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Eco-Efficiency Assessment in Apple Production and Storage in the Northeast of Portugal

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Abstract
Cost reduction, product quality, and customer demands have been pressing the agro-industrial sector to adopt more sustainable practices. Assessing the environmental performance of the food sector worldwide is crucial to reduce the environmental impact of agricultural and industrial practices. This study focus on the assessment of the eco-efficiency of the apple production and storage in the northeastern region of Portugal, one of the largest production regions, using a set of environmental indicators such as energy intensity (EI), water withdrawn intensity (WWI) and GHG emission intensity (GEI). System boundaries include the farming and the storage subsystems. Upstream and down-stream processes such as fertilization production, apple distribution and waste treatment were not taken into account. Inventory information was gathered from two apple farms and one apple storage company. Data was gathered for a reference year. Results show that each ton of apple exiting the system requires on average 32.7 kgoe of primary energy, 74.9 m^3 of water and generates an emission of 75.1 $kgCO_2e$. Apple orchard irrigation was identified as the most energy-demanding activity with up to 63% of the energy input. Industrial cold was identified as the most energy-demanding activity (50%) in the apple storage stage. Water is required in both subsystems but the amount used in the storage is residual (<1%) when compared with its use by agricultural subsystem. Taking into account the GHG emissions from the use of energy, apple cultivation had a lower contribution for GEI (40%) than the apple storage (60%). Unlike other food systems, a more eco-efficient apple production can be accomplished through improvements in both stages, since energy costs and environmental impacts are greatly associated with energy use.

Keywords: Apple production, eco-efficiency, energy use, GHG emissions, water consumption.

1. Introduction

The global growth of human population (Bartlett, 1994) has forced food production to become more intensive and industrialized, thus depleting natural resources and generating pollution (Kramer et al., 1999; Tukker et al., 2006). Energy and water are two of the main resources consumed in industries worldwide, and their importance is recognized in the global economy and the welfare of the human population (Ayres et al., 2013; Jorgenson et al., 2014; Stern, 2010), so its use should be conscious and efficient. The supply of energy to end users also generates environmental impacts such as those resulting from emissions of gaseous contaminants and greenhouse gases (GHG). The large use of water in agriculture, about 70 to 80% of drinking water according to (Jägerskog and Jønch Clausen, 2012), has also a direct influence on the energy consumption and on the carbon and nitrogen cycles. In fact, we all realize that food production, from farming to consumption, triggers many impacts that are harmful to the environment and to human health. To ensure long-term sustainability, all players of the food sector should therefore improve the environmental performance of their products and processes.

The impact assessment in the agri-food sector has essentially been addressed by Life Cycle Assessment (LCA) tools. Its application in the sector has been increasing exponentially in the last decade (Heller et al., 2013). The environmental impact assessment studies can be categorized according to several food products, such as wine (Rugani et al., 2013), fruit (Ingwersen, 2012; Mila i Canals et al., 2007; Mouron et al., 2006), or seafood (Ziegler et al., 2013). Roy et al. (2009) demonstrate the advancements achieved with LCA methodology as well as a very thorough review of its application to the agri-food sector. The combination of LCA with other methods allows the establishment of a database that can inform policy makers, producers, and consumers when choosing eco-efficient products (Roy et al., 2009). Results from these different methodologies allowed for the concept of sustainable development (Basil, 2001; Hasna, 2012; Robert et al., 2005) based on the eco-efficiency (Fet, 2003) to be implemented in the agro-industrial sector with a good worldwide acceptance (Bonny, 1993; Guzmán et al., 2011; Pervanchon et al., 2002; Swanton et al., 1996). There are several key factors, such as cost reduction and quality, that customers demand from products, forcing the sector to adopt measures to meet the aforementioned concepts. Companies from all economic sectors, including small and medium enterprises (SMEs) are under pressure from regulators, clients and investors, and also their employees. The use of these tools is an opportunity for companies, mostly SMEs, to be able of self-assess and identify their inefficiencies and implement changes leading to higher eco-efficiency.

The present article deals with eco-efficiency in two stages of the apple chain (farming and storage) for the northeastern region of Portugal, by using a set of environmental indicators such as energy intensity (EI), GHG emission intensity (GEI) and water withdrawn intensity (WWI). This study was developed as a part of two larger research projects (Ecodeep and Inovenergy) addressing eco and energy efficiency in the Portuguese food sector.

2. Global and Portuguese apple production

Apples bring multiple benefits to human health, especially by preventing chronic diseases such as cardiovascular disease and cancer (Ness and Powles, 1997; Steinmetz and Potter, 1996; Van Duyn and Pivonka, 2000) and so it should be part of meals on a daily basis. For example, Eberhardt et al. (2000) and Boyer and Liu (2004) report that apple has several phytochemicals, many of which have antioxidant activity, which can help to reduce cell cancer proliferation.

Apple is among the most consumed fruits worldwide. According to the United Nations Food and Agriculture Organization (FAO), as of 2012, apple occupied the second place among the global *Fruit Primary* production (FAO, 2014). This classification comprehends a total of 37 different fruits, where apple represents about 12%. Also, China was the largest producer, with almost half of the global apple production (≈ 48%). The European Union was in second with 14% of the global apple production achieved by aggregating the productions of the 28 member countries. Of the EU28 countries, those with the largest representation are Poland with 26%, followed by Italy with 18% and France with 13%. Portugal was the thirteenth largest apple producer in the EU28, with approximately 2% (Fig. 1.A).

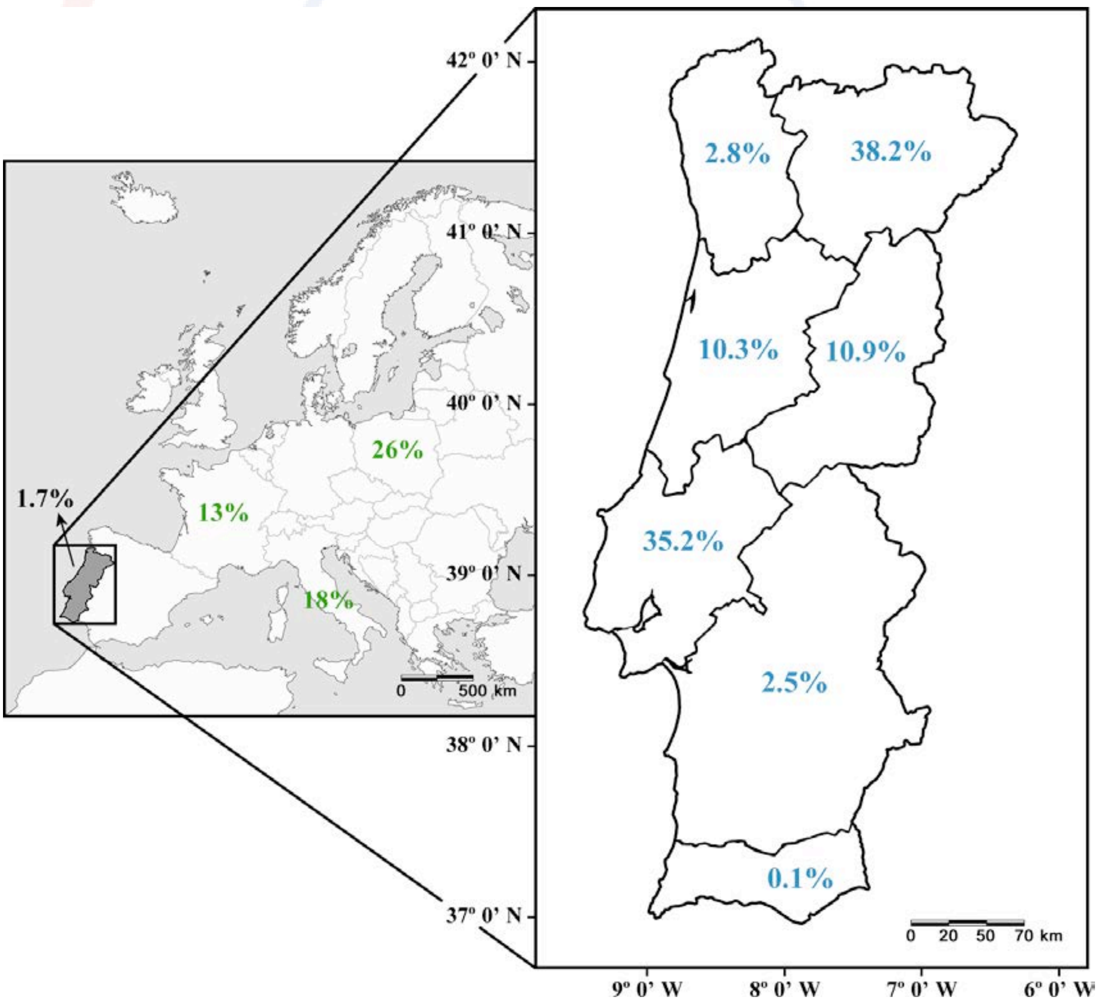

Fig. 1. Major apple producers in the EU28 (A) and percentage of apple production in Portugal by region (B), as of 2012.

As shown in Fig. 1.B, which displays the regional distribution of apple productions in Portugal (INE, 2011), the Northeastern region accounts for more than a third of the Portuguese apple production (38%) and has an average yield higher than the national mean of 17 t/ha. Portuguese apple yields are well below the yields found in other countries, such as Italy or France, where production can reach up to 40 t/ha (FAO, 2014).

3. Methodology

3.1. System boundaries and data collection

Our analysis was applied to a system encompassing the farm (cultivation) and the storage stages only (see Fig. 2). Upstream processes such as fertilizer production and downstream activities such as apple distribution and apple consumption among others were not taken into account.

The study was conducted with the collaboration of two apple farms and an apple storage company, hereinafter referred to as F1, F2 and S1, respectively, located in one of the two sub-regions of apple production in the northeast of Portugal. Both farms are managed according to the specific regulations for integrated production.

Data collected for the apple farming, regarding energy and water consumption, took into account seven farming processes: soil management, irrigation, fertilization, pest control, pruning, apple collection and transport. The two apple farmers were directly approached with surveys regarding the size of the land used for production, the number of apple trees and their age, and the types of apple collected. This survey also gathered information on the farming processes, with special attention to water and energy consumption, and on the use of chemical and organic products.

For the storage characterization, after an initial survey on general industry characteristics (e.g. dimension, annual turnover, etc.), type, costs and amount of energy inputs, raw material and annual production, an energy audit was conducted in order to identify and quantify the major energy consuming processes/equipment, as allowing for the identification of the most relevant energy inefficiencies. This information was then analyzed and used to calculate some environmental/eco-efficiency indicators widely used for benchmarking purposes (see section 3.3).

3.2. System description

The production of apple and its post-harvest storage can be schematized with a simple set of processes. Fig. 2 shows the schematic for apple production and storage, identifying the main inputs and outputs of the two apple chain subsystems focused in this study (farming and storage).

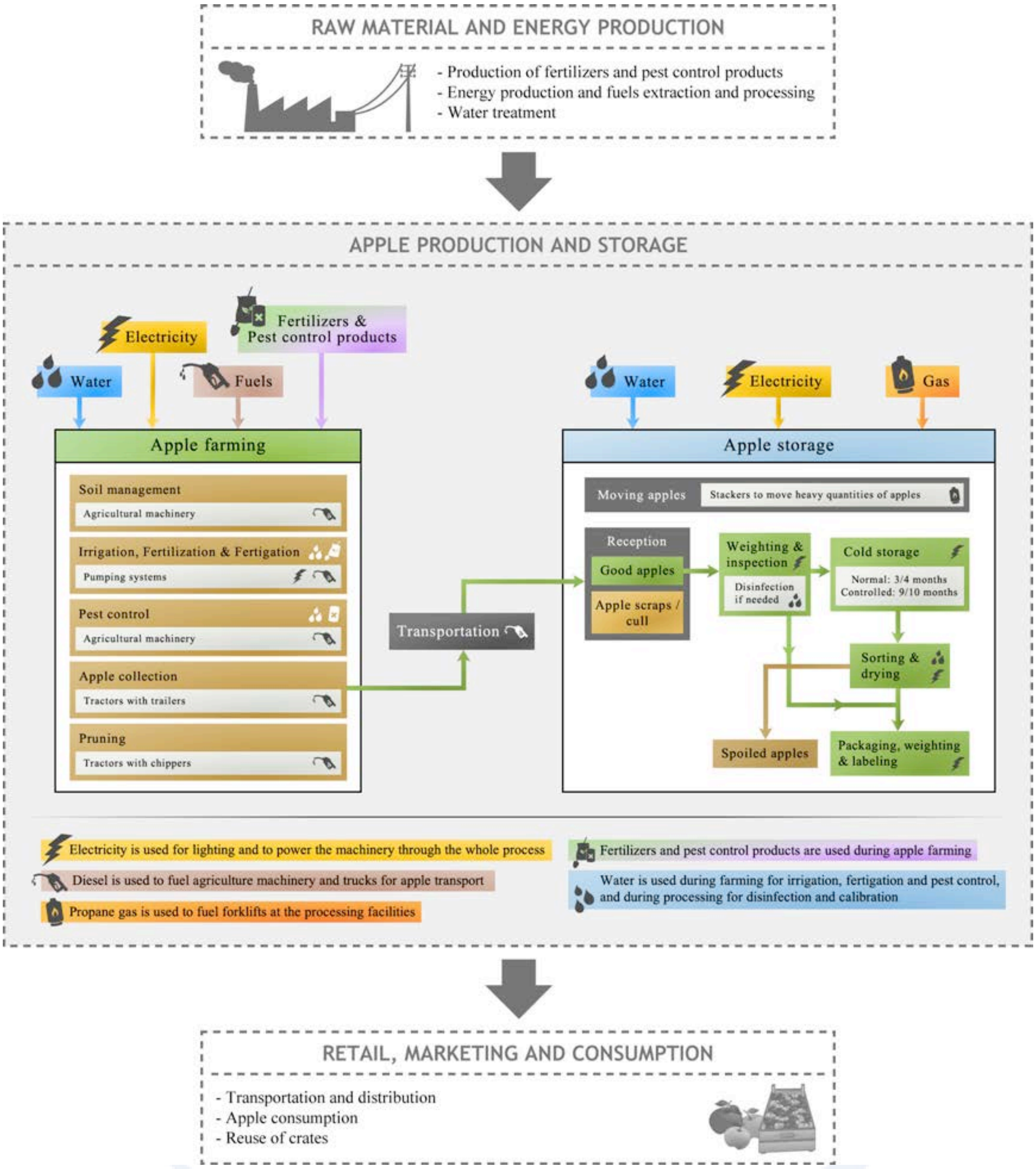

Fig. 2. General schematic for the apple farming and storage stages.

The apple farming is characterized by many processes, occurring yearly, including soil management, irrigation, fertilization, pest control, apple collection and pruning. Soil management in agriculture demands a lot of effort, starting with the soil being plowed (about 3 times a year), in order to clear the soil from weeds and other grass. This treatment is usually done using machinery, consuming fuel and releasing GHG emissions. This process contributes to lessen the use of herbicides. Apple orchards are highly susceptible to both insect and fungi attack, which may on occasions affect productivity. So, the orchards need to be constantly monitored and treated when necessary, using chemicals to prevent or destroy pests. The fertilization is applied directly on the soil and on trees, but it is also takes place along with irrigation (fertigation).

Apple orchards are important water consumers. Water is provided by a set of equipment (e.g. pumps, reservoirs), which in turn consumes energy, either electricity provided by the national grid or generated from the combustion of a specific fuel such as the diesel. After these processes, harvest takes place around September and is usually done by hand with the support of tractors with trailers (or similar transport) to place the apples. The pruning is also done by hand, and so it only consumes energy related to green residues shredding, through the use of diesel powered machinery. After collection, apples are transported to a storage facility to undergo another set of processes in order to ensure its long-term conservation. The transport process is usually done by the farmers using diesel fuelled light-duty trucks or tractors (with trailer), therefore its GHG emissions are accounted for during the farming stage.

Storing apples for a few months can be expensive because a lot of energy is required for several processes. Electricity is required for lighting the facilities and powering its machinery, mostly with the production of compressed air.

When apples are received, first they are separated and the cull (apples with some defect like bruising, sunburns or cut worm) goes to other processing industries (e.g. fruit nectars and flavors). The good apples are weighted and inspected, with disinfection can be applied, and then they are either stored or they are expedited for distribution. The cold storage is done with temperatures below 2 ºC, and in normal atmosphere composition (during 3 to 4 months) or in controlled atmosphere, with an increased nitrogen concentration (during 9 to 10 months). After storage before the product is expedited, it goes once again through manual or automatic sorting, in order to remove spoiled apples which may have decayed during storage. Inside the facilities, apples are most of the time moved by water, so they need to go through electric drying to remove some of that water. Finally, apples are manually packaged, weighted and labeled, thus making them ready for distribution. The facilities also have propane fueled forklifts to move heavy quantities of apples.

3.3. Eco-efficiency indicators

To assess the environmental performance of the farming and storage stages, eco-efficiency indicators such as energy intensity (EI), GHG emission intensity (GEI) and water withdrawn intensity (WWI) were used (Maxime et al., 2006).

The energy intensity, *EI* (Eq. 1), represents the amount of energy, *Q* (primary energy), from source *s*, expended per production volume, *P* (physical unit). Energy units used are based on mass (tons or kilograms) of oil equivalent (toe or kgoe).

$$EI = \Sigma\, Q_s / P \qquad (1)$$

Primary energy in toe or kgoe was obtained by using inventory data and conversion factors displayed in Table 1.

To determine the potential Greenhouse Impact from the different stages of apple production and storage, the GHG emission intensity (GEI) indicator was used (Eq. 2). Its determination requires the greenhouse gas mass (tons of Kg of, *M*, from source *j*, measured in units of carbon dioxide equivalent (tCO_2e or $kgCO_2e$) then divided by the production volume.

$$GEI = \Sigma M_j / P \qquad (2)$$

Only GHG emissions related to energy use (fuel combustion) in each stage were taken into account. Carbon dioxide equivalent emissions were therefore determined for each energy source (see Table 1 for conversion factors) and then normalized by the production volume in order to obtain comparable values for both apple farmers.

Table 1. Conversion to primary energy and CO_2 equivalent emission factors for electric power, diesel and propane.

Energy source	Primary energy	Emission factor	References
Electric Power [a]	215×10^{-6} toe/kWh	2186.0 kg CO_2e/toe	(EMEP/EEA, 2013; PEA, 2013)
Diesel [b]	1.01×10^{-3} toe/kg	3098.2 kg CO_2e/toe	
Propane	1.099×10^{-3} toe/kg	2637.7 kg CO_2e/toe	

[a] Considering an efficiency of 40% on converting primary to final energy;
[a] Liters of diesel were converted to kilograms using its density of 0.835 kg/L.

The third indicator used was the water withdrawn intensity, *WWI* (Eq. 3), which allows for the evaluation of the impact on the water resources consumption, taking into account the volume of water, *V*, withdrawn from each source *o*.

$$WWI = \Sigma V_o / P \qquad (3)$$

All indicators relate to the production volume because it is the only variable that allows comparisons between the different farmers and the storage facility.

4. Results

4.1. Inventory data for the apple farming subsystem

Main inputs and yields for apple farming stage per year and per hectare are displayed in Table 2. Apple trees are arranged in lines, 4 meters apart from each other, for both producers. In each line, the distance between trees is 1.7 meters for F1 with an average age of 10 years. For F2, 70% of the trees were 6 years old and the remaining 30% were 17 years old on average, with a distance of 1.4 meters between each other. The apple varieties produced are very similar between farmers, all within the same species, *Malus domestica*. The Golden apple is the variety with higher production in both cases (F1:70%, F2: 50%), followed by Royal Gala and Red apples. In general, both farmers have similar land area for apple orchards, but F1 has higher yields (50 t/ha) than F2 (30 t/ha). These higher yields in F1 were associated to the higher material and energy inputs. F1 consumed nearly the double of the water and energy used by F2.
The energy use during the farming stage was accounted for a total consumption of 322 GJ (7.7 toe) for F1 and 163 GJ (3.9 toe) for F2.

Table 2. Main inputs and yields for the apple farming stage per year and per hectare.

Apple farming	Farms	
	F1	F2
Water		
Water (m^3)	3702	2230
Energy inputs		
Electricity (kWh)	2600	692
Diesel (L)	164	176
Yield/Production		
Apples (t)	50	30
Area harvested (ha)	11	13

Electricity and diesel are the two sources of energy used by both farmers. Electric power was the most consumed energy source with about 80% in F1, while in F2 it only accounted for about 50% of its energy consumption. In both orchards irrigation is the most energy demanding process.

5.2. Environmental performance of apple farms

In order to evaluate the environmental impact of each apple farms, the eco-efficiency indicators (EI, WWI and GEI) above-described were calculated using the inventory data. Fig. 3 shows the results from such indicators for each farmer. The relative contribution of each apple farming process is also presented.

Concerning the EI indicator, F1 has higher energy inputs per unit of apple produced than farmer 2, about 40% more. Farm 1 has a EI of 13.9 kgoe/t (0.58 MJ/kg) and F2 is characterized by a EI of 9,9 kgoe/t (0.41 MJ/kg). Mila i Canals et al. (2007) reported for European countries values ranging between 0.4 and 3.8 MJ/kg, for the farming subsystem comprising field operations but also energy inputs associated to upstream processes such as fertilizers and agro-chemicals production.

EI values also show that the irrigation process is the most energy demanding in the apple farming subsystem, with energy consumptions (per ton of apple) of 11.1 kgoe (79%) for F1 and 5.0 kgoe (51%) for F2. F2 consumes less water than F1 and therefore requires less energy. Apple collection in F2 represents 15.3% of the total energy expended per ton of apple produced, while in F1 its contribution is about 8%.
As observed for the EI indicator, F1 releases more GHG per ton of apple than F2. The GEI for F1 was 33 kgCO_2e/t while for F2 it was 26.2 kgCO_2e/t due to the higher use of energy resources by the former. Therefore, F1 can reduce GEI by lowering its energy dependence or by replacing current energy sources by carbon free or carbon neutral energy sources. As expected, irrigation process is the major contributor to GHG emissions in both farms. Slight differences detected between the EI and GEI indicators are caused by the differences in the mix of energy sources used in the irrigation process, either electric power or diesel, which have different emission factors.

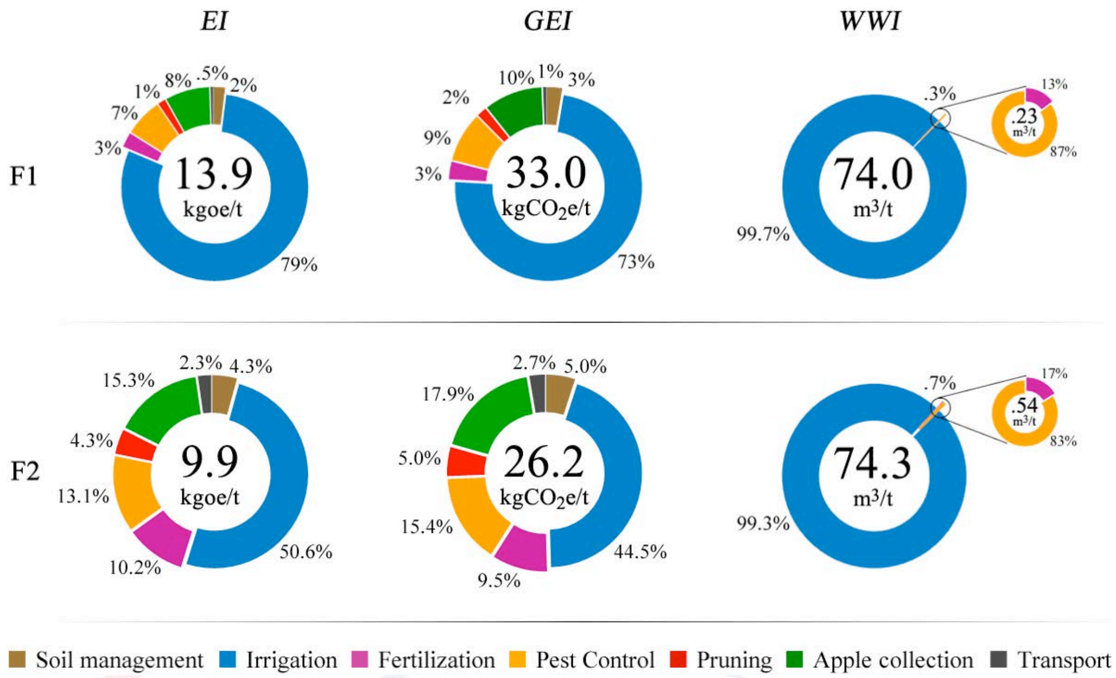

Fig. 3. Energy, GHG emission and water withdrawn intensities for both farms. Relative contributions of farming processes are also displayed.

Regarding water use, both farmers have a similar WWI (≈ 74 m^3/t), although F1 is consuming approximately 1.4 times more water than F2. Therefore, this indicates that a higher consumption of any resource should not be interpreted as a system's inefficiency, as it may lead to higher yields. Similar findings were also observed in studies applied in Swiss orchards (Mouron et al., 2006).

4.3. Inventory data for the apple storage subsystem

The storage facility processes on average six thousand tons of apple per year. The purpose of this stage is to provide the market with apples throughout the year, beyond the harvest season. The unit is equipped with 4 cold chambers with the capacity for 330 tons of apple each, and another 8 cold chambers with a controlled atmosphere, and the equivalent storage capacity.

Electricity is the main source of energy used in the storage unit (see Table 3). About 50% of electricity is used providing cold for storage for up to ten months. Moving apples through the different stages of the processing line requires about 30% of electricity, including the generation of compressed air. The remaining 20% is used for lighting and heating equipment. Propane gas is responsible for only 0.3% of the energy use, as it is only used to power forklifts.

Table 3. Main energy and material inputs for the storage stage per process and per year.

Apple storage	Storage facility S1		
Material inputs			
Apples (t)	6000		
Water (m^3)	4524		
Energy inputs			
Electric power	[kWh]	[toe]	[%]
Apple Processing	176496	37.9	28
Compressed air	13190	2.8	2
Industrial cold	311537	67.0	50
Lighting	74116	15.9	12
Heating devices	52760	11.3	8
Propane	[kg]	[toe]	[%]
Apple Processing	363	0.4	100

4.4. Environmental performance by the apple storage subsystem

Fig. 4 shows the results for the eco-efficiency indicators applied in this study for the storage process. This subsystem of the apple production chain was responsible for the consumption of 20.8 kgoe/t and a GHG emission of about 45.6 kgCO_2e/t.

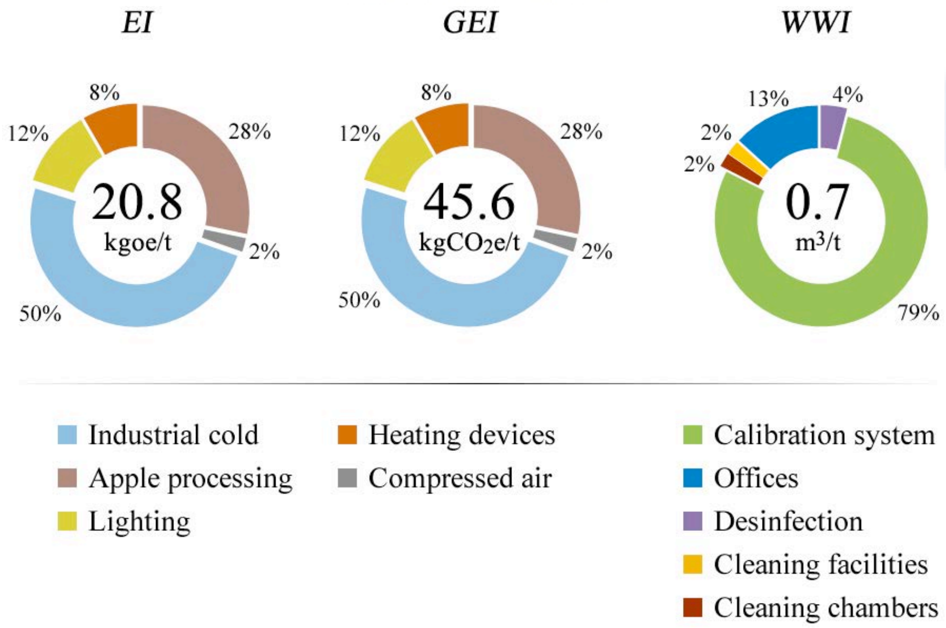

Fig. 4. Eco-efficiency indicators for the storage stage. Relative contributions of the storage processes are also displayed.

The water use in the storage facilities is about 4500 m^3 per year. The apples transport to the calibration system uses about 79% of the total water consumption. Around 13% is used in several office activities and physiological needs (e.g. toilets). The disinfection process can consume up to 4% of the water, and the cleaning of chambers and facility uses about 2%, each. The WWI of the facility was about 700 liters per ton of apple, a much lower value when compared to the apple cultivation.

4.5. Environmental performance for the apple production and storage system

The purpose of this section is to evaluate the environmental performance for the apple in the northeast of Portugal, integrating all stages from farming to storage. To perform such analysis various assumptions have been taken into account. The sub-region has about 455 ha of apple orchards, with an apple yield of around 12000 ton/year. All apples are transported from the different farms to a storage unit having the same characteristics and performance than S1. Furthermore, according to Portuguese statistical data (INE, 2011) the farthest apple orchard is located about 12 km away from the storage facility (see Fig. 5). However, information gathered during the survey performed at the storage unit reveals that on average the cultivars from which storage unit receives apples are located within a 4 km radius. So, two scenarios were established, in which the fuel consumed during the transportation of apple to the storage facility and back was averaged by those two distances, maintaining the same energy consumption for the other processes. Apple transport to the storage facilities was assured through 2 t capacity light-duty trucks (75%) and 4 t tractors with trailers (25%). Both vehicles are equipped with diesel engines with a fuel consumption of 10L/100km and 4L/h, respectively.

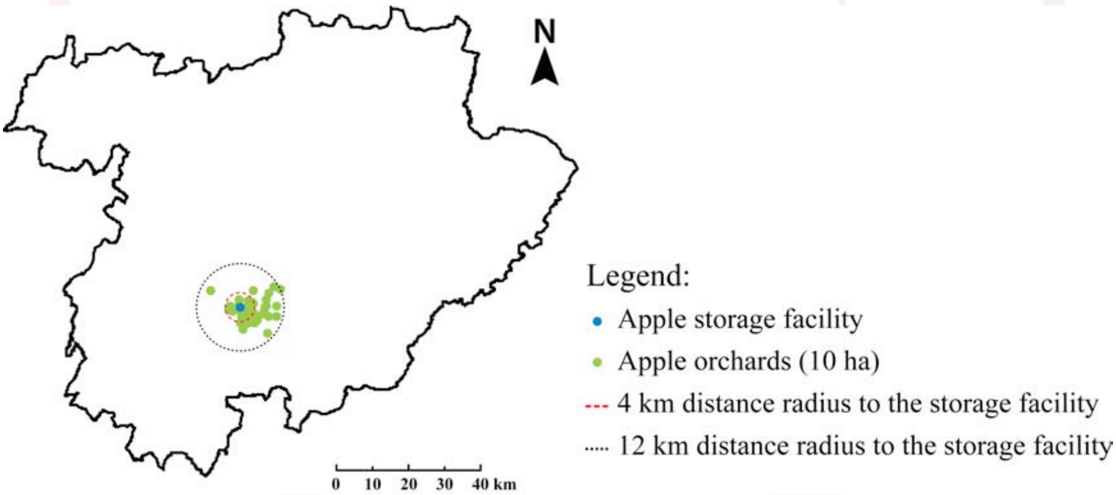

Fig. 5. Main apple cultivars around the storage facility, located at the northeast region of Portugal.

Based on these assumptions, all indicators were calculated for combinations between the apple farms and a storage unit (F+S), regarding the two simple scenarios, whose only difference is the distance associated with the apple transportation from farms to storage (4 km and 12 km).

Fig. 6 shows results for each scenario expressed in terms of EI, GEI and WWI. It also shows the relative contribution of apple farming, apple storage and transport between farms and storage unit for the magnitude of each indicator

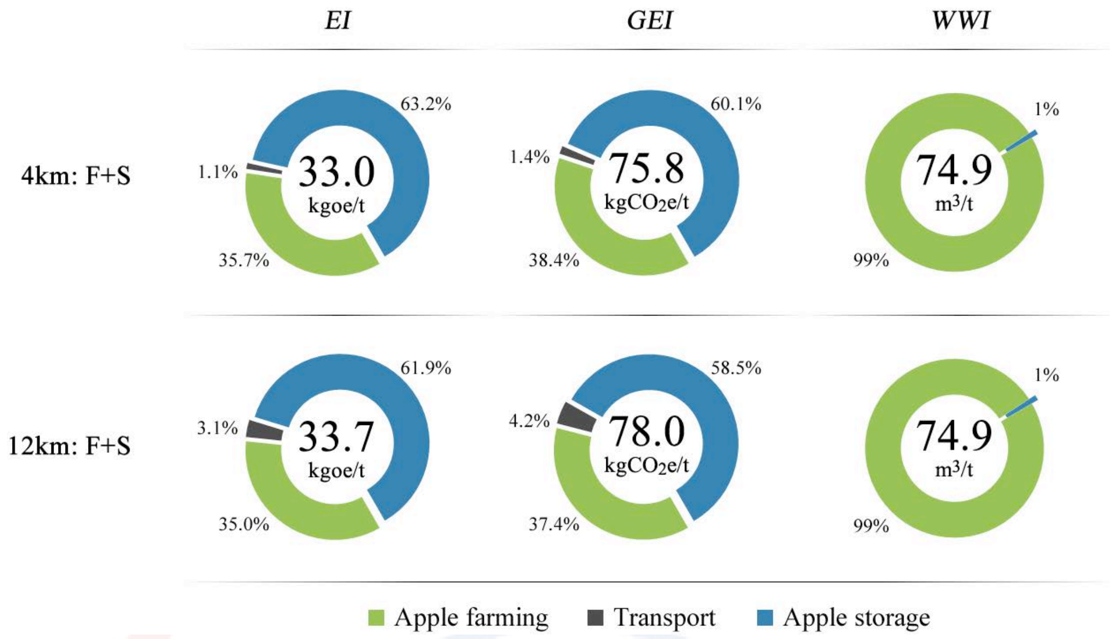

Fig. 6. EI, GEI and WWI for the two scenarios, with the relative contribution of farming, storage and apple transport between the two stages.

On average, a ton of apple at the storage delivered to the market requires about 33.4 kgoe of primary energy and around 75 m^3 of water. Apple storage has a larger demand for energy than apple farming and has a very residual need for water when compared with apple farming. The cumulative GHG emissions for farming, storage and transport from farming to storage was about 77 $kgCO_2eq/t$. Storage has a contribution of about 60% for energy consumption and GHG emissions while the farm stage accounts for about 40%. Transport between orchards and storage unit has a very low contribution to GHG emissions (<5%).

5. Conclusions

This study assesses the environmental performance of two stages of the productive apple chain - cultivation and storage – for a specific geographical context, the northeastern region of Portugal. The assessment was based on three environmental indicators: energy intensity (EI), GHG emission intensity (GEI) and water withdrawn intensity (WWI). The calculation of these indicators was based on inventory data gathered from two medium-size apple growing farms (F1 and F2) and an apple storage company (S1), involving a very complex and time demanding methodology.
Concerning the apple farming stage, despite some differences between the two farms, very similar patterns with regard to energy use, water use and GHG emissions were found. Irrigation was identified as the major contributor to energy and water consumption and to GHG emissions. Irrigation accounts for more than half of the total energy consumption, with 79% for F1 and 51% for F2. Similar contributions were found for GHG emissions resulting from the use of the different sources of energy. However, it doesn't necessarily mean that apple farmers should lower water consumption to become their cultivation more eco-efficient, since apple yields are directly related to water use although its excessive use can lower efficiency levels. Increasing eco-efficiency means more value per impact and, in that way, farmers with

high water consumption but also with high yields can simply improve their eco-efficiency by using more sustainable energy sources.

With regard to storage stage, a large part of the energy is used for apple refrigeration, either in normal or controlled atmosphere, process that guaranties apple availability throughout the year. Industrial cold is therefore the process that should require special attention whenever storage companies intend to improve energy and environmental performance. The continuous maintenance of cold systems is fundamental, because the constant need for its use wears off the equipment, reducing its energy efficiency. Unlike other food systems, where farming represents the most energy demanding stage, the long-term storage of apples is responsible for significant energy consumption, having also a large contribution for the apple carbon footprint. So, improvements should be accomplished in both stages in order to increase the Eco-efficiency in the apple sector.

Although the analysis presented in this article needs to be complemented by further developments based on LCA and other tools, it provided a major insight on the eco-efficiency aspects of the two most relevant stages of the Portuguese apple production chain, helping its players to improve their environmental performance.

Acknowledgements

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