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Carbon footprint of processed sweet cherries (*Prunus avium* L.): From nursery to market

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Abstract

The implementation of scientific studies can help to improve sustainable solutions in the agri-food sector ac- cording to current European policy. The present paper aims to evaluate the carbon footprint, according to ISO/TS 14067:2013, of 0.5 kg of sweet cherries packaged in clamshell made in polyethylene terephthalate (PET). The research assesses the supply chain, from agricultural (from nursery to dismantling) to the processing phase in firms located in the Apulia region. Results show a global warming potential over a fixed period corresponding to 100 years equal to 0.584 kg CO_{2eq}, primarily deriving from agricultural management (0.442 kg CO_{2eq}) and secondly from fruit processing (0.068 kg CO_{2eq}). In the orchard phase, the main impacts derived from electricity consumed to pump groundwater used for irrigation and fertigation activities (15.84% of the total), transportation of manure (6.42% of the total), ploughing activity (4.83% of the total) and produc-tion of nitrogen fertilisers (4.28% of the total). Cherries processing in the collecting centre showed impacts from electricity consumption (5.57% of the total) and from waste deriving from damaged or non-conforming cherries (4.74% of the total). The PET clamshell production phase had an impact deriving principally from the use of PET granulate (0.0743 kg CO_{2eq}). The study highlighted that manure administration and pruning activities contribute to decreasing greenhouse gas (GHG) emissions. Moreover, the sensitivity analysis showed that substitution of electricity-mix deriving from the Italian national grid with a photovoltaic plant lowered GHG emissions by 19%. The present study could contribute in providing suggestions to stakeholders and scholars in reducing GHG emissions and promoting more environmentally sustainable sweet cherry production practices.

Keywords: Carbon footprint Greenhouse gas emissions Sustainability Sweet cherry Manure Polyethylene terephthalate clamshell

1. Introduction

In the last decades, strong concerns regarding the adverse effects of greenhouse gases (GHGs) on climate change have fostered intense scientific debate and the implementation of different measures and tools helping to find sustainable solutions. The protection of the environment and consumers is a multidimensional and multilevel reality that involves all the possible stakeholders (Munasinghe et al., 2019). On a global level, protocols and political and economic guidelines have provided the reductions of GHG emissions by promoting mitigation and adaptation measures. However, the major problems are represented by the non-massive participation of the States and the non-mandatory nature of the commitments assumed. Conversely, the European Union (EU) has implemented several GHG emissions-reducing targets that promote a low-carbon economy. Therefore, in 2014, the European Council published the new 2030 framework for climate and energy, which fixed new targets basically to prevent and reduce climate changes. To reach these targets, the EU has carried out several actions in different economic sectors such as agriculture (European Commission, 2017a; European Commission, 2017b) and renewables (Rana et al., 2016). In this regard, the Common Agricultural Policy (CAP) issued by the EU in 2014 has introduced the use of sustainable farming practices with less environmental impact above all on climate changes.

Moreover, companies show increasing attention to their environ- mental performance through policies of promotion of indicators such as carbon footprint (CF). Specifically this tool assessing the GHG emissions of a product or service is easy to understand by the consumers and allows companies to adapt more and more careful and stringent policies on climate change. At present, the use of this indicator is not mandatory by law, but it can represent a distinctive and characterizing element of the environmental policy adopted by the companies using it (Penz and Polsa, 2018). According to Iriarte et al. (2014), carbon (C) reduction is part of a strategy intended to steer consumers to responsible consumption and to support commercial policies in which products can be competitive in a "widened" economic system that takes into account the commitments made by the States. In addition, it is precisely on this need that the producers and traders have focused.

In this regard, in South Italy, the Apulia region represents a territory characterised by agricultural and commercial vocation and very important fruit production, as it is the largest sweet cherry producer (32%) at the national level (Tricase et al., 2017). Recently, it has issued a programme focused on rural development aiming for environ- mental protection in the agri-food sector, according to the EU, to underpin the local agricultural economy. Therefore, it is important to implement scientific studies that can help the farmers to find and to develop sustainable solutions for the agricultural sector. Indeed, CF studies on fruits such as citrus, apples, mangos, oranges, kiwis, pomegranates, etc. are limited, as emerged in Djekic et al. (2018), who presented a literature review on this topic. Moreover, the majority of these works do not consider the entire life cycle of the orchard, do not include the environmental impact of orchard initial stages or do not assess worker transportations and human labours. In particular, there are only four surveys on GHG emissions of sweet cherry productions performed up to date, and they are incomplete regarding some aspects of the production supply chain.

In this context, the present study intends to improve sustainable sweet cherry production by a) integrating and considering some aspects not present in CF assessments evidenced in the literature re- view, b) enhancing knowledge of the environmental impact connected to sweet cherry production, c) assessing the environmental benefits deriving from manure administration in substituting chemical fertilization during the agricultural phase and d) analysing the carbon balance (CB) in the agriculture phase. Therefore, in this work, the authors evaluated GHGs emission from the production of 0.5 kg of sweet cherries packaged in clamshell made in polyethylene terephthalate

(PET). The methodology used to evaluate the CF is the ISO/TS, 20137:2013 according to the life cycle assessment (LCA) approach.

Finally, the present study could contribute to satisfy consumers' demands, which request increasingly sustainable food products and help firms to win new market shares and to achieve CAP goals.

2. An overview of carbon footprint studies on fresh fruit production

In the present section, the authors intend to carry out an updated analysis (at 15 November 2018) on the literature regarding GHG emissions studies specifically on fruit trees present in international data- bases of acknowledged scientific relevance such as Scopus and ISI Web of Science. The overview considers fruit trees such as sweet cherry, citrus, apple, mango, orange, kiwi, pomegranate, etc. and does not consider palm oil (*Elaeis guineensis* Jacq.), olive tree (*Olea europaea* L.) or Jatropha (*Jatropha curcas* L.). This overview refers to the years 2003–2018, and the authors used the following keywords: carbon footprint, greenhouse gas emissions and life cycle assessment for fruit and sweet cherry. Results showed that researches on environmental sustainability of sweet cherry production are very few and concern the environmental sustainability basically focused on the agriculture phase, such as in Tricase et al. (2017), Bravo et al. (2017) and Tozzini et al. (2015), whereas Tassielli et al. (2018) considered also the processing phase. With regards to studies on other fruits, their number is clearly more than that of the sweet cherries, specifically 35 in Scopus and 46 in Web of Science. These works are mostly in- complete since they do not consider the whole orchard life cycle; do not include the environmental impact of nursery, planting and soil preparation; and do not assess worker transportation. In fact, prudence should be taken when the studies are based only on a few years be- cause unproductive years could increase environmental impact indicators, while productive years could decrease them. Moreover, fruit production requires that workers reach the orchard by cars to perform different agricultural activities (tillage, pruning, harvesting, etc.), con- tributing to CO_2 release. The latter depends on the number of workers involved in the orchard management and on the kilometres covered from their homes to the workplace. Often, data does not allow identifying critical points and finding improvement solutions since they are not specific of each single phase/activity but are aggregated to give general information. Each study uses different system boundaries and co-product allocations (mass or economic value or production unit, etc.), making comparison very difficult. Furthermore, these studies basically focus on agricultural phases considering CO_2 emissions coming from fuel consumption (for tillage, pruning irrigation and pest and fertiliser administration) but neglecting GHG emissions (such as N_2O, CH_4 and CO_2) from soil microbiological activities. In particular, about the CB, only a few studies consider the orchard as a sink to store CO_2 under and above the soil. Indeed, according to Xiloyannis et al. (2016) and Vázquez-Rowe et al. (2017), CB represents a fundamental aspect since it could contribute to the mitigation of GHG emissions. Finally, because the functional unit (FU) often is based on different units such as mass of product (e.g. 1 kg, 1 t, etc.), product prize (e.g. €, $) and land use (e.g. 1 ha), it is not possible to compare them.

3. Material

and methods

The authors, according to ISO/TS, 20137:2013, implemented a CF of sweet cherry production in South Italy to measure the overall amount of GHGs indicated in the Kyoto Protocol released directly or indirectly from agriculture and the processing phase. However, agricultural activities represent the principal emission source of GHGs such as CO_2, CH_4 and N_2O (Bosco et al., 2013). The CF was evaluated according to the (IPCC, 2007) GWP_{100}, a method included in SimaPro 7.3.3 (2006) that converts the direct and indirect GHG emissions in CO_{2eq} over a fixed period corresponding to 100 years.

The present work, being based on the LCA approach (ISO, 2006a; ISO, 2006b), considers the following framework: a) goal and scope definition principally, characterised by the identification of the FU and the system boundary (SB); b) life cycle inventory (LCI) analysis; c) life cycle impact assessment (LCIA); and d) life cycle interpretation. In Fig. 1, a flow chart of the methodology carried out in this work is presented, while in Fig. 2, the entire scheme of sweet cherry pro- duction packed in PET clamshell is presented. The authors chose as FU 0.5 kg of sweet cherries packed in PET clamshell having a weight of 19 g and as SB the phases from the nursery to fruit processing and to the clamshell production process. Apart from the principal FU, the authors considered other FUs related to the processes involved in the study. For instance, in the orchard phase, the FU was equal to 1 ha, whereas it was equal to 1 kg for PET clamshell production. As for the damage allocation in the orchard phase, it was based on the eco- nomic value of fresh cherries and woods (95.05% and 4.95%, respectively), while in the processing phase, the allocation was based on the mass value of conforming and non-conforming cherries (fresh cherries equal to 77.76% and 22.24%, respectively). Regarding PET clamshell production, the allocation was done on mass criteria and was equal to 95.36% for clamshell production and 4.65% for PET scraps.

3.1. *The main characteristics of the supply chain under study*

The supply chain under study included agriculture and processing phases of a variety (Ferrovia) of sweet cherry, commonly cultivated in the Apulia region and destined to market. Tricase et al. (2017) de- scribed deeply the agricultural phase of sweet cherry orchards, sep- arating the cultivation into two stages: pre-production and produc- tion. The first is characterised by zero yields and includes the nursery and the first growing phase, both fundamental for sweet cherry pro- duction. The production phase is represented by the second growing phase and the full production period, starting from the 4th to 6th and 7th to 20th years, respectively. During the pre-production phase, dif- ferent agricultural activities are performed such as tillage, irrigation, organic fertilisation and pest management, and from the 7th year, min- eral fertilisation and mechanised pruning activities are added (Fig. 2).

Pruning consists of chopping branches followed by mixing them with the soil, and the orchard is dismantled at the 20th year. The total production is equal to 228 t/ha, consisting on average of 6 t/ha and 15 t/ ha per year during the second growing phase and the full production, respectively.

To reduce the excessive overheating of sweet cherries, harvest- ing is done in the early morning, and fruit is collected by hand and placed in plastic boxes. The transportation is by truck to the collect- ing centre in which the cherries are firstly cooled, washed and sani- tized with sodium hypochlorite and potassium chloride (hydrocooling) and secondly selected by dimension (calibration), and products that do not conform to market request (selection) are removed. Subsequently, cherries are packed in recycled PET clamshell and are stored in cold rooms to preserve their freshness (Fig. 2).

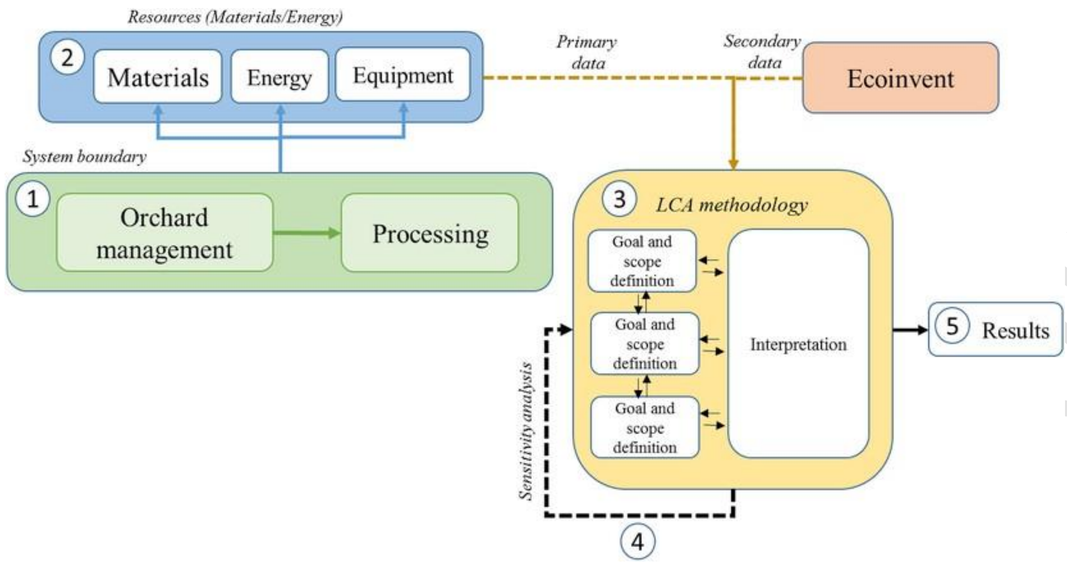

Fig. 1. Process to assess CF of sweet cherry production.

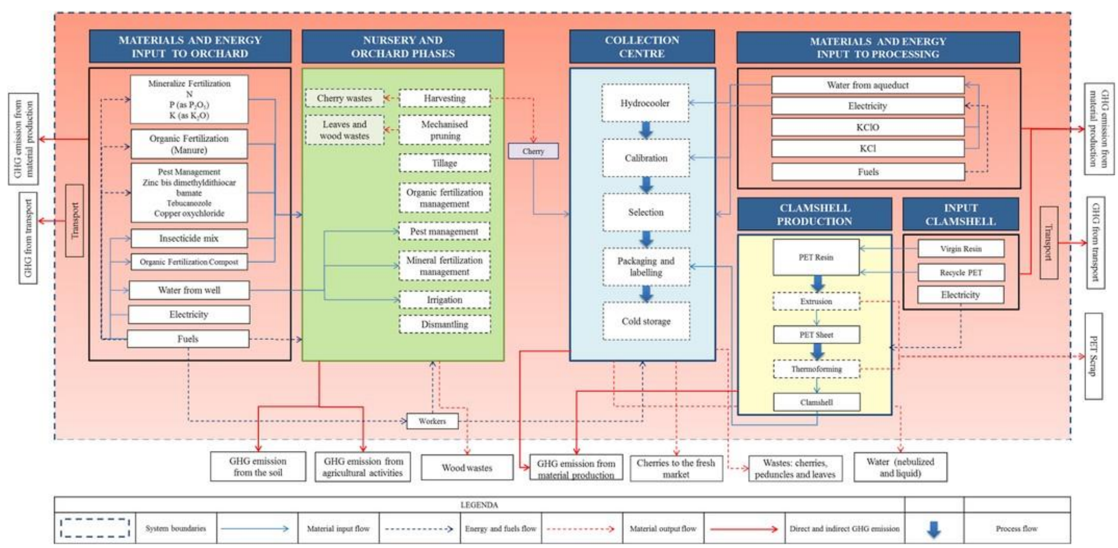

Fig. 2. System boundaries of sweet cherry production.

3.2. *GHG emissions from the orchard and the sweet cherry processing*

The follow section presents the methodology used to evaluate the GHG emissions from the agricultural activity (such as pruning, tillage, etc.) (Tricase et al., 2017) and the subsequent processing phases: a) hydrocooling, b) calibration, c) selection, d) packaging, e) labelling and f) storage in refrigerating rooms (Andriano, 2018).

3.2.1. *GHG emissions from manure administration*

In this paragraph, the authors calculate the GHG emissions from manure storage (maturation) before its administration. Generally, manure administration contributes to soil fertility since it enriches the soil of organic substances and consequently decreases the use of chemical fertiliser. Nevertheless, manure is an essential substrate that can be decomposed, principally during its maturation, by microorganisms producing two important GHGs, such as N_2O and CH_4. The release of these gasses principally depends on the storage time of the organic fertiliser, on the place of storage (e.g. indoor or outdoor), on air temperature and on animal feed used. Because of there is no consensus in literature on the meaning of the term "manure", the authors have preferred to use the term proposed by IPCC (2006), which includes dung and urine (solid and slurry substances) produced by cattle. Furthermore, the primary data was collected by the farmers, whereas those not available were obtained from ISPRA (2016), a report containing many characteristic data of Italian livestock GHG emissions.

To calculate CH_4 emissions from manure maturation, the authors adopted the equation 10.22, Tier 2 approach (IPCC, 2006), as modified by Andriano (2018). Therefore, the total CH4 emissions deriving from the manure maturation administered during the orchard lifetime (20 years) was equal to 343.6 kgCH4.

Regarding nitrous oxide release, it is lost from manure storage in direct and indirect ways due to aerobic/anaerobic processes that modify NH4+ directly in NO2− or to NO3− and subsequently in NO2 (Chadwick et al., 2001). The direct N2O (N2ODirect–N) was estimated according to equation 10.25, Tier 1 approach (IPCC, 2006), as adapted by Andriano (2018).

As for the indirect emissions of N2O, they occur by two indirect pathways: a) volatilisation of N as NH3 and NOx release from agricultural activities and other sources such as fossil fuel combustion, and these gases deposit (on the soils, the surface of lakes or other water bodies) as NH4+ and NO3− after their chemical reduction in the atmosphere;

b) leaching and runoff of N from soil, synthetic and organic fertilizer additions, crop residues and more (IPCC, 2006).

The first pathway was calculated using equations 10.26 and 10.27 (IPCC, 2006), as modified by Andriano (2018), while the second one was not assessed because manure was stored in a structure that did not allow losses of nitrogen compounds. Thus, the total direct and indirect emissions of N2O from the maturation of the administered manure during the orchard lifetime (20 years) was equal to 11.46 kg N2O

3.2.2. *GHG emissions from soil management*

The application of the CF methodology according to ISO/TS, 20137:2013 requires the assessment of direct and indirect amounts of CO_2, CH_4 and N_2O coming from soil management. Generally, about the CH_4 emitted from manure administered on the soil, it decreases in a few days since the methanogenesis process is prevented from the presence of atmospheric oxygen (Chadwick et al., 2011). Conse-quently, in the present work, CH_4 emissions from manure administration were not evaluated since they were considered negligible. Regarding N2O release, it depends, principally, on different aspects such as a) the quantity of nitrogen compounds presents in the soil that vary in relation to the soil's characteristics and fertilization typology (chemical or organic) and b) the biochemical reactions like nitrification and denitrification that occur in the soil (Ingrao et al., 2015). In this study, the evaluation of direct and indirect NO2 (N2ODirect and N2OIndirect) emissions was calculated using the equations 11.1, Tier 1, and 11.9 of IPCC methods (2006), respectively, and adapted by Andriano (2018).

Therefore, for the orchard, N2O direct emissions principally came from the administration of mineral and organic fertilizations and crop residues (leaves and wood wastes) and was equal to (108.48 kg/ha). Furthermore, the direct and indirect NO2 emission values were equal to 59.21 and 11.29 kg/ha, respectively.

During the last century, C losses as CO2 from cultivated soils have in part contributed to the increasing trend for global warming (IPCC, 2007). Currently, numerous studies on the CF of agricultural systems do not consider C sequestration and C emission from soil. The assessment of these aspects in CF studies can clarify the magnitude of

soil organic carbon (SOC) sequestration and represent a GHG emissions mitigation tool (Adewale et al., 2018). In particular, in an orchard, the CO2 balance depends principally on agricultural activity, especially from a) fuels used for agricultural activity (such as tillage, mineral and organic fertiliser administration, etc.), material production (fertiliser, pesticides, etc.) and workers/material transportation; b) electricity consumption for groundwater pumping in which the water extracted is principally used for irrigation; c) oxidation of SOC caused mainly by tillage; and d) carbon sequestration deriving from biomass waste such as branches (from pruning activity) and leaves. According to Andriano (2018), the total consumption of diesel and electricity is equal to 9349.63 L and 30,380 kWh, respectively.

In the last five decades, agricultural activities such as tillage, mineral fertilisation and elimination of pruning residues have contributed to oxidation of SOC (e.g. about 1% in Mediterranean soil) and consequently to the increase in CO_2 emissions in the atmosphere (Xiloyannis et al., 2015). Especially in conventional orchards, the SOC reduction is produced mainly by tillage and the burning of branches and shoots. In this paper, tillage was the only negative activity that caused CO_2 emission because branches and shoots were not burned but were copped and milled with the soil, thus enhancing the SOC amount. The net ecosystem carbon balance (NEBC) of the sweet cherry under study is reported in Table 1. Data were acquired from farmers and from literature (Zanotelli et al., 2015; Andriano, 2018).

To calculate the CB of the sweet cherry orchard, the authors adopted the following equation (Zanotelli et al., 2015):

Table 1
Carbon balance of sweet cherry orchard during orchard lifetime (data is expressed in $kg\ C\ dw\ ha^{-1}$).

Biomass			1st growing-phase (3 years)	2nd growing-phase (3 years)	Full production (14 years)	Total
			$kg\ C\ dw\ ha^{-1}$			
NPP_{tree}	Above soil	FH	0	854.04	16,606.52	17,460.56
		Pruning	62.94	125.85	8364.44	8553.23
		Cherry waste	0	61.50	859.60	921.10
		Leaves	302.80	604.56	11,568.48	12,475.32
		$Woods_{\text{yearly increment}}$	780.12	1560.24	30,338	32,678.36
	Below soil	$Roots_{\text{yearly increment}}$	384.48	768.96	14,952	16,105.44
NPP_{Weeds}	Above soil	$Weeds_{\text{Leaves and stuck}}$	405	405	1890	2700
	Below soil	Roots	60	60	280	400
$\mathbf{NPP_{Total}}$			**1994.82**	**4440.15**	**84,859.04**	**91,294.01**
R_h			9318	9318	43484	62120
NEP			**−7323.18**	**−4877.85**	**84,859.04**	**29,174.01**
LTC		OF	5136.69	5136.69	23,971.22	34,244.6
NECB			**−2186.5**	**258.84**	**65,346.21**	**63,418.55**

$$NEBC = NEP + LTC \quad (0)$$

where:

NEP is the net ecosystem production, $kg C ha^{-1} yr^{-1}$, deriving from the difference between the net primary production (NPP) (biomass produced above and below ground) and the soil respiration (Rh). In particular, in the present work, NPP is also represented by biomass left on the soil such as weeds, leaves, damaged cherries and pruning residue (e.g. branches and shoots copped and milled with the soil). Furthermore, Rh includes the soil oxidation deriving from tillage. Fi- nally, the authors assumed a constant value of Rh for the orchard life cycle (3106 kg C dw $ha^{-1} yr^{-1}$) considering soil characteristics and weather.

LTC is the lateral transportation of C that is considered the import of organic fertiliser (OF) and export of fruit harvested (FH) involved in the orchard (Montanaro et al., 2017).

Results are presented in Table 1. In particular, in the first and sec- ond growing phases, the C released by the soil was more than that absorbed by the plants due to the low biomass production during this phase. On the contrary, in the full production phase, the soil repre- sented a C sink since it accumulated a high quantity of C (2955.36 kg C dw ha^{-1}), in compliance with Freibauer et al. (2004). The sustainable agricultural management practices of orchard, such as, for instance, manure administration and pruning, can increase C sequestration and represents a potential tool to mitigate the consequences of climate change (Holmes et al., 2015). However, in the orchard under study, these practices partly compensated for the release of C deriving from the respiration of the soil since the latter overcame the biomass addi- tion. Regarding cherry production, woods and roots were considered C neutral since the former was eaten by consumers and consequently C is transformed in CO_2 during human digestion, whereas the latter was burned after dismantling. Moreover, the authors decided to not con- sider the nursery phase (2 years) on CB, because it affected less than 1% of the total NECB.

According to ISO/TS, 20137:2013, in the present work, the eval- uation of GHGs deriving from direct land use change (dLUC) was not considered since the soil was used to produce fruits from over 50 years.

3.2.3. *Fuel consumption from transportation of materials and workers*

In this paragraph, all the fuel consumption connected with the activities performed during cultivation of cherries and processing in the collecting centre is evaluated. The fuel consumption associated with the transfer of workers from home to the firm and conversely and all materials from the production place to the cherry orchard and collecting centre is also assessed. According to Sim et al. (2007), in fact, distance between production and consumption of a substance is an important factor to consider in CF assessment since it can highly impact the environmental sustainability of food supply chains.

The diesel consumption deriving from the transportation of materials and workers during the orchard agricultural phase (20 years) was calculated according to Tricase et al. (2017) and is reported in Table 2.

To assess the diesel consumption derived from the transportation of materials and workers involved in the processing phase, the procedure proposed by Tricase et al. (2017) was adopted. This procedure firstly considers the evaluation of the material/worker transportation and then the calculation of fuel consumption. Therefore, to assess the fuel consumption of cherry transportation from orchard to collecting centre and the transportation of PET from firm production to collecting centre, the following equation was applied:(see Table 3)

Table 2
Diesel consumption from transport of materials and workers involved in the agricultural phase.

Category	Diesel
Consumption L	
Orchard management	7199.18
Materials (to orchard)	3364.03
Workers (to orchard)	439.89
Total	**11,003.10**

$TF = T_A x D$ (1)

where:

- TF: transport flow related to the cherries harvested and PET, expressed as t*km (extrapolated from ecoinvent, 2011);
- TA: total amount of sweet cherries harvested (t) and PET used to produce clamshell;
- D: distance from the orchard to collecting centre (km) and from PET firm production to collecting centre.

The same procedure was applied to evaluate the fuel consumption of workers transportation. In this case, it was calculated using the following equation:

$TF_{WP} = N_{WP}$ x D_{RT} x N_{WP} (2)

where:

- TF_{WP}: transport flow related to the workers from home to collecting centre and conversely, expressed as person*km; the workers covered a daily distance of about 10 km to reach the workplace;
- N_{WP}: number of workers in the collecting centre (20 persons);
- D_{RT}: total round-trip distance from the workers' houses to the collecting centre (km).

According to Tricase et al. (2017) and ecoinvent (2011), the assessment of fuel consumption related to the total transport flow for workers, PET clamshell and cherries was calculated using the following equation:

FC = TF x C_0F_{ac} (3)

where:

- FC: fuel consumption (L of diesel) associated with the transportation of PET clamshell, cherries and workers;
- TF: transport flow calculated according to equation (2);
- C_oF_{ac}: conversion factor; this is equal to 0.026 LDiesel/kg*km for the PET clamshell (transport on road) and 0.0025 LHeavy_fuel-oil/ kg*km (transport transoceanic freight ship), 0.114 LDiesel/kg*km for cherries harvested and 0.0398 LDiesel/person*km for the workers (extrapolated from Ecoinvent, 2011).

According to equations (2) and (3), the diesel consumption related to transportation of PET, workers and cherries is shown in Tables 4 and 5, while the processing phase, principally characterised by the electricity consumption, is reported in Table 4.

4. Inventory analysis

The inventory analysis was carried out to quantify the use of resources and materials as well as the transportation and the environmental releases involved in the system under study. In this case, it is possible to create a model as close-to-reality using the following data: a) from Tricase et al. (2017) concerning the agricultural phase, b) collected by managers involved in the processing phase (Andriano,

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2018) and c) extrapolated from ecoinvent v.2.2. database within the SimaPro software in the 7.3.3 version. In fact, ecoinvent can be considered as a reliable data source containing several background materials and processes necessary to perform the LCAs of products or services (Frischknecht and Rebitzerb, 2005). In particular, the ecoinvent modules used in this paper were the following:

- extraction and production of raw materials (e.g. fertilisers and pesticides),

energies and fuels (e.g. diesel);

- agricultural activities (e.g. tillage, pruning, etc.);

- transportation of products (e.g. cherries, pesticides, fertilisers, etc.)and workers.

In the agricultural phase, pest management, ploughing and fertilizer administration were implemented, adapting models already contained in ecoinvent. In each of those modules, the inventory took into account the diesel fuel consumption, the amount of agricultural machinery used and the surface occupied by the shed. In addition, these models took into consideration the amount of emissions to air from diesel combustion and the emissions to soil from tyre abrasion during the process. However, as mentioned above, it was necessary to adjust these models according to the primary data. For instance, diesel consumption and the relative emissions (including those of GHGs) were modified to proportion the emission values already present within ecoinvent to the diesel consumption values specifically provided by the farmers. It should be remarked that the corrections of soil emissions derived from tyre abrasion were not considered since they were unknown. Moreover, the “electricity, low voltage, production IT, at grid” consumptions came from groundwater pumping stations used

for the different irrigation activities, with a consumption factor of 0.883kWh per m3 of extracted water. In particular, this ecoinvent model considered the production of electricity in Italy.

Diesel consumption related to material and workers transportation was calculated according to equations 1, 2 and 3 shown above.

Table 3 reports the input/output data of each agricultural phase (from nursery to full production). The PET clamshell production inventory data is shown in Table 4. The transfer of raw materials occurred using maritime and road transport. In particular, virgin resin came from Suape, Brazil (where the material is produced) to Rotterdam, Holland (7685km) with a ship (maritime transport). The virgin resin was transported successfully by lorry from Rotterdam to Rutigliano, Italy (centre of operations of recycled PET and clamshell production company) (1543 km). Finally, PET clamshell was transferred from Rutigliano to the collecting centre (60km) using road transport. Data were provided by producers and elaborated according to ecoinvent modules. In Table 5, the inventory data of processed cherries is reported. In this phase, from the processing of 1 t of cherries, the following data was obtained: 70% of cherries conforming to the market (first caliber), 20% to the second calibre and 10% of cherries as waste. Also, these data were provided by producers and elaborated according to ecoinvent modules.

Table 3
Input/output inventory-data of the agricultural phase of 1 ha of cherry orchard.

Input/Output	Unit	Nursery	I-III year	IV-VI year	VII-XX year	Note
Input	ton	251.44	2100.9	3906.9	28,146	P
Resources						
Water, groundwater consumption						
Raw materials and fossil fuels	kg		75,000	75,000	350,000	P
Manure Spreading						
Compost at plant	kg	1400				P
Fertiliser (N)	kg	6.48		61.8	574	P
Fertiliser ($P_2 0_5$)	kg	10.8		121.8	854	P
Fertiliser (K_2O)	kg	4.32		250.8	1414	P
Insecticides	kg	0.576		0.9	14	P
Fungicides	kg	1.68	2.7	10.35	67.2	P
Agricultural treatments	L		135	135	840	Dc; P
Pest Management						
Ploughing	L		300	300	1400	Dc; P
Fertiliser Administration	L		135	135	630	Dc; P
Chainsawing, hand felling and delimbing	hr				7	P
Transport	L	0.462	0.442	2.156	15.83	Dc; PEI
Fungicides and insecticides road transport/Transport, lorry 3.5–7.5 t, EURO4						
Compost road transport/Transport, lorry 3.5–7.5t, EURO4	L	6.35				Dc; P
Fertiliser NPK road transport/Transport, lorry 3.5–7.5t, EURO4	L	2.33		150.91	849.08	Dc; P
Manure road transport, lorry 7.5–16t, EURO4	L		346.37	346.37	1616.37	Dc; PEI
Worker transportation, city car, EURO5	L	0.26	14.02	59.58	359.81	Dc;PEI
Electricity	kWh	222	1855	3450	24,853	PEI
Electricity, low voltage, production IT, at grid						
Output	kg		10.58	10.58	49.35	
Emissions to air						
Dinitrogen monoxide (dir/ind from soil)						
Dinitrogen monoxide (dir/ind from manure)			1.72	1.72	8.02	
Methane	kg		51.54	51.54	240.52	
Carbon dioxide	kg		12,299	10,732.59	−12,660.37	
Materials	ton			18	210	P
Sweet cherry production						
Wood from dismantling	ton				190	P

Legend:
Dc: Diesel consumption.
P: primary data.
PEI: Primary data provided by farmer according to the Ecoinvent model.

Table 4
Inventory-data referred to 1 kg of PET.

Input/Output	Unit	Amount	Note
Input	kg	0.8217	PEI
Raw materials and fossil fuels			
Polyethylene terephthalate, granulate, amorphous, at plant			
Recycled postconsumer PET pellet	kg	0.1783	PEI
Thermoforming, with calendering	kg	0.9752	PEI
Transport	L	0.01659	Brazil - Rotterdam
Transport, transoceanic freight ship			
Road transport, lorry >32t, EURO 4	L	0.0346	Rotterdam - Rutigliano
Road transport, lorry >32t, EURO 4	L	0.0016	Rutigliano - Bisceglie
egend:			

L
PEI: Primary data provided by farmers according to the Ecoinvent model.

Table 5
Inventory-data referred to 1 t of Processed Cherry in the collected centre.

Input/Output	Unit	Amount	Note
Input	L	12000	P
Resources			
Water			
Raw materials and fossil fuels			
Sodium hypochlorite	kg	0.3577	PEI
Potassium chloride	kg	1.7875	PEI
Transport	L	0.105	PEI
Worker transportation, diesel, EURO5			
Cherry/Transport, lorry 3.5–7.5t, EURO4	L	1.722	PEI
Diesel, at regional storage	kg	0.0874	PEI
Electricity	kWh	116.21	PEI
Electricity, low voltage, production IT			
Output	t	0.143	PEI
Waste to treatment			
Scrap of cherries processed/Disposal, municipal solid waste, to sanitary landfill			
Cherry second caliber	t	0.286	P
Water	L	3000	

Legend:
PEI: Primary data provided by farmer according to the Ecoinvent model.
P: primary data.

5. Results and discussion

The data assessment shows that the CF of 0.5 kg of sweet cher- ries packaged in PET clamshell was equal to 0.584 kg CO_{2eq}. In Fig. 3, main contributions to the GHG emissions of the supply chain

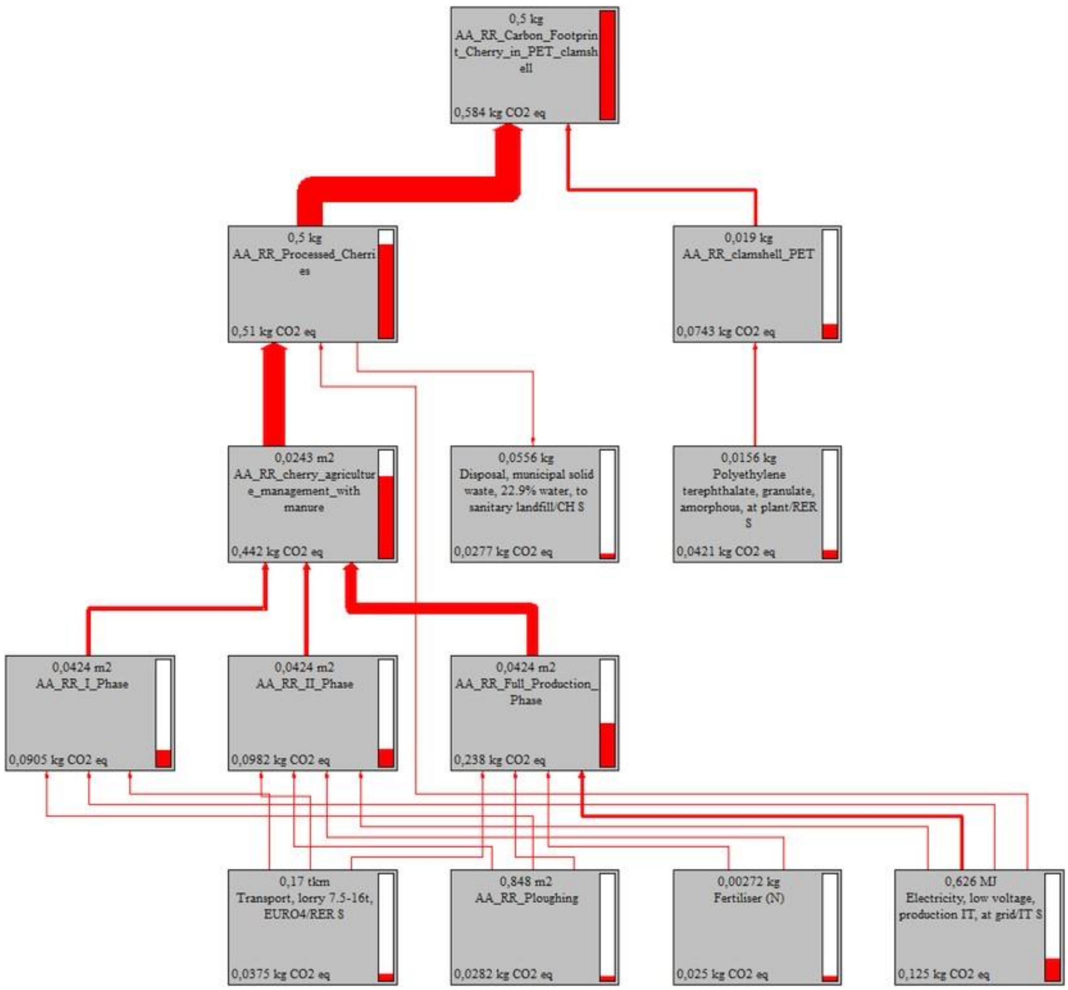

Fig. 3. Sankey diagram of the sweet cherry supply chain under s

analysed are reported, highlighting the most burdening phases as the following:

a) “processed cherries” equal to 0.51 kg CO_{2eq}, which included the “agriculture management” equal to 0.442 kg CO_{2eq} (75.68% of the total) and the “processing phase” where cherries are prepared for the market and equal to 0.068 kg CO_{2eq} (11.64% of the total);
b) “clamshell PET” that regards the production of PET clamshell and
was equal to 0.0743 kg CO_{2eq} (12.7% of the total).

According to Tricase et al. (2017), the most impacting phase is the orchard management. The most significant contribution to the GHG emissions comes from the full production phase caused by the huge consumption of materials (such as chemicals, water and fuels) and by the greater time span (14 years) of this phase compared to the previous ones. In particular, the activities that contributed mostly to GWP_{100} were the following:

1) the orchard irrigation and fertigation due to the electricity demand for the groundwater pumping. For this reason, the GWP_{100} related to the agricultural phase was equal to 0.0925 kgCO_{2eq}, which rep- resented 15.84% of the total; Improvement solutions were lim- ited since the irrigation systems used by the farmers was already low-demanding and therefore no alternatives can be proposed;
2) the manure transportation from cattle shed to orchard (40 km) re- leased 0.0375 kgCO_{2eq} (6.42% of the total). Although the distance covered by the lorry was not so far (40 km) compared to the other materials transported (e.g. fertiliser and pesticides coming from 1766 km), high GHG emissions derived from the high quantity of manure transported;
3) the ploughing activity contributed 0.0282 kgCO_{2eq} (4.83% of the total). This activity is made two times per year and consumes 100 L of diesel. According to Tricase et al. (2017), the high fuel con- sumption is due to the use of obsolete agriculture machineries con- tributing to increases in the GHG emissions value;
4) As underlined by Ingrao et al. (2015), generally the fertiliser pro- duction contributes greatly to CO_2 emissions since it requires the use of a high quantity of fossil fuels. In the present study, the pro- duction of N was more impacting than K_2O and P_2O_5 and was equal to 0.025 kgCO_{2eq} (4.28% of the total).

Starting from the Plassmann and Norton (2017) study, which af- firmed the importance of all co-products to give credits for biogenic C during the entire life cycle of an orchard, the authors considered the biomass residues as by-products. Therefore, although the full pro- duction phase represented the most burden, it produced a positive ef- fect since it contributed to the accumulation of C in the soil (−9080 $kgCO_{2eq}$) deriving from organic fertiliser, leaves, weeds and pruning residues left on the soil surface (CO_2, green bar, in Fig. 4). On the contrary, as already mentioned, the first and second phases were char- acterised by a low biomass production and a high rate of SOC ox- idation. This caused the release of CO_2 in the atmosphere equal to 12,300 $kgCO_{2eq}$ and 11,200 $kgCO_{2eq}$, respectively (Fig. 4). To de- crease CO_2 emissions during these phases, conservative agriculture techniques (such as no-tillage) could be introduced, characterised by the reduction of soil ploughing and therefore the oxidation of C's organic matter (Holmes et al., 2015). According to Lal et al. (2015), other advantages of improving C in the soil include enhancing food and nutritional security, increasing renewability and quality of water resources, improving biodiversity and reinforcing elemental recycling. For better comprehension, it should be remembered that in this bal- ance, cherry production, trunks and roots were not included since they were considered as C neutral (Table 1). Regarding the releases of N_2O and CH_4 and CO_2 deriving from fossil fuels, they were proportionated to the time span of each phase.

Cherry processing was characterised basically by the electricity consumed mostly by air conditioning in the processing room (35.44% of the total) and by hydrocooler treatment (32.98% of the total), as shown in Table 5. Furthermore, the processing phase produced wastes consisting in damaged or non-conforming market cherries, peduncles and other scraps, which were sent to the landfill. These wastes con- tributed to the GHG emissions, principally, due to their decomposi- tion, which released CH_4, CO_2 and SF_6. Therefore, in this phase, the most impact came from the following modules:

- “electricity” equal to 0.0325 $kgCO_{2eq}$ (5.57% of the total GHG emis- sions);
- “disposal, municipal solid waste” equal to 0.0277 kg CO_{2eq} (4.74% of the total GHG emissions).

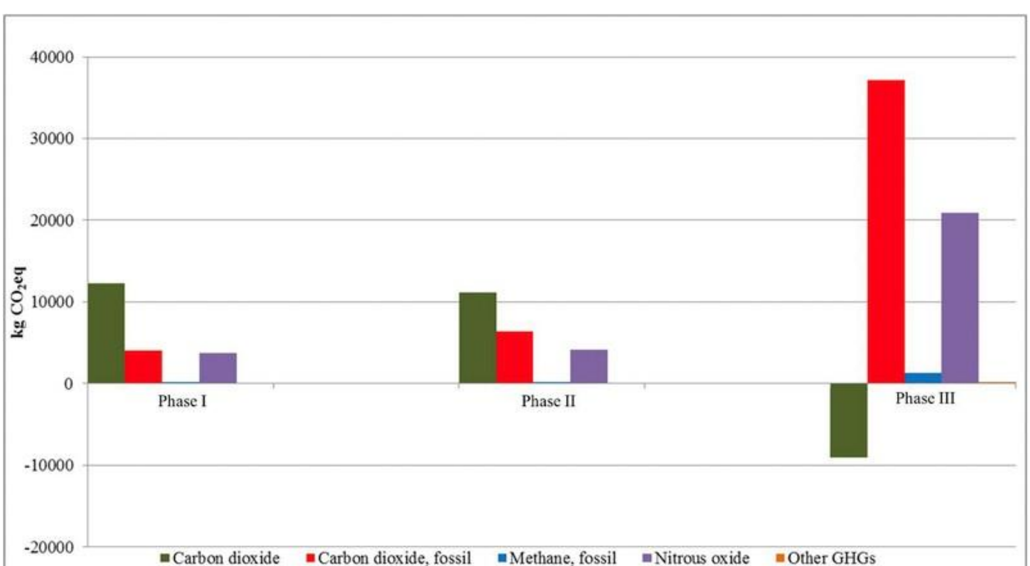

Fig. 4. GHG emissions from each agricultural phase of sweet cherry production.

Waste impact reduction could be achieved by using these prod- ucts as raw materials in other processes (e.g. production of flavour or aroma compounds, antioxidants, natural colorants and dietary nutri- ents), and in this sense, an important role could be played by the col- lecting centre in expanding the processing line to other product lines.

Regarding the environmental impact of PET clamshell packaging, it mainly derived from PET granulate production and was equal to 0.0421 kgCO_{2eq} (7.21% of the total GHG emissions) with contribu- tions of the following processes:

- thermoforming for 0.0145 kg CO_{2eq} (2.48% of the total GHG emis- sions);
- extrusion for 0.00995 kg CO_{2eq} (1.7% of the total GHG emissions).

This impact could be reduced using more recycled PET or alterna- tive packaging (such as edible coating). However, the value of CF ob- tained from the present study was higher than that proposed by Bravo et al. (2017) and Tassielli et al. (2018), probably due to following rea- sons: a) the former considered only the agricultural phase and a few input data; b) the latter did not specify the consumption of electricity deriving from the groundwater pumping for irrigation.

Consequently, the authors changed the most impactful inputs with other ones to propose an alternative scenario with less GHG releases than the case under study. As already underlined, the main source of GHG emissions was represented by the electricity consumption (equal to 21.3% of the total GHG emissions). To reduce this environmen- tal impact, the authors substituted the electricity deriving from the Italian national grid with a photovoltaic plant, assuming a roof-top, grid-connected PV power plant's 30-year lifetime according to ecoin- vent v.2.2 (2011). The assessment showed that the GHG emissions de- rived from electricity consumption decreased from 0.125 to 0.0119 kg CO_{2eq}. Consequently, the total CF of 0.5 kg of sweet cherries pack- aged in PET clamshell changed from 0.584 kg CO_{2eq} to 0.472 kg CO_{2eq} (more than a 19% decrease).

The authors computed CF benefits deriving from manure admin- istration instead of chemical fertilisers such as urea (CH_4N_2O), triple superphosphate ($Ca(H_2PO_4)_2\ H_2O$) and potassium oxide (K_2O). The authors chose these products because they are more concentrated (in terms of nutritional principles) than the other chemical fertilisers (In- grao et al., 2015). The substitution analysis shows that the CF of 0.5 kg of fresh sweet cherries packed in PET clamshell was equal to 1.09 kg CO_{2eq}. This result, according to Bartzas and Komnitsas (2017), clearly indicates that manure administration fundamentally contributes to sus- tainable agriculture since it halves the CF value. As previously under- lined, the CO_2 emission reduction was principally due to the lack of fertiliser production and the accumulation of C in the soil.

The authors underlined that the manure administered (25 t) by the farm was lower than that generally carried out locally (ranging from 40 to 80 t/ha) (Andriano, 2018). Therefore, if the company increases its manure administration, according to local practices, the relative benefit will improve in terms of CO_2 released.

Reported in Fig. 5 is the Monte Carlo uncertainty distribution re-
lated to the FU used in the paper in the form of probability distribution histograms obtained with 1,000 iterations of 0.5 kg of sweet cherries in PET clamshell, computed with the IPCC (2007) GWP 110a V1.02 according to the method used in the present work and following the guidelines introduced by Clavreul et al. (2012). The obtained standard deviation (SD) was equal to 121 kg CO_{2eq}, with a confidence interval of 95%.

The Monte Carlo uncertainty distribution related to different sce- narios: photovoltaic plant used instead of electricity-mix deriving from the national grid, and, finally, chemical fertilizers instead of ma- nure administration revealed that the SD had slight variations (121, 126 and 129 kgCO_{2eq}, respectively), indicating that changes in scenar- ios do not affect final values of CFs. The uncertainty propagation de- rived basically on primary data used in this work.

6. Conclusions

The present work has implemented the CF of the sweet cherry sup- ply chain (from the nursery to the processing phase), assessing the GHG emissions associated with 0.5 kg of fresh sweet cherries wrapped in PET clamshell and considering the effects of manure administration to reduce the CO_2 release from the soil, the use of good primary qual- ity data obtained directly from the farmers and taking into account the entire useful life cycle of the orchard (20 years), its C balance and the effects of land management and transportation of workers.

The results showed a GWP_{100} equal to 0.584 kg CO_{2eq} deriving from the agricultural management of the orchard (0.442 kg CO_{2eq}) and secondly from fruit processing (0.068 kg CO_{2eq}), the results of which are difficult to compare with other similar papers due to the different FUs considered. About the orchard phase, the main impacts derived were from electricity consumed to pump groundwater aquifer used for irrigation and fertigation activities (15.84% of the total), transporta- tion of manure (6.42% of the total), ploughing activities (4.83% of the total) and production of nitrogen fertilisers (4.28% of the total). Concerning the collecting centre, the major impacts derived were from the electricity consumption (5.57% of the total GHG emissions) and from waste and damaged or non-conforming cherries (4.74% of the total GHG emissions).

Manure administration and pruning activities contributed to reducing GHG emissions since they reduced chemical fertiliser use and enriched the soil of organic C; the same also applied to conservative agriculture techniques (with no tillage). Substitution of electricity-mix deriving from the national grid with photovoltaic plants lowered the GHG emissions from 0.584 to 0.472 kg CO_{2eq} (19% decrease). This study could represent a first step to implementing best practices for the agriculture sector according to European rules (i.e. CAP 2014–2020), providing important information to stakeholders (as farmers, food processing industries and policy planners) that could be used to promote or enhance the environmental sustainability of the sweet cherry sup- ply chain. Specific product certification (carbon labelling) of sweet cherries may represent future development of the present work, which could give to manufacturers the marketing tools useful to reach sustainable consumer behaviour and to improve the organization's reputation.

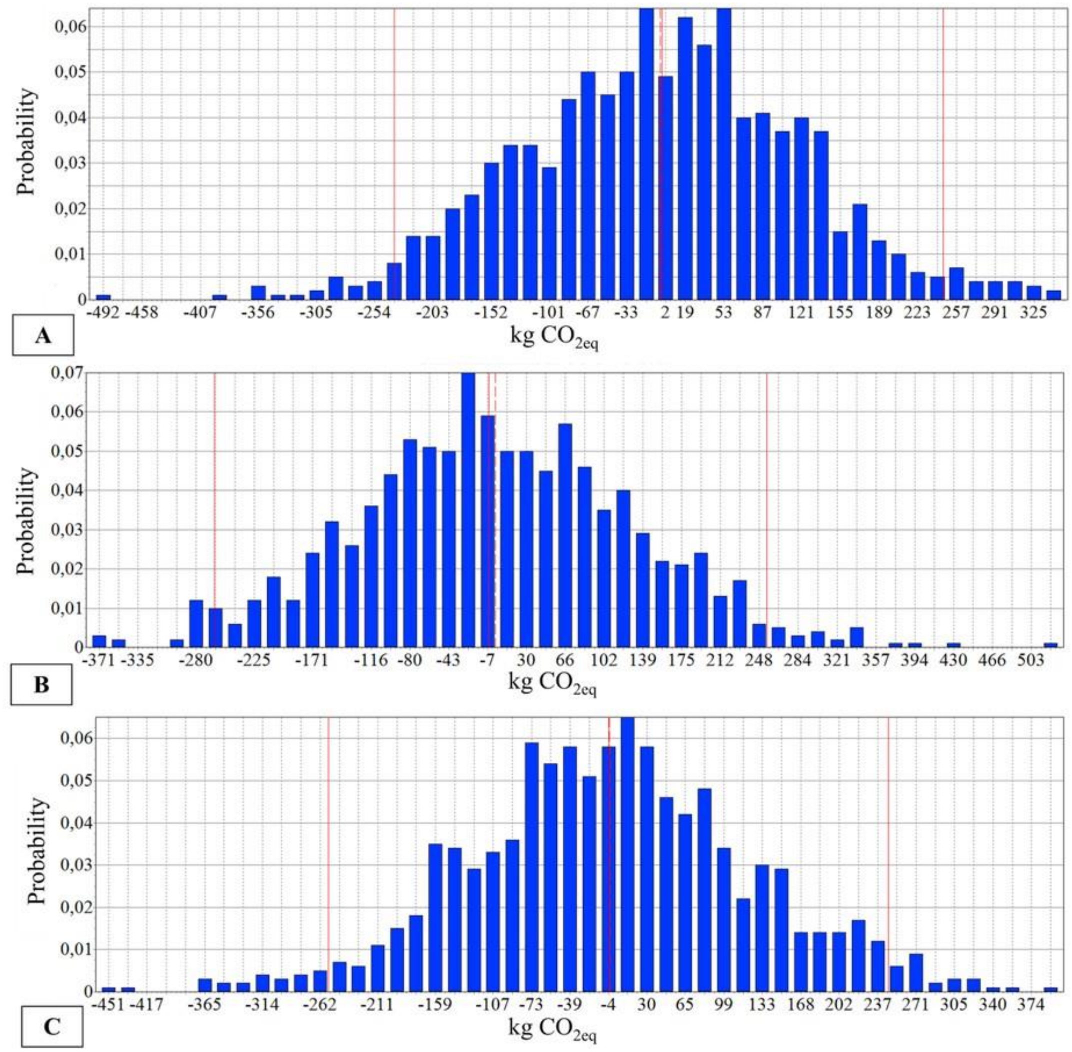

Fig. 5. Probability distribution histograms of Monte Carlo calculation of three different scenarios with 1,000 iterations of 0.5 kg of sweet cherries in PET clamshell, computed with IPCC (2007) GWP 110a V1.02 method: a) supply chain under study; b) photovoltaic plant used instead of electricity-mix deriving from the Italian national grid; c) chemical fertilisers instead of manure administration.

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