of the apples.

2.6.2. Packaging scenarios

We considered the following major types of packaging used by the two packinghouses (Table 2):

1) Display case (one layer), comprising a paperboard case, a celled plastic tray to position the apples, and a plastic film to cover them.
2) Display case (two layers), similar to the previous one, but with two layers of fruit and a double layer of celled plastic trays.
3) Bags case, a simple plastic bag in which the apples are placed and that is placed in a paperboard box.
4) Tray pack case, formed by a covered paperboard box, coated internally with a plastic layer. The apples are placed in four cellulose-pulp cell layers, and the top apple layer is protected with a bubble-wrap sheet.
5) Four-fruit tray that is a small polystyrene tray, covered with plastic film, that contains four apples. A paperboard box is used as a further protective package, containing 20 trays.
6) No packaging, which means the apples are sold in large plastic bins, which are returned to the cooperative and reused repeatedly.

Before loading onto the trucks, all the packages (with the exception of the bins), are piled on wooden pallets. Details about packages are reported in Table 2.

Usually, bins are used for the local fruit selling, tray-packs are preferred in the international trade, whereas all the other packages are used in the national market.

2.6.3. Electricity scenarios

Two scenarios have been considered. One (named ItMix) is the most used option at national level, where electricity from the Italian national grid mix is used by the packinghouses. The source of the electricity grid is mainly fossil fuel (IEA, 2016), as shown in Table 3. An additional scenario, based on renewable resources (called ReEl) is depicted, where electricity is entirely derived from hydro- and photovoltaic power. The two storage facilities analyzed in our study, in fact, currently buy electricity only from a company that produce energy exclusively from hydropower plants. In addition, 12% of the electricity needed in the post-harvest process is produced in-house, by means of photovoltaic panels (Table 3). The shares of renewables have been measured, and the energies used from the two facilities are certified. We applied these two scenarios to the operations carried out by and within the warehouses only.

2.6.4. Transport scenarios

Three distribution scenarios, differing in the mode and in the length of transportation, have been considered and modeled (Table 4). These are:

1) local distribution with a small truck (7.5–16 t) to cover an average distance of 50 km;
2) a national distribution scenario, subdivided into three different areas, namely, i) short-distance distribution in Northern Italy (on average 300 km, for example from Bolzano to Milan), which can be carried out by three different carriers, such as small trucks (7.5–16 t), an articulated lorry (16–32 t), and rail transport (train); ii) medium-distance distribution (on average 600 km, for example from Bolzano to Rome, Central Italy), covered by an articulated lorry of 16–32 t or by train; and, iii) long-distance distribution (from Bolzano to Palermo in the southern part of Italy, 1500 km), covered by road (with a 16–32 t container truck), by rail, or by sea (with a transoceanic tanker);
3) international transport options, at continental level (Europe) (from Bolzano to Oslo, 1850 km) or overseas (from Bolzano to Alexandria in Egypt, 4800 km), carried out by truck, train, or a transoceanic tanker, depending on the final destination.

When the railway option ('train') was used, we included in the scenario the distance from the packinghouse to the departure train station, and from the destination train station to the retailer (100 km with a 16–32 t truck). When the option 'ship' was used, this distance was included, which varied according to the location of the shipping port.

Table 3
Percentage of electricity sources involved in the two electricity production options, i.e., electricity from the Italian grid mix (ItMix), and electricity obtained from renewable energies (ReEl). Emission factors related to the GHG emissions and the energy requirements are given.

Electricity scenario	Sources	Shares %	Emission factors GHG *kgCO2eq/kWh*	Emission factors Energy *MJ/kWh*
Italian electricity grid mix (ItMix)	natural gas	38	0.521	8.985
	hard coal	17		
	hydropower	16		
	photovoltaic	9		
	oil	5		
	wind	5		
	biogas	3.1		
	geothermal	2		
	waste	1.7		
	biofuel liquid	1.7		
	biofuel solid	1.5		
Renewable electricity (ReEl)	hydropower	88	0.013	4.002
	photovoltaic	12		

Table 4
Transport scenarios. The loads change according to the packaging used. In the last column, the share of transported apples according to the scenarios is reported.

Transport scenarios		Means of Transport	Average km	Load (t)	% apple
Local		Truck 7.5–16 t	50	10–14	7.8
National					
	short-distance distribution	Truck 7.5–16 t	300	10–14	23.4
	Northern Italy (e.g. to Milan)	Truck 16–32 t		19–24	
		Truck 16–32 t + Train	100 + 200		
	medium-distance distribution	Truck 16–32 t	600	19–24	23.4
	Central Italy (e.g. to Rome)	Truck 16–32 t + Train	100 + 500		
	long-distance distribution	Truck 16–32 t + Ship	500 + 1000	16–20	23.4
	Southern Italy (e.g. to Palermo)	Truck 16–32 t + Train	100 + 1500		
		Truck 16–32 t	1500		
International					
	to Egypt	Truck 16–32 t + Ship	300 + 4500	16–20	15.4
	to Norway	Truck 16–32 t + Train	100 + 1750	16–20	6.6
		Truck 16–32 t	1850		

3. Results

3.1. Contribution of single processes

The contribution of the average apple (AA) in each phase of the post-harvest processes to the GWP and CED is presented in Table 5.

The average GWP using the ItMix electricity scenario, amounted to 164.5 gCO_{2eq}/kg_{AA} (Table 5), 92.4% of which is due to emissions of fossil CO_2. These emissions were generated mainly during the production and the use of non-renewable energies (60%), and during the production of raw materials used in the post-harvesting cycle, especially for packaging. The CED was 3.06 MJ/kg_{AA}, 96% of which represented by non-renewable energies, especially from fossil sources (91%).

Packaging had the highest effect of all the various processes on GWP and CED, being 44% and 46.1%, respectively (Table 5). The initial refrigeration accounted for 17.4% of the GWP and 19.7% of the CED. The GWP of this process derived mainly (70%) from the emission related to electricity production and the production of the ethylene (27%). The cold-keeping process generated 17.7% of the GWP and 15.7% of the CED of the AA, ascribed entirely to the production and consumption of electricity (Table 5). Carbon dioxide and methane accounted for almost all (98%) the GWP involved in the initial refrigeration and refrigeration maintenance phases.

The pre-calibration phase accounted for 6% of the GWP and the 5.3% of the CED, while the conservation of the pre-calibrated fruits contributed approximately for 9% of the GWP and for 8% of the CED. The conservation of the AA accounted for 5.3% of the GWP and 4.7% of the CED (Table 5), almost entirely as a consequence of electricity production and consumption, and the emissions of fossil CO_2.

3.2. Sensitivity analysis results

3.2.1. Scenarios for different conservation atmosphere

The three methods for controlling the conservation atmosphere showed slight differences in terms of GWP and CED (Table 5). DCA had the highest effect on GWP and CED because of its higher electricity demand (0.022 kWh of electricity per kg of apples) compared with the other techniques (0.014 and 0.016 kWh/FU for CA and ULO, respectively).

3.2.2. Packaging scenarios

The GWP and the CED per FU of the six different packaging methods are presented in Table 5. The GWP derived mainly from the CO_2 emitted by the fossil fuels during the production and processing of the raw materials (from 86% for the bin to 92.2% for the tray pack). The production of the polyethylene was the main contributor to the GWP of the bins (63%), whereas the corrugated board production (28%) and the polystyrene production (22%) contributed to the GWP of the “tray four fruits” packaging method. The production of the corrugated board accounted for most of the GWP in the other packages (approximately 42% for the display case ‘1 layer’, 40% for the display case ‘2 layers’, 38% for the tray pack, and 35% for the bag case).

On average, the CED of the packages was caused by the electricity and the energy required for the production processes

Table 5
GWP and CED of the post-harvest chain. GWP is expressed in gram of CO_{2eq}, CED is expressed in MJ. Results refer to the FU (1 kg of apples) and to 1 kg of an 'average apple' (AA), which represents the average apple of the Trentino-Alto Adige region that is managed according to the proportion reported in the column 'Weight (%)'.

Supply chain steps			Impact/FU		Weight (%)	Impact/AA	
			GWP (gCO_{2eq})	CED (MJ)		GWP (gCO_{2eq})	CED (MJ)
1	Internal handling		0.135	0.002	100	0.135	0.002
2	Initial refrigeration		28.623	0.604	100	28.623	0.604
3	Refrigeration-maintenance		29.181	0.482	100	29.181	0.482
4	Conservation	*CA*	*7.399*	*0.122*	*10*		
		ULO	*8.442*	*0.139*	*75*		
		DCA	*11.464*	*0.189*	*15*		
		Total Conservation			100	8.791	0.145
5	Pre-calibration		9.874	0.163	100	9.874	0.163
6	Conservation of the pre-calibrated fruit		29.181	0.482	50	14.590	0.241
7	Packaging	Display case (1 layer)	*94.658*	*1.744*	*35.55*		
		Display case (2 layers)	*77.796*	*1.480*	*31.6*		
		Bags case	*68.096*	*1.294*	*3.95*		
		Tray pack case	*98.213*	*1.723*	*3.95*		
		Four fruits tray	*92.554*	*1.880*	*3.95*		
		No packaging (bin)	*18.620*	*0.620*	*21*		
		Total packaging			100	72.370	1.411
8	Picking-room		0.951	0.016	100	0.951	0.016
Total average apple						164.52	3.06

(approximately 74%), and by the processes related to the plastic production.

The higher the amount of packaging material used, the higher the GWP and CED per kilogram of fruit (Fig. 2). Accordingly, the no-packaging solution, like the large plastic bin, showed the lowest GWP and CED per functional unit. The construction of a single large bin requires 37 kg of high-density polyethylene (HDPE), corresponding to GWP of 111.7 $kgCO_{2eq}$ and CED of 3919.4 MJ. However, as it contains approximately 300 kg of apples and can be reused for its entire life cycle (we assumed a lifetime of 20 years), this option performed better than the others.

The bag case is the package option with the second least effect, as a small amount of material is used per kilogram of packed apples (48.8 g/kg). Moreover, it is made from corrugated board (92%), which does not present significant levels of GWP and CED (Table A1).

The tray pack and the display case (one layer) had the highest GWP at 98.2 gCO_{2eq}/FU and 94.7 gCO_{2eq}/FU, respectively. This is attributable to the high amount of packaging material per kilogram of packed fruit (91.3 g/kg in the tray pack and 79.2 g/kg in the one-layer display case). The four-fruit tray had the highest level of CED due to the highest amount of plastic used per kilogram of apple.

3.2.3. Energy scenarios

Switching from fossil fuels-based electricity generation to renewable energy sources significantly reduced the GHG emissions. As shown in Table 6, the ReEl caused an average reduction of approximately 50% in the GWP effect and a reduction of approximately 25% of CED as compared with the ItMix. Significant benefits derived from the shifting of energy sources occurred in all the electricity-dependent phases of the post-harvest cycle. As most of the energy consumed in the packaging phase falls outside the system boundaries of this study, switching from fossil fuels-based electricity to renewable energy sources had no effect on the GWP and on the CED of packaging (Tab. 6).

3.2.4. Transport scenarios

The specific GHG emissions and energy requirements relevant to each type of transport carrier considered in this study are given in Table A3.

The fossil-fuel CO_2 emitted during transport was responsible almost entirely for the GWP of all the processes associated with transport (Figs. 3 and 4).

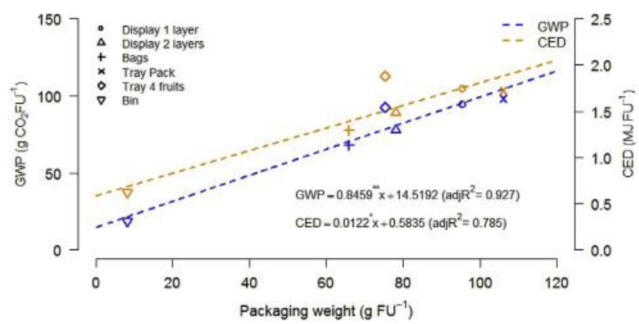

Fig. 2. Correlation between package weight and GWP/CED. The slope parameter of the linear models was significant at the 95% (*) and the 99% (**) probability levels for CED and GWP, respectively.

As expected, short-distance transport (~50 km) generated the least effects (on average, 10.64 gCO_{2eq} and 0.16 MJ per FU). Using rail or ships could lead to a significant reduction in the environmental effects, especially for distances exceeding 300 km. For example, if apples were shipped to Southern Italy, a reduction of 65% in both GHG emissions and CED compared with road transport by truck would be expected. Similarly, transporting apples by rail contributes to a reduction of 72% in GHG emissions and an energy saving of up to 70%. The transport of apples to the north of Egypt (4800 km) by ship produced lower GWP and CED per kilogram of apples compared with the transport to Rome (600 km) with a standard 16–32 t truck (Fig.s 3 and 4).

Figs. 5 and 6 show the total GWP and CED of the entire post-harvest cycle. For simplicity, we show the results for the ULO conservation scenario, while results for the other two types of conservations are reported in the Appendices (A4 and A5). Data clearly show that the type of transportation causes a significant source of variability in the final results. The GWP ranged from approximately 135 gCO_{2eq} to 502.6 gCO_{2eq}, and the CED from 2.7 MJ to 8.1 MJ per kilogram of apples.

4. Discussion

The results show that the cooling phase and the packaging of the apples play the most important role in GHG emissions and energy

Table 6
GWP and CED of the two electricity scenarios. Results refer to 1 kg of average apples (AA).

Processes		GWP (gCO_{2eq}/kg_{AA})			CED (MJ/kg_{AA})		
		ItMix	*ReEl*	savings (%)	*ItMix*	*ReEl*	savings (%)
1	Internal handling	0.14	0.003	97.5	0.002	0.001	53.5
2	Initial refrigeration	28.62	8.75	69.4	0.60	0.42	29.9
3	Refrigeration-maintenance	29.18	0.74	97.5	0.48	0.22	53.5
4	Conservation	8.79	0.22	97.5	0.15	0.07	53.5
5	Pre-calibration	9.87	0.25	97.5	0.16	0.08	53.5
6	Conservation of pre-calibrated fruit	14.59	0.37	97.5	0.24	0.11	53.5
7	Packaging	72.37	71.87	0.7	1.41	1.41	0.3
8	Picking-room	0.95	0.02	97.5	0.02	0.007	53.5
Total		164.52	82.22	50	3.06	2.32	24.4

requirements of the storage process. Comparing our results with literature data was complicated because of the differences in the methodologies employed and the assumptions made (system boundaries, technology used, impact assessment methods). Moreover, most studies provide an aggregated result for post-harvest and it was not possible to distinguish the contribution of the individual steps. However, a qualitative comparison could be attempted here. The GWP and CED for 1 kg of average apples obtained in the present study by using the Italian electricity mix scenario were 164.5 gCO_{2eq}/kg and 3.1 MJ/kg, respectively. The results obtained by Longo et al. (2017) for the conventional supply chain in a similar production area (Northern Italy) showed higher values (GWP of 256 gCO_{2eq}/kg and CED of 5.9 MJ/kg) compared with our results. The differences could be due, at least in part, to the different boundaries, processes and data sources, which in Longo et al. (2017) were not explicitly given. Keyes et al. (2015) reports GWP of 193 gCO_{2eq}/kg and CED of 2.7 MJ/kg for storage and packaging of Canadian apples. Surprisingly, the GWP figures reported in two other studies were lower than our results. McLaren et al. (2010), employing the LCA method, calculated that the cool-storage/pack-house stage of apples in New Zealand generated only 57.6 gCO_{2eq}/kg. Cerutti et al. (2011b) reported GWP for storage, packaging, and transport of Italian apples ranging from 3.8 to 122 gCO_{2eq} per kg of apples, according to the different supply chains (i.e., direct selling, fresh markets, and regional distribution centers).

In comparison with the study by McLaren et al. (2010), our own case study could simulate a lower GWP scenario (29 gCO_{2eq}/kg) only when the electricity is substituted entirely with renewable sources and the ‘no-packaging’ solution is adopted (apples stored and sold in large plastic bins).

Milà i Canals et al. (2007) reported that the storage of apple from European countries used between 0.25 and 2 MJ/kg, depending on the duration of the storage. Apples stored in CA at 1 °C for five months showed a PEU of 0.99 MJ/kg. Blanke and Burdick (2005) reported a similar result (0.896 MJ/kg) for similar storage conditions. Both studies present slightly lower figures of the energy requirements as those reported in our case study for the same storage conditions, amounting to approximately 1.2 MJ/kg.

In our study, the energy requirement for packaging ranged from 0.6 to 1.9 MJ/kg of apples, depending on the package used. Although packaging plays a key role in the environmental effects of the post-harvest life of apples, relatively few studies have reported specific relevant data. For example, Longo et al. (2017) stated that 60–90% of all the effects attributed to the post-harvest phase were caused by packaging; however, they reported data only for CED (approximately 4 MJ/kg), i.e., three times higher than our average result. Blanke and Burdick (2005) reported that the packaging costs (open-top trays) represented 0.65 MJ/kg of the retailed apples. Milà i Canals et al. (2007) found that using an expanded polystyrene tray plus a polyethylene film containing four apples could increase the energy cost to 4.7 MJ/kg. Our results suggest that to lower the GWP and CED during the post-harvest phase, it would be preferable to reduce the amount of packaging or even to eliminate it entirely. This would generate a saving up to the 39% of the GWP and up to 34% of the CED in the post-harvesting phase. However, without proper packaging, the quality of the fruit could decline during long

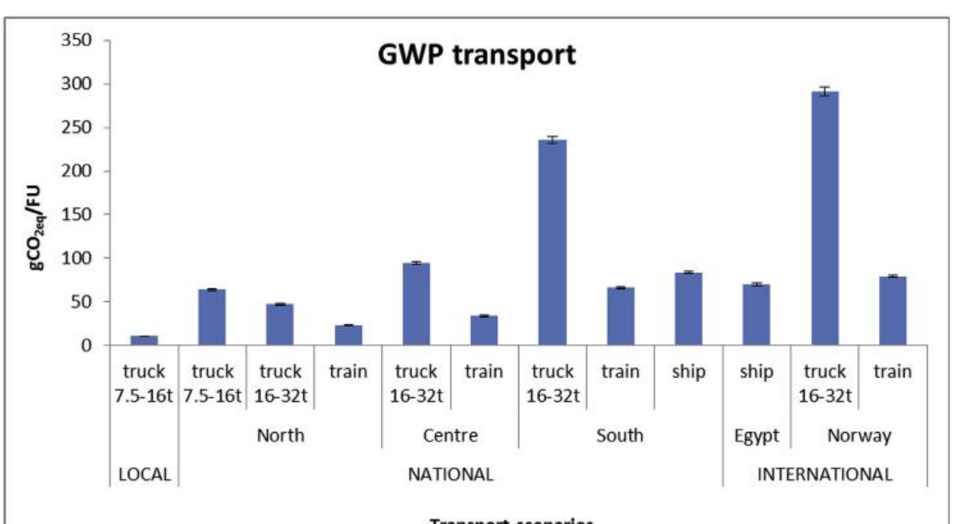

Fig. 3. GWP generated by transportation. The results refer to FU (1 kg of apples). The error bars refer to the standard deviation (n = 6), attributable to the different packages.

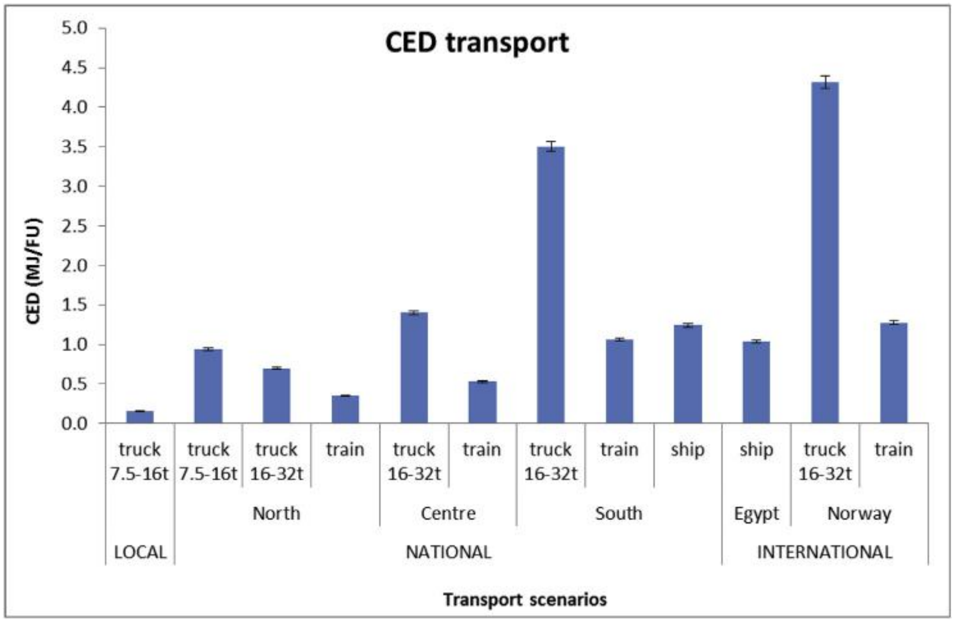

Fig. 4. CED associated with the transportation. The results refer to FU (1 kg of apples). The error bars refer to the standard deviation (n = 6), attributable to the different packages.

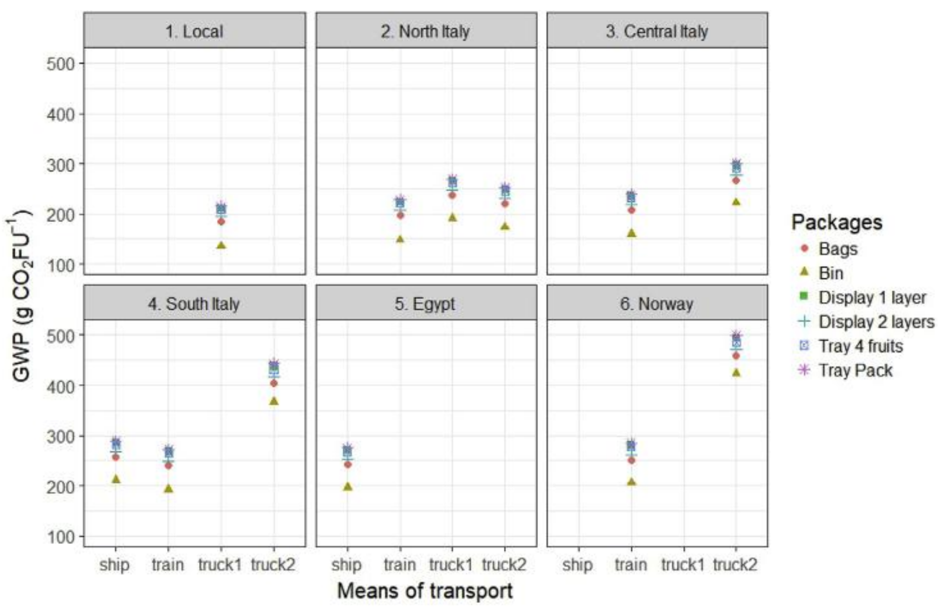

Fig. 5. The GWP of the entire post-harvest chain. Each symbol represents a different type of packaging. The x-axes indicate the four carriers used for transporting the apples to the target destination. Truck 1 refers to the smaller truck (7.5–16 t) and truck 2 represents the larger truck (16–32 t).

transportation and storage, leading to food losses (Corrado et al., 2017). Therefore, it is important to develop packaging solutions that use less material and that can be reused several times before being recycled or landfilled. Nevertheless, to understand which packaging solution should be preferred for the apple supply chain, a specific LCA should be carried out for the entire packaging life cycle, including the effects from packaging waste, as well as those generated or prevented by the food-waste chains.

In agreement with the findings of other studies (Keyes et al., 2015; Sim et al., 2007), the GWP and the CED of the post-harvest phase of apples were found to derive mainly from the production and use of electricity. Our results showed that switching from fossil-derived electricity to renewable energy sources could bring about substantial ecological benefits, especially with regard to the energy-consuming processes carried out in the packinghouse. Similar results are present in Keyes at al. (2015), who showed that moving away from coal-based electricity generation to natural gas or renewable energy sources could decrease the GWP and the CED of the Canadian apples up to approximately 33% and 12%, respectively reduce. In our study, the ReEl energy option, already employed by the two monitored packinghouses, which comprises auto-produced photovoltaic and certified hydroelectric sources, decreased the GWP and CED by approximately 50% and 25%, respectively, compared with the Italian electricity grid mix.

The transport scenarios showed a clear decrease in GHG emissions and energy consumption when the product was sourced

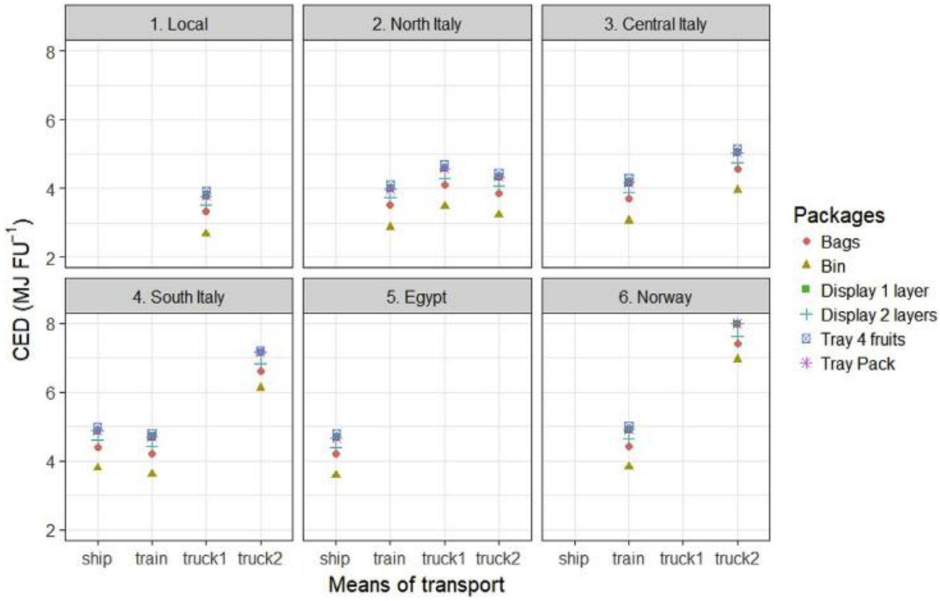

Fig. 6. The CED of the entire post-harvest chain. Each symbol represents a different packaging method. The x-axes indicate the four carriers used for transporting the apples to the target destinations. Truck 1 refers to the smaller truck (7.5–16 t), while truck 2 represents the larger truck (16–32 t).

closer to the retail point. On the other hand, our results confirmed that when long-distance transport was unavoidable (for example, for export to international markets, or for distances exceeding 300 km), transport by train or ship is preferable, as the environmental costs are significantly lower than were those of road transport. It should be borne in mind that the LCA we conducted was not a full 'cradle-to-grave' analysis. However, to understand the extent of the effects deriving from the post-harvesting cycle and the transportation of produce to retailers in an overall view of the entire apple supply chain, it would be useful to widen the system boundaries to include the entire life cycle of apples, i.e., from cultivation to consumption to waste management.

Two LCA studies on the pre-harvest phase of apples (Boschiero et al., 2015; Sessa et al., 2014) indicated that the management of apple orchards in Trentino-Alto Adige region could lead to a GWP from 40 to 87 gCO_{2eq}/kg of apple, and to a CED of 1.12 MJ/kg (Boschiero et al., 2015). It should be however born in mind that relatively high amounts of CO_2 naturally enter the orchard by photosynthesis, are allocated as organic carbon to its above and belowground compartments (Martinez et al., 2016), and leave the systems by respiration (Scandellari et al., 2015), leading to a net CO_2 removal from the atmosphere of about 2.5 t CO_2 ha^{-1} $year^{-1}$ (Zanotelli et al., 2015). The post-harvest cycle of the apples clearly contributes more to GWP and CED than the pre-harvest phase. Total (pre and post-harvest) GWP would therefore range from 204.5 to 251.5 gCO_{2eq}/kg of apple and total CED would be around 4.18 MJ/kg of apple. If transportation to a retailer were included, the cumulated GWP and CED would increase by 4% when the apple is consumed locally, whereas these figures doubled when the fruits are transported to Norway by road truck.

5. Conclusions

The findings of this study demonstrate that the post-harvest process and the transportation play a significant role in the overall C footprint of the apple and on the amount of energy needed to deliver an apple from the farm to the retailer. The post-harvesting cycle causes an approximate threefold increase in the GWP and CED generated in the pre-harvesting phases (i.e., cultivation phase) when the average Italian energy mix source was considered.

Packaging and cooling are the most significant processes influencing the GHG emission and CED during the post-harvest. Accordingly, two strategies could be adopted to reduce energy needs and limit the emission of GHGs: i) reducing the amount of packaging. When the apples must be transported over long distances, using train and ship transport is preferable to cut down the GHG emissions and energy demand of the food-transportation phase significantly; and ii) employing renewable energies, as is currently applied in the warehouses of the Trentino-Alto Adige region, which is crucial to limit the GHGs emissions from the cooling phase.

Finally, this study underlines the need for more and transparent information on LCA in the literature. Such information is required to overcome the difficulties in comparing the results from different studies and, especially, to present a system picture that mirrors the system reality to the citizens and consumers.

It should be stressed that this study is limited to the GHG emissions and energy performance of the apple post-harvest process; however other environmental, economic and social impacts should be considered as well in order to identify the most sustainable alternatives to be used by policy makers and companies.

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References

Akdemir, S., Akcaoz, H., Kizilay, H., 2012. An analysis of energy use and input costs for apple production in Turkey. J. Food Agric. Environ. 10, 473–479.

Alaphilippe, A., Simon, S., Brun, L., Hayer, F., Gaillard, G., 2013. Life cycle analysis reveals higher agroecological benefits of organic and low-input apple production. Agron. Sustain. Dev. 33, 581–592. https://doi.org/10.1007/s13593-012-0124-7.

Albritton, D.L., Meira-Filho, L.G., 2001. Technical summary. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Xiaosu, D. (Eds.), Climate Change 2001: the Scientific Basis - Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press.

Beccali, M., Cellura, M., Iudicello, M., Mistretta, M., 2010. Life cycle assessment of Italian citrus-based products. Sensitivity analysis and improvement scenarios. J. Environ. Manag. 91, 1415–1428. https://doi.org/10.1016/j.jenvman.2010.02.028.

Blanke, M.M., 2013. Carbon footprint of different thinning strategies in a fruit orchard. Acta Hortic. 998, 125–128.

Blanke, M.M., Burdick, B., 2005. Food (miles) for thought. Energy balance for locally-grown versus imported apple fruit. Enviornmental Sci. Pollut. Res. 12, 125–127. https://doi.org/https://doi.org/10.1065/espr2005.05.252.

Boschiero, M., Kelderer, M., Schmitt, A.O., Andreotti, C., Zerbe, S., 2015. Influence of agricultural residues interpretation and allocation procedures on the environmental performance of bioelectricity production - a case study on woodchips from apple orchards. Appl. Energy 147, 235–245. https://doi.org/10.1016/j.apenergy.2015.01.109.

Caffrey, K.R., Veal, M.W., 2013. Conducting an agricultural life cycle assessment: challenges and perspectives. Sci. World J. 1–13, 2013. https://doi.org/10.1155/2013/472431.

Canals, L.M.I., Muñoz, I., McLaren, S., Miguel, B., 2007. LCA Methodology and Modelling Considerations for Vegetable Production and Consumption. CES Working Papers 02/07, vol. 46. United Kingdom, Cent. Environ. Strateg. Univ. Surrey. https://doi.org/1464-8083.

Cellura, M., Longo, S., Mistretta, M., 2011. Sensitivity analysis to quantify uncertainty in Life Cycle Assessment: the case study of an Italian tile. Renew. Sustain. Energy Rev. 15, 4697–4705. https://doi.org/10.1016/j.rser.2011.07.082.

Cellura, M., Ardente, F., Longo, S., 2012. From the LCA of food products to the environmental assessment of protected crops districts: a case-study in the south of Italy. J. Environ. Manag. 93, 194–208. https://doi.org/https://doi.org/10.1016/j.jenvman.2011.08.019.

Cerutti, A.K., Bruun, S., Beccaro, G.L., Bounous, G., 2011a. A review of studies applying environmental impact assessment methods on fruit production systems. J. Environ. Manag. 92, 2277–2286. https://doi.org/10.1016/j.jenvman.2011.04.018.

Cerutti, A.K., Galizia, D., Bruun, S., Mellano, G.M., Beccaro, G.L., 2011b. Assessing environmental sustainability of different apple supply chains in northern Italy. In: Finkbeiner, Matthias (Ed.), Toward Life Cycle Sustain. Manag. Springer, pp. 341–348. https://doi.org/10.1007/978-94-007-1899-9.

Cerutti, A.K., Bruun, S., Donno, D., Beccaro, G.L., Bounous, G., 2013. Environmental sustainability of traditional foods: the case of ancient apple cultivars in Northern Italy assessed by multifunctional LCA. J. Clean. Prod. 52, 245–252. https://doi.org/10.1016/j.jclepro.2013.03.029.

Cerutti, A.K., Beccaro, G.L., Bosco, S., De Luca, A.I., Falcone, G., Fiore, A., Iofrida, N., Lo Giudice, A., Strano, A., 2015. Life cycle assessment in the fruit sector. In: Notarnicola, B., Salomone, R., Petti, L., Renzulli, P.A., Roma, R., Cerutti, A.K. (Eds.), Life Cycle Assessment in the Agri-Food Sector Case Studies. Methodological Issues and Best Practices. Springer International Publishing. https://doi.org/10.1007/978-3-319-11940-3_6.

Corrado, S., Ardente, F., Sala, S., Saouter, E., 2017. Modelling of food loss within life cycle assessment: from current practice towards a systematisation. J. Clean. Prod. 140, 847–859. https://doi.org/10.1016/j.jclepro.2016.06.050.

EC, 2013. Regulation (EU) No 1306/2013 of the European Parliament and of the Council of 17 December 2013 on the Financing, Management and Monitoring of the Common Agricultural Policy and Repealing Council Regulations (EEC) No 352/78 (EC) No 165/94, (EC) No 2799/98.

Fakouri, N.B., Smejtek, L., Denis, A., 2008. Life Cycle Analysis and Propositions of Environmental-Friendly Alternatives for 3 Different Swedish Horticultural Productions.

Frater, T.G., 2010. Energy in New Zealand Apple Production (Dr. Thesis).

Girgenti, V., Peano, C., Bounous, M., Baudino, C., 2013. A life cycle assessment of non-renewable energy use and greenhouse gas emissions associated with blueberry and raspberry production in northern Italy. Sci. Total Environ. 458–460, 414–418. https://doi.org/10.1016/j.scitotenv.2013.04.060.

Guinee, J.B., 2002. Handbook on life cycle assessment operational guide to the ISO standards. Int. J. Life Cycle Assess. 7–311. https://doi.org/10.1007/BF02978897.

Hischier, R., Weidema, B., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., Frischknecht, R., Hellweg, S., Humbert, S., Jungbluth, N., Köllner, T., Loerincik, Y., Margni, M., Nemecek, T., 2010. Implementation of Life Cycle Impact Assessment Methods Data v2.2 (2010). Ecoinvent Rep. No. 3.

Huijbregts, M.A.J., 1998. Application of uncertainty and variability in LCA. Int. J. Life Cycle Assess. 3, 273–280. https://doi.org/10.1007/BF02979835.

Huijbregts, M.A.J., Rombouts, L.J.A., Hellweg, S., Frischknecht, R., Hendriks, J.A., Van de Meent, D., Ragas, A. m J., Reijnders, L., Struijs, J., 2006. Is cumulative fossil energy demand a useful indicator for the environmental performance of Products? Environ. Sci. Technol. 40, 641–648. https://doi.org/10.1021/es051689g.

IEA, 2016. International Energy Agency. Italy - Energy System Overview [WWW Document]. https://www.iea.org/media/countries/Italy.pdf.

IPCC, 2007. Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, p. 996.

ISO, 2006a. ISO 14040: 2006 Environmental Management - Life Cycle Assessment - Principles and Framework.

ISO, 2006b. ISO 14044:2006. Environmental Management – Life Cycle Assessment – Requirements and Guidelines.

Jones, A., 2002. An environmental assessment of food supply chains: a case study on dessert apples. Environ. Manag. 30 (4), 560–576. https://doi.org/10.1007/s00267-002-2383-6.

Keyes, S., Tyedmers, P., Beazley, K., 2015. Evaluating the environmental impacts of conventional and organic apple production in Nova Scotia, Canada, through life cycle assessment. J. Clean. Prod. 104, 40–51. https://doi.org/10.1016/j.jclepro.2015.05.037.

Longo, S., Mistretta, M., Guarino, F., Cellura, M., 2017. Life Cycle Assessment of organic and conventional apple supply chains in the North of Italy. J. Clean. Prod. 140, 654–663. https://doi.org/10.1016/j.jclepro.2016.02.049.

Martinez, C., Alberti, G., Cotrufo, M.F., Magnani, F., Zanotelli, D., Camin, F., Gianelle, D., Cescatti, A., Rodeghiero, M., 2016. Belowground carbon allocation patterns as determined by the in-growth soil core 13C technique across different ecosystem types. Geoderma 263, 140–150. https://doi.org/10.1016/j.geoderma.2015.08.043.

McLaren, S.J., Hume, A., Mitraratne, Nalanie, 2010. Carbon management for the primary agricultural sector in New Zealand: case studies for the pipfruit and kiwifruit industries. Proc. VII Int. Conf. Food LCA 1, 293–298.

Milà i Canals, L., Burnip, G.M., Cowell, S.J., 2006. Evaluation of the environmental impacts of apple production using Life Cycle Assessment (LCA): case study in New Zealand. Agric. Ecosyst. Environ. 114, 226–238. https://doi.org/10.1016/j.agee.2005.10.023.

Milà i Canals, L., Cowell, S.J., Sim, S., Basson, L., 2007. Comparing domestic versus imported apples: a focus on energy use. Environ. Sci. Pollut. Res. 14, 338–344. https://doi.org/10.1065/espr2007.04.412.

Moser, R., Raffaelli, R., 2012. Consumer preferences for sustainable production methods in apple purchasing behaviour: a non-hypothetical choice experiment. Int. J. Consum. Stud. 36, 141–148. https://doi.org/10.1111/j.1470-6431.2011.01083.x.

Mouron, P., Scholz, R.W., Nemecek, T., Weber, O., 2006. Life cycle management on Swiss fruit farms: relating environmental and income indicators for apple-growing. Ecol. Econ. 58, 561–578. https://doi.org/10.1016/j.ecolecon.2005.08.007.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. J. Clean. Prod. 140, 399–409. https://doi.org/10.1016/j.jclepro.2016.06.071.

Pennington, D., Wolf, M.-A., Bersani, R., Pretato, U., 2007. Overcoming barriers to the broader implementation of life cycle thinking in business and public administration. Int. J. Life Cycle Assess. 12, 458. https://doi.org/10.1065/lca2007.07.355.

Provincia Autonoma di Bolzano, 2015. Relazione agaraia e forestale 2015 181.

Rees, D., Farrell, G., Orchard, J., 2012. Crop Post-Harvest: Science and Technology. Blackwell Publishing Ltd. https://doi.org/10.1002/9781444354652.

Sala, S., Anton, A., McLaren, S.J., Notarnicola, B., Saouter, E., Sonesson, U., 2017. In quest of reducing the environmental impacts of food production and consumption. J. Clean. Prod. 140, 387–398. https://doi.org/10.1016/j.jclepro.2016.09.054.

Scandellari, F., Zanotelli, D., Ceccon, C., Bolognesi, M., Montagnani, L., Cassol, P., Melo, G.W., Tagliavini, M., 2015. Enhancing prediction accuracy of soil respiration in an apple orchard by integrating photosynthetic activity into a temperature-related model. Eur. J. Soil Biol. 70, 77–87. https://doi.org/10.1016/j.ejsobi.2015.07.006.

Sessa, F., Marino, M., Montanaro, G., Piaz, A.D., Zanotelli, D., Mazzetto, F., Tagliavini, M., 2014. Life Cycle Assessment of apples at a country level : the case study of Italy. In: Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector Life, pp. 1244–1248.

Sim, S., Barry, M., Clift, R., Cowell, S.J., 2007. The relative importance of transport in determining an appropriate sustainability strategy for food sourcing. Int. J. Life Cycle Assess. 12, 422–431. https://doi.org/10.1007/s11367-006-0259-3.

Stoessel, F., Juraske, R., Pfister, S., Hellweg, S., 2012. Life cycle inventory and carbon and water footprint of fruits and vegetables: application to a Swiss Retailer. Environ. Sci. Technol. 46, 3253–3262. https://doi.org/10.1021/es2030577.

Thomassen, M.A., Dalgaard, R., Heijungs, R., De Boer, I., 2008. Attributional and consequential LCA of milk production. Int. J. LCA 339–349.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D., 2001. Forecasting agriculturally driven global environmental change. Science 292, 281–284. https://doi.org/10.1126/science.1057544.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 9, 1218–1230.

Zanella, A., Stürz, S., 2015. Optimizing postharvest life of horticultural products by means of dynamic CA: fruit physiology controls atmosphere composition during storage. Acta Hortic. (Wagening.) 1071, 59–68.

Zanotelli, D., Mazzetto, F., Tagliavini, M., 2014. Carbon footprint and primary energy use in fruit production. Italus Hortus 1, 59–68.

Zanotelli, D., Montagnani, L., Manca, G., Scandellari, F., Tagliavini, M., 2015. Net ecosystem carbon balance of an apple orchard. Eur. J. Agron. 63, 97–104. https://doi.org/10.1016/j.eja.2014.12.002.