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Life Cycle Assessment of organic and conventional apple supply chains in the North of Italy

Sonia Longo [a,*], Marina Mistretta [b], Francesco Guarino [a], Maurizio Cellura [a]

[a] Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici (DEIM), Università degli Studi di Palermo, Viale delle Scienze Ed.9, 90128 Palermo, Italy

[b] Dipartimento di Patrimonio, Architettura e Urbanistica (PAU), Università degli Studi Mediterranea di Reggio Calabria, Salita Melissari, 89124 Reggio Calabria, Italy

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ABSTRACT

This paper compares the energy and environmental impacts of organic and conventional apples cultivated in the North of Italy, by applying the Life Cycle Assessment (LCA) methodology.

The authors examined the supply chain of apples, including the input of raw materials and energy sources, the farming step, the post-harvest processes and the distribution of apples to the final users.

The paper develops two original contributions: 1) it enhances the limited number of studies on LCA applied to apples; 2) it compares organic and conventional apples produced in lands characterized by the same climatic conditions, to evaluate which of the two products is more competitive from an energy and environmental point of view.

The results showed that, despite a lower productivity, preferring organic apples versus conventional apples could help to reduce the environmental impacts for most of the examined impact categories. With a few exceptions, differences lower than 7% occur between the eco-profiles of the two examined products.

A relevant share of the primary energy consumption and almost all of the examined environmental impacts are caused by the post-harvest processes and by transport to the final users, assuming that the products are distributed on local, national and international markets.

Furthermore, a detailed analysis of the farming step showed that a significant share in the overall energy and environmental impacts is due to the use of fertilizers and pesticides and to diesel consumption of agricultural machines.

1. Introduction

The agricultural sector has a relevant impact on the environment through the resource use and emissions (Cellura et al., 2011a). In detail, farmers manage 40% of the land and every year an estimated 12 million hectares of agricultural soil are lost to land degradation. Agriculture consumes 70% of total global 'blue water' withdrawals from available rivers and aquifers (Beddington et al., 2012). The increasing use of fertilizers involves a significant contribution to greenhouse gases emissions and causes nitrogen emissions (NH_3, N_2O), nitrate leaching, and potassium and phosphorus losses to water (UNEP, 2002).

Agricultural activities in the EU-28 generated 464.3 million tons of CO_{2eq} in 2011, corresponding to about 10% of total greenhouse gas emissions on a world scale. The majority of these emissions are related to agricultural soils (accounting for about a half of agricultural emissions), enteric fermentation (about one third) and manure management (about one sixth). The other sources of agricultural greenhouse gas emissions (field burning of agricultural residues and rice cultivation) are only minor contributors (EU, 2013).

Generally, the environmental impacts from agriculture can be reduced through organic farming, which is an agricultural system that respects natural life-cycle systems.

This technique combines best environmental practices, a high level of biodiversity, the preservation of natural resources, the application of high animal welfare standards and a production

* Corresponding author. Tel.: +39 091 23861927; fax: +39 091 484425.
E-mail address: sonialongo@dream.unipa.it (S. Longo).

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Nomenclature

Acronyms

Acw	acidification
BS	base scenario
CC	climate change
FE	freshwater eutrophication
FE_{tox}	freshwater ecotoxicity
FU	functional unit
GER	global energy requirement
HT_{ce}	human toxicity – cancer effects
HT_{nce}	human toxicity – non-cancer effects
IR_{hh}	ionizing radiation HH
IR_{e}	ionizing radiation E (interim)
LCA	life cycle assessment
LU	land use
ME	marine eutrophication
OD	ozone depletion
PM	particulate matter
POF	photochemical ozone formation
RD	mineral resource depletion
SA	sensitivity analysis
TE	terrestrial eutrophication
WRD	water resource depletion

method in line with the preferences of some consumers for products grown using natural substances and processes (EU, 2007).

Organic farming practices include[1]:

- Wide crop rotation for an efficient use of on-site resources;
- Strict limits on chemical synthetic pesticide and fertiliser use, livestock antibiotics, food additives and processing aids;
- Prohibition of the use of genetically modified organisms;
- Taking advantage of on-site resources;
- Using plant and animal species resistant to disease and adapted to local conditions;
- Raising livestock in free-range, open-air systems and providing them with organic feed;
- Using animal husbandry practices appropriate to different livestock species.

The European Commission adopted different regulations and guidelines on organic farming. Among these, it is important to report:

- Council Regulation (EC) No. 834/2007 that provides the basis for the sustainable development of organic production (EU, 2007);
- Commission Regulation (EC) No. 889/2008 laying down detailed rules for the implementation of Council Regulation (EC) No 834/2007 (EU, 2008);
- Action Plan for the future of Organic Production in the European Union (EC, 2014).

Organic production allows farmers to be more competitive and market-oriented, to keep their land in good agricultural and environmental conditions and to comply with European standards in the fields of environment, food safety and animal health and welfare.

In recent years, prompted mainly by quality concerns and environmental and food safety and in spite of the economic crisis and the growing price of organic products, the European consumers spent over €22 billion in 2013 in this sector, helping the organic market to grow by nearly 6% in comparison to the previous year (Katsarova, 2015).

Policy-makers also have recognised the potential of organic farming as a mean of food production that meets the demands of sustainability and market place.

Around one eighth of the world's organic producers (260,000) are in Europe and, in 2013, they were associated with 10.2 million hectares of land (5.7% of the EU's agricultural area).

In 2013, over 43 million hectares in 170 countries around the world were cultivated organically. However, organic farmland only accounts for 1% of the total worldwide farmland.

Over the past 30 years, international sales of organic foods have grown from almost nothing to over €66 billion in 2013. The largest single market for organic food is USA (€24.3 billion) followed by Europe (€22.2 billion) and China (€2.4 billion) (Katsarova, 2015).

The above figures show that the market of organic food is increasing, and this growth can make important contributions to food supply stability and farmer livelihoods by establishing soil fertility and providing diversity and thus resilience to food production systems in light of the many uncertainties of climate change (Niggli et al., 2007).

The Life Cycle Assessment (LCA) methodology can be the basis for assessing the environmental sustainability of organic agriculture, and for identifying options aimed at improving the global environmental performance of agricultural products.

In detail, three distinct stakeholder groups could benefit from using LCA as a decision support tool (Ardente et al., 2012):

- Producers: to improve the environmental performance of a productive system;
- Consumers: to orient purchasers;
- Policy-makers: to inform and direct long-term strategies.

The extension of the assessment to the whole supply chain allows identifying “where” and “how” the resources are consumed and the emissions occur (Cellura et al., 2012). The life-cycle thinking approach can ensure that the environmental impacts throughout the life-cycle are viewed in an integrated way and consequently that they are not just shifted from one step to another (Ardente et al., 2006). Such a product-based approach addresses competitiveness issues and key environmental impacts of selected products where it is most appropriate in their life-cycles (EC, 2007).

In this context, the aim of this paper is to investigate the potential energy and environmental advantages due to the cultivation of organic products in comparison to conventional ones. In detail, the LCA methodology was applied to compare the eco-profiles of apples cultivated with organic and conventional agricultural techniques.

The paper is organized as follows: Section 2 presents the state-of-the-art of LCA applied to organic and conventional products, and in particular to apples. Section 3 describes the case study of the LCA applied to apples, including the goal and scope definition (Section 3.1), life cycle inventory (Section 3.2), life cycle impact assessment (Section 3.3), and interpretation (Section 3.4). In Section 4, the authors provide some final remarks.

[1] http://ec.europa.eu/agriculture/organic/organic-farming/.

2. LCA applied to apples: state-of-the-art

Several LCA studies compared the environmental impacts of the same products cultivated with organic and conventional practices, even if some authors criticize the appropriateness of using LCA or some LCA impact categories in agriculture (Haas et al., 2000).

Some authors have reviewed previous studies to assess the environmental effects of organic and conventional farming on energy use and greenhouse gas emissions. Others have performed simulation studies to predict the effects on energy use and greenhouse gas emissions of converting from conventional farming to organic farming (Lee et al., 2015).

A review carried out by Meier et al. (2015) showed that most of these studies have reported lower environmental impacts from organic products on a per area and year basis, but higher impacts have been found when evaluating emissions per product unit, mainly due to lower yields of organic farming systems.

With reference to apples, some LCA studies available in scientific literature are summarized below.

Reganold et al. (2001) analysed organic, conventional and integrated[2] apple production systems in Washington State from 1994 to 1999. The results showed that organic and integrated apple production systems were not only better for soil and environment than the conventional but have comparable yields and, for the organic system, higher profits and greater energy efficiency.

Jones (2002) assessed the environmental performance of the fresh apples supply chain and investigated different food transport options of dessert apples to the UK consumer. The analysis showed that transportation was responsible for a considerable fraction of the total energy consumption in the life-cycle of fresh apples and, in most cases, exceeded the energy consumed in commercial apple cultivation. Furthermore, authors highlighted that a process of localization can be a direct approach for reducing or avoiding the negative environmental impacts of international transportation, freight distribution, and car use.

Cerutti et al. (2011) examined the environmental impacts of apples in Northern Italy, focussing on the production and retail phases. In detail, three scenarios of retail were examined (direct selling, distribution to local markets, and distribution to national markets), showing the importance of retailing strategies for the environmental sustainability of apples.

Milà i Canals et al. (2006) applied LCA to three commercial apple orchards and two reference orchards, representing standard practices in New Zealand. A "from cradle-to-gate" approach was applied and the selected functional unit (FU) was 1 apples ton harvested at a central location on the orchard ready for cool storage and/or packing. Non-renewable energy consumption was variable from about 400 to about 700 MJ/tons. The production of pesticides and agricultural machinery was significant in the overall energy consumption of the orchard; they represented 10–20% and 7–12% of energy consumption respectively, in all study sites.

Mouron et al. (2006) investigated the influence of the management on environmental impacts of integrated apple growing in Switzerland. The LCA was applied to analyse eight impact categories. Furthermore, a principal component analysis was performed to reduce the complexity of the impact categories and a statistical risk assessment was carried out to analyse the management influence. The results showed that there is an important effect of management for energy and environmental impacts and that the promotion of environmentally sound apple growing is not only a matter of choosing one or the other farming system (e.g. organic versus integrated farming) but also that an understanding of the system specific management influence is crucial.

Cerutti et al. (2013) investigated three representative ancient apple cultivars in the Northern Italy and compared the environmental impacts of these cultivars with those of the commercial cultivar "Golden Delicious". Authors performed the study using the cradle-to-gate approach and selecting three different FUs: the production of 1 tons of fruit, the growth of 1 ha of orchard, and the earning of €1000 income by the grower. Considering impacts per tons of product, "Golden Delicious" had the best environmental performance in most impact categories investigated. However, considering impacts per hectare and €1000 income, the ancient cultivars performed best in almost all impact categories. The study highlighted an important issue in the LCA of food: the impacts of fruit production depend heavily on the FU chosen and the use of different FUs may lead to different results.

Sessa et al. (2014) carried out a LCA of 1 kg of apples produced in Italy, with the aim of compiling an environmental product declaration certification and understanding the contribution of the different cultivation phases to the carbon footprint. The research followed a "from cradle-to-retailer approach". The results showed that 1 kg of apples has a global warming potential of 0.20 kg CO_{2eq}, a photochemical ozone creation potential of 0.18 g C_2H_{4eq}, an impact on the acidification and eutrophication that is 1.12 g SO_{2eq} and 0.62 g ${PO_4}^{3-}{}_{eq}$ respectively. The main contributor to the carbon footprint during the cultivation step is the consumption of fuel for machinery, which significantly changed according to the distance from the farm centre and the field size.

Alaphilippe et al. (2014) examined two apple production systems (intensive and semi-extensive), in order to assess the incidence of the non-productive stages in the orchard life-cycle impacts. Authors followed an approach "from cradle-to-the gate of the apple storage place". Two FUs were selected: 1 tons of apples for the cumulated yield over the whole orchard lifetime, and 1 $ha^{-1}year^{-1}$ of land used to produce apples over the whole orchard lifetime. The results of the analysis showed that unproductive stages weighted up to 21% and 28% of the studied impact categories, in the semi-extensive and intensive orchard respectively, with little contribution of the nursery stage.

Keyes et al. (2015) applied LCA to analyse the environmental performance related to conventional and organic apple systems in Canada. Results indicated that the combustion of diesel fuel, the use of fertilizers, and pest and disease management were major contributors to the environmental impacts on both conventional and organic orchards. Extending system boundaries to cradle-to-retail locations revealed that electricity needed for long-term storage resulted in substantial burdens and that consuming locally produced apples when in season was found to be environmentally preferable to those requiring year round storage. The comparison between organic and conventional apples highlighted that seven out of eleven examined impact categories reported worse results for organic apples. The exceptions were represented by the impact on human and aquatic toxicity and on freshwater eutrophication.

Furthermore, an interesting and complete review of studies assessing LCA application in fruit production systems can be found in Cerutti et al. (2014). Authors, starting from literature studies, described a reference framework for LCA applications in fruit production systems.

The main findings of the above studies are summarized in the following list:

- Conflicting findings were obtained comparing organic and conventional apples: in some cases organic apples performed

[2] Integrated farming is a system that helps farmers improve the way they farm for the benefit of the environment, the profitability of their business and social responsibility, including all important aspects of sustainable development (EISA, 2012). It combines the best organic and conventional production methods.

better than conventional ones, in other cases they showed worse results. However, the comparison is based on a static situation and not on the evolution of the examined systems. A complete comparison, especially when organic apples are more impacting, has to take into account other aspects, such as the better organoleptic quality of organic apples, their higher levels of antioxidants, their longer shelf life than non-organic apples (Theuer, 2006), the maintenance of the fertility of the soil arising from organic agriculture, etc.;
- Transports to final users and electricity needed for long-term storage were the main cause of the energy impacts of apples. Thus, local sales of fresh apples can be a strategy for reducing the above impacts;
- During the cultivation step, the use of pesticides and fertilizers, and agricultural machines (consumption of diesel) were identified as the main contributors to the impacts.

The contributions of the paper to the previously described state-of-the-art are: 1) further contribution to the limited number of LCA studies of apples; 2) the comparison between organic and conventional apples produced in the same climatic conditions, to evaluate if the former is competitive with respect to the latter from an energy and environmental point of view.

3. Case study: LCA of apples in the North of Italy

LCA is a useful tool to assess resource use (energy and raw materials), energy and environmental burdens related to the full life-cycle of products and services. In this paper, it was applied according to the international standards of series ISO 14040 (ISO 14040, 2006; ISO 14044, 2006).

3.1. Goal and scope definition

The goal of the study is to assess the energy and environmental impacts of organic and conventional apples cultivated in the North of Italy, in order to answer the following questions: are organic apples more sustainable than conventional ones from the energy and environmental point of view? If yes, how much is the difference between the eco-profiles of the two examined products significant? For each system, which is the contribution to the total impacts of each examined life-cycle step?

3.1.1. Functional unit and system boundaries

The selected FU is 1 tons of apples packed in 120 kg of carton and distributed to final consumers.

The selection of a mass-based FU has the goal of comparing two products (organic and conventional apples). A land-based FU was not considered because land use is not directly a service and does not provide a productive function (Cerutti et al., 2013). Moreover, the comparison of two cultivating areas is outside the goal of the study.

The system boundaries include the following steps (Fig. 1):

- Raw materials and energy supply;
- Cultivation of apples, including machines management, pruning, land management, fertilization, irrigation, thinning, anti-parasitic treatment, harvest. This step also takes into account the final treatment of input materials packaging. Authors excluded from the analysis the orchards stages that occur first and after the period of full production (propagation of the plants in the nursery, establishment of the orchard, low yield due to young plants, low yield due to declining plants, and the destruction of the orchard (Cerutti et al., 2010)) due to the lack of site-specific data;
- Transfer of apples to warehouses;
- Post-harvest processes, including post-harvest defence (only for conventional apples), storage, washing and calibration, packaging, and internal transports;
- Transport of apples to final users, assuming that the product is distributed on local, national and international markets.

The storage of apples by final consumer, their use and the treatment of organic waste after use, as well as the end-of-life of apples packaging were not taken into account because these steps may vary significantly depending on the consumer's behaviour.

Nitrogen compounds emissions during cultivation were accounted for according to Brentrup et al. (2000); on-field pesticide emissions were estimated according to Birkved and Hauschild (2006); CO_2 absorbed by plants during their vegetative cycle and greenhouse gas emissions due to the plant decomposition was neglected.

The end-of-life of wastes due to the packaging of input materials used during the cultivation step was accounted for. These wastes are classified as hazardous wastes and it was assumed that they were disposed of in special waste dumps, according to the practices currently used by the investigated firm.

The end-of-life of batteries was taken into account considering that they were dismantled and treated by a pyrometallurgical process.

3.1.2. Impact assessment methodology and impact categories

The following impact categories are chosen to have an overview of the inventory data: global energy requirement (GER); climate change (CC); ozone depletion (OD); human toxicity – cancer effects (HT_{ce}); human toxicity – non-cancer effects (HT_{nce}); particulate matter (PM); ionizing radiation HH (IR_{hh}); ionizing radiation E (interim) (IR_e); photochemical ozone formation (POF); acidification (Ac); terrestrial eutrophication (TE); freshwater eutrophication (FE); marine eutrophication (ME); freshwater ecotoxicity (FE_{tox}); land use (LU); water resource depletion (WRD); mineral resource depletion (RD).

The characterization factors for GER are from the Cumulative Energy Demand (Frischknecht et al., 2007) method, that allows the estimation of the consumption of energy from renewable (biomass, wind, solar, geothermal, water) and non-renewable (fossil, nuclear) sources. The environmental characterization factors are from the ILCD 2011 impact assessment method (EC, 2012).

3.1.3. Other information

No allocation procedures were performed. All the energy and environmental loads were attributed to apples, the only output of the system (Ardente and Cellura, 2012).

3.2. Life cycle inventory

The inventory analysis was performed to quantify the environmentally significant inputs and outputs of the examined system, by means of mass and energy balances of the selected FU.

The main energy and material inputs and outputs of the apple supply chain were collected from local investigations in an experimental farm located in the territory of Trentino Alto Adige (North of Italy), and they are representative for one-year field operations in a 5 ha plot of land.

According to the information provided by farmers, the period of full production of the orchard is 15 years. After this period, the crop yields would start decreasing, thus making a substitution of the orchard needed. In the period of full production, the average yield is 50 and 70 tons/ha of apples for organic and conventional cultivation respectively. Thus, the productivity of organic orchards is 28% lower than that of conventional ones. The above values are of the

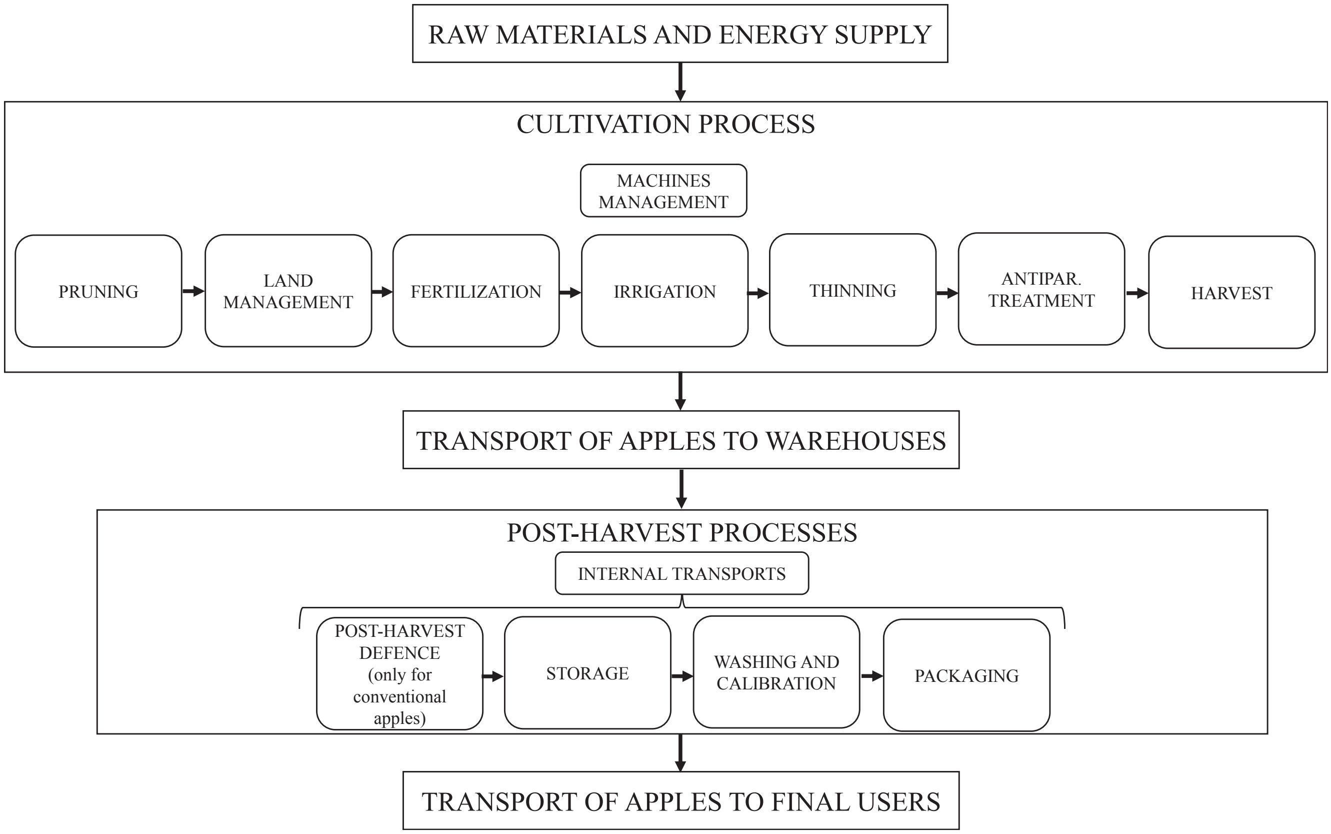

Fig. 1. System boundaries.

same order of magnitude of those reported in literature (Mazzetto et al., 2012).

As already briefly mentioned, cultivation practices can be subdivided into the following steps:

- Machines management, including the yearly substitution of lubricant oil and batteries in the agricultural machines. In this step, no significant differences occur for the two examined agricultural practices (organic and conventional);
- Pruning, carried out through mechanical techniques. Pruning helps to remove branches and leaves, control or direct the growth of branches by a correct shaping, increase the yield, and improve or maintain health and quality of apples. After pruning, branches and leaves are broken up into small chunks and mixed into the soil. Also in this case, there are not relevant differences between organic and conventional cultivation;
- Land management, which helps to control the growth of weeds. In organic agriculture this step is made by using mulchers, brushing machines and ploughs, while in the conventional agriculture mulchers and herbicides (active substances: glyphosate and MCPA) are used;
- Fertilization treatments, aimed at ensuring the soil fertility. Nitrogen organic fertilizers and mineral fertilizers (nitrogen, phosphorus, boron, calcium chloride, magnesium hydroxide and manganese carbonate based compounds), both mixed with water, are used in the organic and conventional farms, respectively. Both farms use agricultural machines in this step;
- Irrigation with sprinklers or drip irrigation equipment. Water is taken from wells and pumped onto the orchard using electric pumps;
- Thinning, that is the selective removal of flowers to allow adequate space for the remaining ones to grow efficiently. In organic agriculture this step is performed by using a thinning machine; in addition, calcium polysulphide is used to prevent germination. In conventional agriculture, chemical agents are used (6-benzyladenine, amide of the alpha-naphthaleneacetic acid, and ammonium thiosulphate based compounds). In both processes the thinning products are mixed with water and distributed with mechanical machines;
- Antiparasitic treatments, aiming at making the plant immune to parasites. Insecticides and fungicides, sometimes mixed with water, are distributed by the irrigation system and the use of an air-spray system. In the conventional process, pesticides (copper, sulphur, mineral oil, difenoconazole, cyprodinil, imidacloprid, chlorantraniliprole, spinosad, bupirimate, dithianon, captan, fluazinam, and metiram-based compounds) are obtained from chemical synthesis. In the organic process, the antiparasitic action is carried out by using natural compounds (copper hydroxide, mineral oil, sulphur, copper, calcium polysulphide, pyrethrum, and azadirachtin based compounds) and microorganisms antagonists of cryptogams, aphids and larvae (codling moth granulosis virus, and entomopathogenic nematode *Steinernema carpocapsae*);
- Harvest is mainly manual; self-propelled carts are used to reach the highest branches.

Table 1 shows the main inputs and outputs of the cultivation process of organic and conventional apples, referred to the selected FU. All input materials are purchased from local shops and transports occur by vans that cover a distance of about 20 km.

Table 1
Main inputs and outputs in the cultivation process, referred to 1 ton of apples.

	Organic apples	Conventional apples
Input		
Fertilizers (kg)	1,20E + 01	6,50E + 00
Pesticides (kg)	6,91E + 00	1,29E + 00
Water (kg)	5,67E + 04	5,08E + 04
Diesel (MJ)	8,29E + 02	7,14E + 02
Electricity (kWh)	2,83E + 00	2,54E + 00
Plastic packaging (kg)	7,07E − 02	6,18E − 02
Cardboard and paper packaging (kg)	1,71E + 00	1,16E − 02
Composite packaging (cardboard and plastic) (kg)	–	3,54E − 03
Lubricant oil (kg)	6,00E − 02	4,30E − 02
Batteries (kg)	1,32E − 01	9,40E − 02
Output		
Waste packaging plastic (kg)	7,07E − 02	6,18E − 02
Waste cardboard and paper packaging (kg)	1,71E + 00	1,16E − 02
Waste composite packaging (kg)	–	3,54E − 03
Waste oil (kg)	6,00E − 02	4,30E − 02
Batteries (kg)	1,32E − 01	9,40E − 02
Branches and leaves (kg)	1,59E + 02	1,33E + 02

After the harvest, apples are transferred to the warehouses (medium distance 20 km) for the post-harvest defence (only for conventional process: use of 1-methylciclopropene), and the cold storage in rooms with an ultra-low oxygen controlled environment (temperature 1 °C, relative humidity 95–98%). This step allows for slowing down the ripening of the fruits and for avoiding qualitative, organoleptic and nutritional deterioration.

After the storage, apples undergo the following processes: washing and calibration, packaging, loading in the trucks and transport to the final users. No differences occur in the organic and conventional process for all steps starting from cold storage to loading of trucks. Despite this, in order to estimate the contribution of each life-cycle step to the total impacts, the above processes were included in the analysis.

Inputs in the post-harvest processes are the following: electricity 165 kWh/tons, water 2900 kg/tons, packaging 120 kg/tons.

Details on the transport of final products are given in Table 2.

Eco-profiles of energy sources, materials, transports, and waste treatments were included in the analysis from international environmental databases (Frischknecht et al., 2005). Since the eco-profiles of some pesticides were not available in the environmental databases, alternative materials with the same chemical properties and/or similar function were chosen for the assessment (see Table 3).

Environmental information on microorganisms used as pesticides were not included in the analysis due to the lack of data.

The eco-profile of electricity is referred to the Italian electricity mix. The eco-profiles of input materials are mainly referred to the European context; the only exceptions are diesel used by agricultural machines and organic fertilizer, referred to the Swiss context, and battery and some pesticides, which are average worldwide data.

The data collected were elaborated to calculate the eco-profiles of the two products in terms of raw materials and energy consumption, emission to air, water and soil, and production of waste.

3.3. Life cycle impact assessment and discussion of the results

The life cycle impact assessment results are detailed in the following.

GER of organic and conventional apples was 11.2 GJ/tons and 11.4 GJ/tons, respectively, of which about 85.5% is from non-renewable energy sources. The difference between the two examined products is lower than 2%. The post-harvest processes are responsible of about 51–52% of the total energy impact (Fig. 2), transport of apples to the final users causes about 32–33% of the impact, and the remaining 15–17% is due to the cultivation (about 14–15%) and the transport of apples to warehouses (about 0.9%).

The packaging process causes the main energy impact during the post-harvest step, about 71.5% for both the examined apples (organic and conventional). The cold storage and the washing and calibration of apples are responsible of about 23.8% and 4.1%, respectively. The other steps (intermediate transports and post-harvest defence) have an incidence lower than 0.3%.

Referring to the transport to final users, the delivery to international markets causes about 82% and 94% of the energy impact for conventional and organic apples, respectively. The transport to national markets gives a contribution variable from about 6% (organic) to about 17.8% (conventional), while a contribution lower than 0.15% is caused by the transport to local markets.

A detailed analysis of the cultivation step (Fig. 3) showed that the main impacts for organic apples are due to harvest (26.5%), irrigation (25.5%), and antiparasitic treatment (22.2%). The other steps give a contribution variable from 0.9% to 8.8%.

Table 2
Transport of the final product.

Market	Apples to market (%)	Medium distance (km) and means of transport
Organic apples		
Regional	4.7	30 (Truck)
National	20.8	344 (Truck)
International	74.5	1530 (Truck)/100 (Ship)
Conventional apples		
Regional	6.9	30 (Truck)
National	36.1	570 (Truck)/155 (Ship)
International	57.0	1750 (Truck)/180 (Ship)

Table 3
Use of pesticides: detail of alternative materials used in the analysis.

Fertilizers and pesticides	Alternative materials
Organic production	
Copper hydroxide-based pesticide	Copper oxide
Pyrethrum-based pesticide	Pyretroid compounds
Conventional production	
Amide of the alpha-naphthaleneacetic acid	Acetamide–anilide compounds
Bupirimate-based pesticide	Parathion
Cyprodinil-based pesticide	Mancozeb
Chlorantraniliprole-based pesticide	Organophosphorus compounds
Difenoconazole-based pesticide	Generic fungicide
Dithianon-based pesticide	Dithiocarbamate compounds
Flonicamid-based pesticide	Pyridine compounds
Fluazinam-based pesticide	Mancozeb
Imidacloprid-based pesticide	Pyretroid compounds
Metiram-based pesticide	Dithiocarbamate compounds

The high contribution of harvest, irrigation and antiparasitic treatment is mainly due to the consumption of diesel, which causes 100% of GER in the harvest step, about 92.3% of GER in the irrigation step, and about 59.7% of GER during the antiparasitic treatment.

The main contributors to GER during the cultivation process of conventional apples are the fertilization (23.0%), the harvest process (22.2%), the irrigation (20.1%), and the antiparasitic treatment (18.4%). The remaining steps give a contribution variable from 1.7% to 5.1%.

For the conventional process, diesel consumption is responsible of the whole GER of the harvest step, of 92.3% of GER due to the irrigation step, and of 56.6% of GER due to the antiparasitic treatment. About 87.9% of GER of the fertilization step is caused by the use of fertilizers.

The environmental impacts, referred to the FU, are showed in Table 4.

Organic apples are characterized by lower impacts for almost all the examined impact categories, except for HT_{nce} that is higher than that of conventional apples due to the higher consumption of diesel per ton of fruit during the agricultural step. Differences are lower than 7% and very small for many impact categories, aside from HT_{nce} and FE for which differences are about 9.8% and 12.4%, respectively.

The share of each life-cycle step on the total impact is showed in Table 5. For each impact category, the same life-cycle step was identified as hotspot for both the examined products. In detail, the impact on HT_{nce} was mainly caused by the cultivation step both for organic apples (about 77.9% of the total impact) and for conventional apples (about 75.8% of the impact). The post-harvest processes and the transport to final users are the main contributors to the remaining impacts.

The environmental impacts of the cultivation of organic apples are mainly caused by irrigation, antiparasitic treatments and harvest. The only exception is the impact on OD, of which 49.7% is caused by the machine management.

In detail, irrigation gives the higher contribution to the following impacts, mainly caused by the diesel consumption during this step: about 22.5% of HT_{ce}, about 27.1% of ME, and about 25.1% of IR_{hh} and IR_e. Furthermore, irrigation causes about 46.3% of the WRD.

FE and FE_{tox} are the main impacts generated during the antiparasitic treatments (24.1% and 22.7%, respectively). Once again, diesel consumption is the main contributor to the above impacts.

For the remaining impact categories, the harvest process (consumption of diesel) gives a contribution variable from 23.5% to 30.9%.

For the agricultural step of conventional apples, the irrigation gives the main contribution to the impact on WRD (34.6%), the use of battery during the machine management to the impact on OD (34.4%), and the antiparasitic treatments (in particular diesel consumption and some pesticides) to the impact on FE_{tox} (24.9%). Fertilization (in particular nitrogen and phosphorus-based compounds) and harvest (consumption of diesel) are main contributors of the other impacts.

The analysis of the post-harvest processes showed that about 60–90% of all impacts is caused during the packaging step, with the only exception of the impact on WRD that is mainly generated by the cold storage step (about 52%).

Referring to the transport to final users, the main impacts are due to the delivery to international markets (about 94% for organic

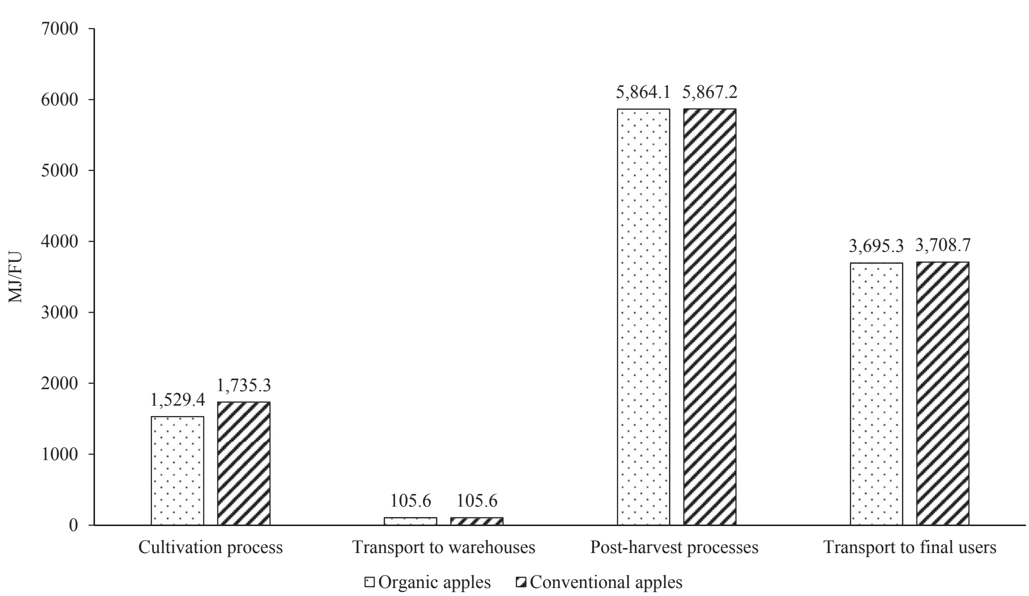

Fig. 2. GER of apples: contribution of each life-cycle step.

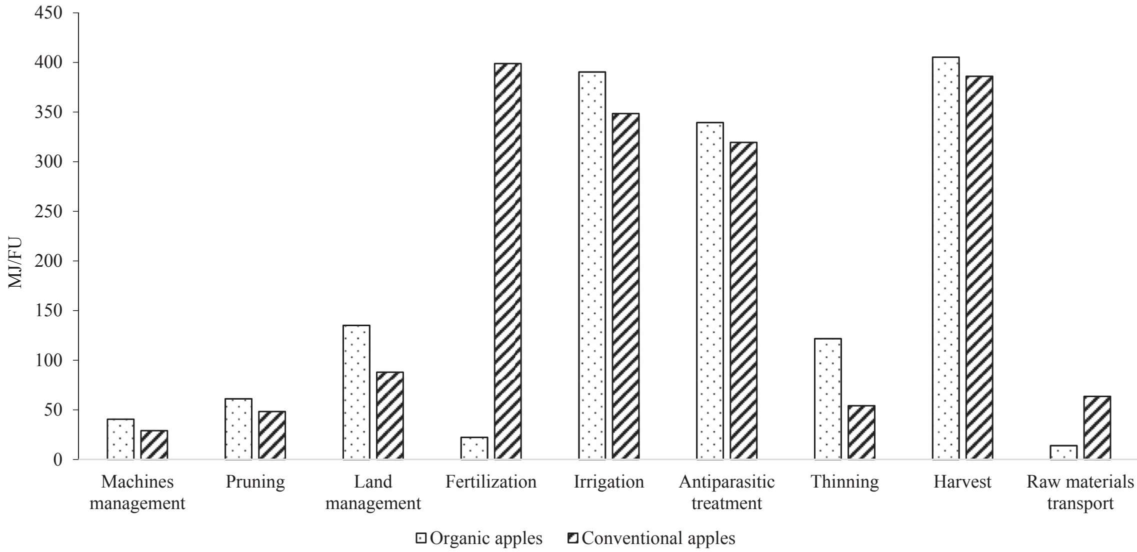

Fig. 3. GER of the cultivation process: contribution of each step.

Table 4
Environmental impacts of 1 ton of organic and conventional apples.

Impact category	Organic	Conventional	Differences (%)
CC (kg CO_{2eq})	5.88E + 02	6.12E + 02	−3.96
OD (kg CFC-11_{eq})	8.46E − 05	8.54E − 05	−0.99
HT_{ce} (CTUh)	2.67E − 05	2.81E − 05	−5.00
HT_{nce} (CTUh)	5.45E − 04	4.96E − 04	+9.75
PM (kg $PM2.5_{eq}$)	2.96E − 01	3.19E − 01	−7.11
IR_{hh} (kBq $U235_{eq}$)	7.35E + 01	7.83E + 01	−6.11
IR_e (CTUe)	2.27E − 04	2.42E − 04	−6.02
POF (kg $NMVOC_{eq}$)	3.69E + 00	3.69E + 00	−0.06
Ac (molc $H^+{}_{eq}$)	3.82E + 00	3.97E + 00	−3.66
TE (molc N_{eq})	1.37E + 01	1.39E + 01	−1.21
FE (kg P_{eq})	1.14E − 01	1.30E − 01	−12.38
ME (kg N_{eq})	1.32E + 00	1.33E + 00	−0.83
FE_{tox} (CTUe)	2.89E + 03	3.07E + 03	−5.79
LU (kg C deficit)	1.70E + 03	1.71E + 03	−0.24
WRD (m^3 $water_{eq}$)	2.52E + 02	2.59E + 02	−2.64
RD (kg Sb_{eq})	1.11E − 02	1.12E − 02	−0.89

apples and about 82% for conventional ones). Impacts lower than 0.17% are caused by transport of apples to local markets.

3.4. Life cycle interpretation

The results of the analysis allowed answering to the questions reported in the goal and scope of the study. In detail, they showed that, despite the lower productivity, organic apples are characterized by lower energy and environmental impacts than conventional ones for all of the examined impact categories, except for the impact on HT_{nce}. The higher impact of organic apples on HT_{nce} is caused by the higher consumption of diesel during the cultivation process (+16% if referred to the FU, +17% if referred to 1 ha of farmland).

However, the differences between the eco-profiles of the two products are not very significant, being lower than 12.4%.

A contribution analysis pointed out that the post-harvest processes and final transports are the main contributor to the examined impacts, except for HT_{nce} mainly attributable to the cultivation of orchards. Referring to the cultivation step, a significant share of the impacts is due to the use of diesel, fertilizers and pesticides. The above findings are generally coherent with those of literature studies mentioned in Section 2.

3.4.1. Sensitivity analysis

Authors made some assumptions on the input secondary data for fertilizers and pesticides. In particular, due to unavailability of specific data:

- The eco-profiles of microorganisms used as pesticides in the antiparasitic treatment for organic cultivation were not included in the analysis (Base Scenario − BS);
- The eco-profiles of alternative materials were used for modelling the life-cycle of some pesticides, both in the organic and conventional processes, as detailed in Table 3 (BS).

To assess the incidence of the above assumptions on the results of the study, authors carried out a sensitivity analysis (SA) on secondary data (Cellura et al., 2011b).

In detail, the eco-profiles of generic pesticides (Frischknecht et al., 2005) were used as eco-profiles of the microorganisms. Differences lower than 1% occurred in the life-cycle results, except for the impacts on OD (about 2% higher than that of the BS), FE (+3%), and FE_{tox} (+4.4%). The new calculated impacts for OD and POCP resulted higher if compared with those of conventional apples (+1% and +0.05%, respectively).

Furthermore, the eco-profiles of generic pesticides (Frischknecht et al., 2005) were substituted to those of alternative materials detailed in Table 3, both for organic and conventional processes. The results of the SA are showed in Tables 6 and 7. In this case, for organic apples differences lower than 1% were found.

For conventional apples, differences are lower than 0.7%, with the only exception of impacts on OD and FE, for which differences are about ±2.5%.

The SA demonstrated that, in this specific case study, the results of the analysis are not very sensitive to the selection of different secondary data for pesticides eco-profiles.

4. Conclusion

The LCA methodology can support the development of studies that aim at reducing energy and environmental impacts throughout the supply chain of products and can contribute to the application of sustainable production and consumption strategies.

Table 5
Incidence of each life-cycle step on the environmental impacts.

	Cultivation process	Transport to warehouses	Post-harvest processes	Transport to final users
Organic apples (%)				
CC	17.31	1.05	43.46	38.18
OD	30.46	0.86	26.95	41.73
HT_{ce}	10.87	2.44	43.96	42.72
HT_{nce}	77.95	3.62	12.03	6.39
PM	22.68	1.24	50.62	25.47
IR_{hh}	9.98	1.60	61.66	26.76
IR_{e}	9.86	1.56	62.22	26.35
POF	26.92	1.39	21.30	50.39
Ac	26.10	1.18	33.33	39.39
TE	27.83	1.30	20.67	50.19
FE	11.52	1.31	70.74	16.43
ME	25.47	1.24	25.69	47.60
FE_{tox}	19.36	1.53	52.70	26.41
LU	11.15	2.49	56.03	30.32
WRD	12.88	2.35	68.50	16.27
RD	29.70	3.30	15.89	51.10
Conventional apples (%)				
CC	20.37	1.01	41.76	36.86
OD	31.02	0.85	26.74	41.38
HT_{ce}	14.97	2.32	41.82	40.89
HT_{nce}	75.78	3.98	13.22	7.02
PM	27.98	1.15	47.04	23.83
IR_{hh}	15.31	1.50	57.96	25.23
IR_{e}	15.12	1.47	58.54	24.87
POF	26.44	1.39	21.30	50.88
Ac	28.29	1.14	32.13	38.44
TE	28.16	1.29	20.42	50.13
FE	20.97	1.15	63.35	14.53
ME	25.42	1.23	25.63	47.72
FE_{tox}	23.77	1.44	49.91	24.88
LU	11.08	2.49	55.90	30.53
WRD	15.10	2.29	66.72	15.89
RD	30.00	3.15	15.17	48.53

Table 6
Sensitivity analysis for organic apples: substitution of alternative materials with generic pesticides.

Impact category	BS	SA	Differences (%)
GER (GJ)	1.12E + 01	1.12E + 01	−0.06
CC	5.88E + 02	5.87E + 02	−0.05
OD	8.46E − 05	8.55E − 05	1.07
HT_{ce}	2.67E − 05	2.67E − 05	−0.09
HT_{nce}	5.45E − 04	5.44E − 04	−0.09
PM	2.96E − 01	2.96E − 01	0.00
IR_{hh}	7.35E + 01	7.35E + 01	−0.01
IR_{e}	2.27E − 04	2.27E − 04	−0.01
POF	3.69E + 00	3.69E + 00	−0.01
Ac	3.82E + 00	3.83E + 00	0.05
TE	1.37E + 01	1.37E + 01	−0.01
FE	1.14E − 01	1.13E − 01	−0.14
ME	1.32E + 00	1.32E + 00	0.06
FE_{tox}	2.89E + 03	2.88E + 03	−0.28
LU	1.70E + 03	1.70E + 03	−0.02
WRD	2.52E + 02	2.52E + 02	−0.03
RD	1.11E − 02	1.11E − 02	−0.05

Table 7
Sensitivity analysis for conventional apples: substitution of alternative materials with generic pesticides.

Impact category	BS	SA	Differences (%)
GER (GJ)	1.14E + 01	1.14E + 01	0.12
CC	6.12E + 02	6.13E + 02	0.12
OD	8.54E − 05	8.77E − 05	2.58
HT_{ce}	2.81E − 05	2.81E − 05	0.08
HT_{nce}	4.96E − 04	4.93E − 04	−0.66
PM	3.19E − 01	3.18E − 01	−0.37
IR_{hh}	7.83E + 01	7.84E + 01	0.19
IR_{e}	2.42E − 04	2.42E − 04	0.19
POF	3.69E + 00	3.69E + 00	−0.01
Ac	3.97E + 00	3.95E + 00	−0.63
TE	1.39E + 01	1.39E + 01	0.01
FE	1.30E − 01	1.30E − 01	0.07
ME	1.33E + 00	1.33E + 00	0.20
FE_{tox}	3.07E + 03	2.99E + 03	−2.38
LU	1.71E + 03	1.71E + 03	0.02
WRD	2.59E + 02	2.59E + 02	0.03
RD	1.12E − 02	1.12E − 02	−0.40

The study focused on the analysis of impacts of organic and conventional apples. The application of LCA allowed comparing two farming techniques and assessing the share of each life-cycle step of apples supply chain on the overall impacts, and selecting the hotspots of the examined systems, by the identification of steps and processes responsible of the largest impacts.

The obtained results highlighted the environmental advantages of organic farming. Despite the lower productivity of organic apples, preferring them to conventional apples could help to reduce the environmental impacts for the majority of the examined impact categories.

This result is in agreement with those of some literature studies that have found organic farming to be superior.

Furthermore, the systems examined in this study have most of their impacts beyond the farm gate, resulting in environmental burdens that are not accounted for when the LCA stops at the farm gate. This finding highlights the importance to take into account life-cycle steps following the cultivation process, especially for food that is not immediately consumed and that needs to be stored.

One key issue of the analysis was the selection of secondary data for modelling the life-cycle of pesticides. Even if a SA showed that the influence of the choices made is not very relevant, the study allowed exploring the complexity of carrying out the LCA of agricultural products, and the limited availability of process-specific data for pesticides. This lack of data is mainly linked to the fact that there is a very high number of chemical agents that can be used in agriculture, and no appropriate measurement of the life-cycle impacts can be possible for all of them. For these products, it could be necessary to use estimation from literature data and this may cause uncertainties in the study. For this reason, the application of the SA is of paramount importance for the reliability of the results.

Despite the above limitations, the study highlights the relevant role of the LCA in the decision-making processes connected to the definition of environmental strategies and to the selection of the more performing products.

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