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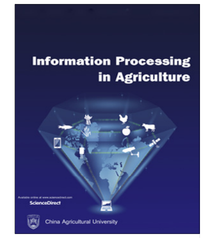

Comparative life cycle assessment of pistachio, almond and apple production

G. Bartzas [a], D. Vamvuka [b], K. Komnitsas [b,*]

[a] School of Mining and Metallurgical Engineering, National Technical University of Athens, 15780 Zografos, Greece
[b] School of Mineral Resources Engineering, Technical University of Crete, 73100 Chania, Greece

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A B S T R A C T

A comparative life cycle assessment (LCA), with the use of GaBi 6 software and specific related databases, of three water intensive tree cultivation systems was conducted in order to evaluate environmental impacts and energy consumption. The tree crops are traditionally cultivated in two representative areas in Greece, namely Aegina island, Attica region, for pistachios and Agia, East Thessaly region, central Greece, for apples and almonds. The impact categories considered include global warming potential (GWP), eutrophication potential (EP), acidification potential (AP) and cumulative energy demand (CED). Based upon the results obtained, it is deduced that pistachios and almonds show minor differences for all impact categories considered, while apples exhibit the best environmental profile. The phases of fertilizers production, irrigation system and field management were identified as the main "hot-spots" for all crops, exhibiting the highest environmental impacts and energy consumption. A sensitivity analysis was performed to explore actions that can be considered at farm scale, such as water desalination for irrigation purposes, transition to organic production and use of renewable energy, in order to reduce water requirements and promote energy conservation, especially in semi-arid and arid Mediterranean regions which suffer from water shortage and are prone to salinization. Finally, the results of this study were compared with the results derived from other relevant LCA studies.

1. Introduction

Irrigated agriculture constitutes by far the largest consumer of freshwater at global scale and produces around 40% of global food supply [1]. In the semi-arid and arid regions of Southern Europe, freshwater resources required for agricultural use account for up to 80% of the total withdrawal and abstraction rates often exceed the long-term natural rates of groundwater replenishment. In Greece, the irrigated land has doubled over the last 45 years and now represents 37% of the total cultivated agricultural area [2]. As a result of intensive agriculture, 3763 cubic meters of water were used per hectare of irrigated land in 2010, implying great energy consumption for withdrawal, transport and water application to crops and thus increase in associated greenhouse gas (GHG) emissions.

* Corresponding author.
E-mail addresses: gbartzas@metal.ntua.gr (G. Bartzas), vamvuka@mred.tuc.gr (D. Vamvuka), komni@mred.tuc.gr (K. Komnitsas).
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In order to meet water needs the development of strategic plans is required, considering also the option of recycling treated municipal wastewater for agricultural irrigation [3] or the use of soil amendments such as compost, zeolite or biochar produced from agricultural wastes to minimize water and fertilizer losses [4,5].

Life Cycle Assessment (LCA) has been widely applied to assess the environmental impacts of many agricultural products [6,7]. However, most LCA studies carried out so far provide information for the environmental impacts associated with the cultivation of fruit trees at farm scale and only very few refer to nut trees, such as pistachios and almonds [8,9]. These studies have shown that the irrigated cultivation of both nuts is more beneficial in terms of growth and yield, crop quality and orchard longevity when compared to cultivations carried out under rain-fed/drought conditions [10]. In fact, it has been shown that both pistachios and almonds are considered among the most water-intensive crops when irrigation is applied [11]. To this context, the present LCA study attempts to (i) analyze and compare the life cycle of pistachio, almond and apple production in Greece, (ii) identify critical processes that are energy intensive and cause the highest environmental impacts, and (iii) provide suggestions for improving the environmental performance of the cultivation systems under study. Special emphasis is given to the most important cultivation practices (i.e. irrigation and fertilization) used for the production of pistachios in the semi-arid island of Aegina, Greece, in relation to those applied for other fruit and nut trees in more humid and rainy agricultural regions of mainland Greece.

2. Study areas and methodology

2.1. Study areas

Two study areas representative of the production of pistachios, almonds and apples in Greece were selected, namely (i) Aegina island, located in the prefecture of Piraeus, region of Attica, and (ii) Agia, located in the prefecture of Larissa, region of Thessaly, central Greece, as shown in Fig. 1.

Aegina is located approximately 16.5 miles south of Athens and is the second largest island of the Saronic Gulf with a total surface area of 87 km^2 and a population of 13,056 inhabitants. The northern part of the island is relatively flat with hills less than 150 m above sea level (a.s.l), while the southern part is hilly to semi-mountainous with elevations reaching up to 513 m a.s.l and slopes of up to 45%.

Aegina island is characterized by semi-arid Mediterranean climate, with a mean annual temperature of 19 °C and an annual rainfall of 295 mm, of which almost 80% is recorded in the wet period (November–April), while summers are usually dry [12]. With respect to land uses, 32% of the total cultivated area is irrigated and involves the cultivation of pistachios (63%), olive trees (20%), lemon trees (4%), vineyards (2%) and others 11%. Although, Aegina produces only 11% of the total pistachio production of the country [13,14], it is renowned for its ideal climate that yields/promotes the production of high quality Protected Designation of Origin (PDO) pistachios with premium pricing in the EU market, due to their particular organoleptic characteristics, excellent flavor and appeal.

On the other hand, Agia is located about 35 km east of the capital city of the region, Larissa, and 12 km away from the Aegean coast. It has a population of 3169 inhabitants, while its total valley area is 63 km^2, 75% of which is arable. The climate in this area is typical Mediterranean, with mean summer temperature ranging between 16.5 and 20.4 °C, and mean winter temperature of almost 6 °C [12]. The mean annual temperature for the period 2012–2015 was 15.4 °C while the average annual precipitation, mostly concentrated in autumn, was 638 mm. The topographic relief is semi-mountainous and reaches 1518 m a.s.l in the north western part (Ossa mountain). Agia produces 18 and 20% of the total annual Greek production of almonds and apples, respectively [13,14].

2.2. LCA methodology

The LCA methodology adopted in this study was based on the principles and specific requirements of the International Organization for Standardization (ISO) 14040-14044 standard series [15,16]. The functional unit (FU) selected was the marketable production of 1 tonne of in-shell pistachios, in-shell almonds and fresh apples. This functional unit was set as reference to assess and in particular compare the varying input and output flows of the three different crops. Since the main purpose of this study was to compare the three cultivation systems on a common basis, it was deemed inappropriate to follow any allocation approach. Therefore, co-product credits were not estimated.

LCA modeling was performed using the software package Gabi 6.5 [17] and the characterization factors of the well-established CML Baseline 2001 method (April 2013 version) [18] including the cumulative energy demand [19]. As a result, indicators for four environmental impact categories were estimated, namely global warming potential for 100 years (GWP in kg CO_2-eq), eutrophication potential (EP in kg PO_4-eq), acidification potential (AP in kg SO_2-eq) as well as cumulative energy demand (CED in GJ-eq), as energy flow indicator. The impact categories and the CML method adopted for their calculations are the most frequently used for tree cultivations [20]. The system boundaries used in this study took into consideration all the production processes involved, from raw materials extraction (i.e. the cradle) to post-harvesting (i.e. the farm gate) (Fig. 2).

Based on the system boundaries, foreground and background processes/flows were structured in six common and stand-alone phases to facilitate data compilation and comparative assessment (Fig. 3). Depending on the tree cultivation system, the phases included were irrigation system, fertilizers production, pesticides production, agricultural machinery (production and maintenance), field management employing farm level operations such as agrochemical application, land preparation/ploughing, tillage, pruning and harvest as well as post-harvest (sorting, pre-cleaning, dehulling drying, cleaning, and temporary storage to warehouses) as well as waste management. For the transportation of raw materials (fertilizers and pesticides), road transport by truck/lorry and the associated fuel consumption were considered.

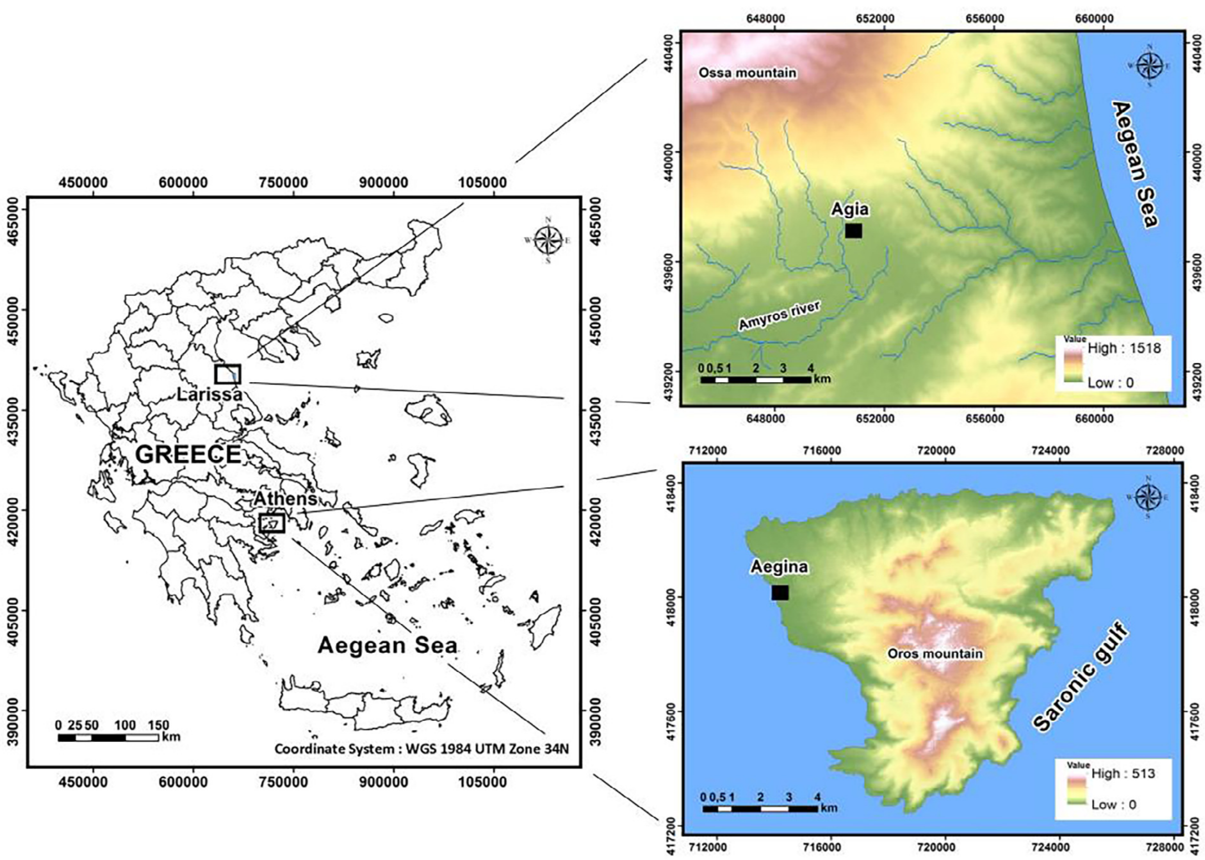

Fig. 1 – Location and topography of study areas.

The life cycle inventory (LCI) of the three tree cultivation systems was built using primary data for the period 2011–2015 which were collected from 28 orchards with full productive mature trees and by considering a 6-month seasonal period of irrigated agricultural activities per year. Data obtained from questionnaires which were filled through personal interviews with experts, farmers and representatives of farmer associations. Thus, all relevant inputs and outputs related to crop production and their associated indirect/direct emissions were identified and quantified. To support reliability and representability, survey data were compiled into average-weighted inputs for operations and outputs in each area studied. Background data were retrieved from national and EU databases, literature as well as the available LCI databases (Professional [21] and Ecoinvent v.3.1 [22]) of the software used. Table 1 presents the main LCI data (mean values) for the production of PDO pistachios in Aegina as well as for apples and almonds in Agia.

3. Results and discussion

3.1. *Cumulative impacts per tree cultivation system*

The absolute values of each impact category and the cumulative energy demand for the three studied cultivation systems are presented in Table 2. For example, the production of 1 tonne of pistachios in Aegina has an overall impact of 8.71 kg SO_2-eq for AP, 3.84 kg PO_4-eq for EP, 2119 kg CO_2-eq for GWP and 28.05 GJ for CED. The results show that the cultivation of pistachios and almonds causes higher and almost similar impacts, while the cultivation of apples is characterized by the lowest impacts for all impact categories assessed.

3.1.1. *CED and GWP*

The cumulative energy consumption was 28.05 GJ t^{-1} for pistachios, 27.33 GJ t^{-1} for almonds and 1.21 GJ t^{-1} for apples. As a result, pistachios and almonds exhibited significantly higher value for GWP than apples (2119 and 2009 kg CO_2-eq., respectively, vs 89 kg CO_2-eq. per tonne produced). This was mainly because lower yields are obtained for pistachios and almonds (2.5 and 3.3 t ha^{-1}, respectively), compared to fresh apples (32.4 t ha^{-1}). Thus, it is deduced that pistachio and almond orchards are characterized by almost identical CED (difference 2%) and impacts (difference 5–6%). This is due to the similar orchard management practices followed in both nut tree cultivation systems and to some extent, the balance among inputs of raw materials (N/P/K fertilizers, pesticides and irrigation water).

3.1.2. *AP and EP*

With regard to AP and EP impact categories, the main differences were due to the higher rate of N-containing fertilizers applied in almond and pistachio orchards (180 and 230 kg ha^{-1} respectively, vs 80 kg ha^{-1} for apples) and subse-

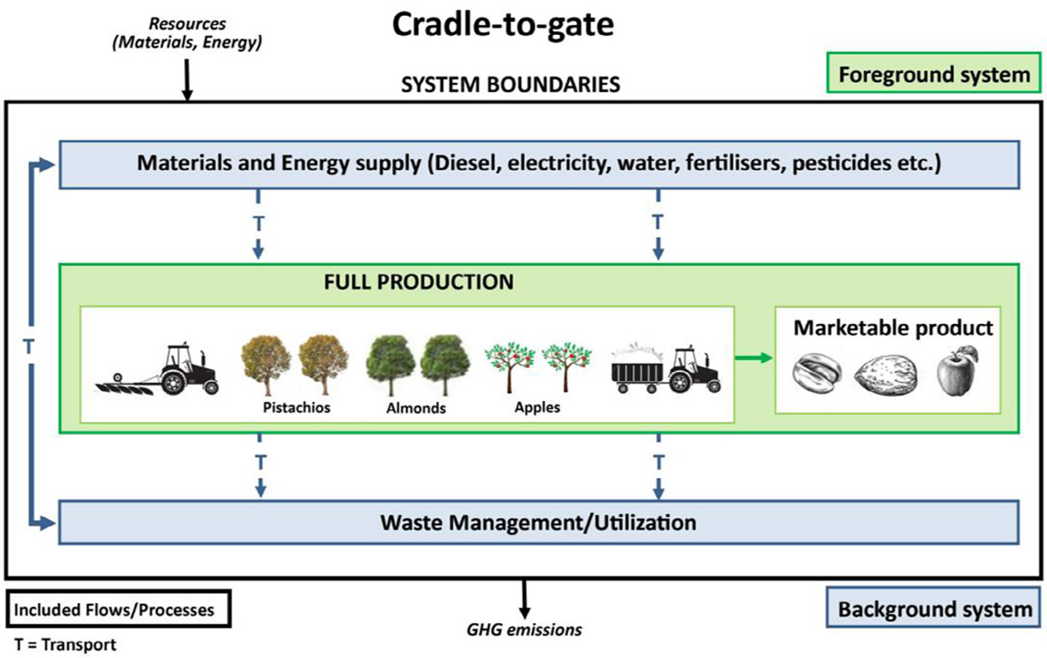

Fig. 2 – System boundaries.

quently the higher associated emissions for both nut cultivations, mainly as nitrous oxides, from related raw materials extraction and manufacture of machinery and tools used in agricultural activities. More specifically, the AP of the studied life cycles increased from 0.95 kg SO_2-eq for apples to almost 8.24 kg SO_2-eq for almonds and 8.71 kg SO_2-eq for pistachios. Regarding EP, the lowest value obtained in this study was 0.44 kg PO_4-eq. for apples, followed by almonds (8.24 PO_4-eq.) and pistachios (8.71 PO_4-eq.).

The high AP determined for pistachio and almond crops affects (i) vegetation and plants causing leaf damage, (ii) the quality of soil as a result of increased acidity and (iii) surface waters, by affecting the solubility and hence the availability of nutrients and trace elements plants can take up. These impacts are particularly important in agricultural areas exhibiting water shortage and Mediterranean islands or coastal areas suffering from groundwater salinization. In addition, the high EP determined for pistachio crops may cause deterioration of the quality of limited water bodies, surface- and groundwater, in small islands such as Aegina. All these impacts result in increase of production cost, worsen the quality of life for farmers and prevent the development of sustainable agriculture [6,23].

3.2. *Contribution analysis*

In order to elucidate the origin of environmental and energy burdens, associate them with specific LCI phases and identify the main "hot spots", a contribution analysis was carried out. Fig. 4 shows the comparative contribution of each production phase, expressed in% for each impact category considered, for the three cultivation systems under assessment.

For pistachio and almond orchards, fertilizers production had the highest and almost similar contribution to all impact categories, varying between 33–35% and 31–33%, respectively. This contribution was heavily influenced by the substantial fertilizer requirements for pistachio and almond production in both regions, Aegina and central Greece, due to emissions derived from raw materials (phosphate ores, ammonia, potassium chloride, fossil fuels, sulfuric acid for ore leaching) extraction and processing during their entire life cycle. On the other hand, for apple tree cultivation the highest contribution to all impact categories originated from the phase of field management, which contributed 30–34% to the cumulative impacts, mostly due to high dose of pesticides applied (46 kg ha^{-1}) and the contribution of the associated on-field air, soil and water emissions.

In more detail, fertilizers production was responsible for approximately 33% of the estimated cumulative impacts for AP in both nut tree cultivation systems. This was attributed primarily to NH_3 and NO_x emissions caused during production of mineral fertilizers, as well as SO_2 emissions derived from fossil fuel combustion during transportation of raw materials to tree orchards. The second highest contributor to AP was the field management phase, which accounted for 20% and 23% in the pistachio and almond cultivation systems, respectively. In the case of apple production, field management was the most impactful phase, responsible for 34% of the cumulative impacts for AP, mainly due to the use of considerable amounts of agrochemicals. Production of fertilizers represented also a significant burden for the AP impact category, contributing 28% in the cumulative impacts, followed by pesticides production phase (20%).

As for the EP impact category, field management was the phase that exhibited the highest burden in the apple orchards, contributing 34% in the cumulative impacts, followed by the phases of fertilizers production (27%) and pesticide production (18%), as a result of raw materials extraction and

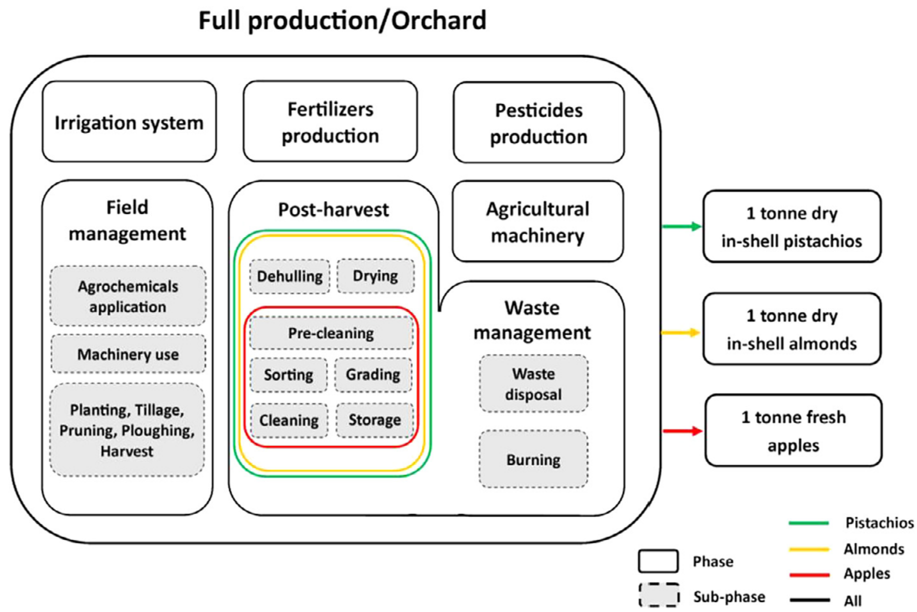

Fig. 3 – Flow diagram of the main phases and sub-phases included in the LCA study for the three tree cultivation systems.

manufacture of machinery and tools. In almond and pistachio orchards, EP was dominated by emissions originated from the production of chemical fertilizers, accounting for about 32% of the total cumulative impacts for both nuts.

Regarding GWP, contribution analysis showed that field management was the most impactful phase for apple production, accounting for 30% of the cumulative impacts. As in the case of AP and EP impact categories, the phases of fertilizers production and irrigation system allocated the highest share of the GWP in almond and pistachio orchards, due to the big quantities of fossil fuels required for manufacture/production operations and pumping groundwater, respectively.

Regarding CED, the most energy consuming phase in both nut crops was fertilizers production, which contributed 32% and 33% to the total energy inputs for almond and pistachio orchards, respectively. Significant energetic impacts were calculated in terms of CED for the irrigation system phase (22% and 24% for almonds and pistachios, respectively), due to electricity consumption for pumping groundwater and fossil fuels requirements for the manufacture of irrigation system components, namely steel for pumps and injectors, polyethylene for pipes and polyvinyl chloride for electro-valves [6]. Regarding the apple orchards, the phase of field management dominated the total energy inputs accounting for 31% of the CED cumulative impacts, followed by fertilizers production (24%) and pesticides production (14%).

All other phases included in the LCA had lower contributions to the impact categories assessed. Averaged across

Table 1 – Main LCI data of the three cultivation systems adopted in this study.

Characteristics	Unit[a]	Orchards		
		Pistachios	Almonds	Apples
Cultivar	–	Aegina	Texas	Granny Smith
Number of orchards	–	10	10	8
Orchard age	Years	40	30	25
Density	t ha^{-1}	250	300	850
Yield[b]	t ha^{-1}	2.5	3.3	32.4
Harvest period	–	1st week of September	3rd week of September	3rd week of October
Irrigation technique	–	Furrow and drip irrigation	Double drip irrigation	Drip irrigation and micro-sprinklers
Irrigation period	–	April–September	April–September	June–October
Fertilizers rate				
N	kg ha^{-1}	230	180	80
P (as P_2O_5)	kg ha^{-1}	90	100	90
K (as K_2O)	kg ha^{-1}	200	200	180
Pesticides	kg ha^{-1}	5.4	8.2	46
Water requirements	m^3 ha^{-1}	4450	4650	3400
Fuel consumption	L ha^{-1}	435	458	513
Electricity	MJ ha^{-1}	2600	2890	3050

a Mean values are given for the period 2011–2015.
b Refer to functional unit (FU) production.

Table 2 – Environmental impact categories of the three cultivation systems under analysis.

Impact category	Acronym	Pistachios	Almonds	Apples
Acidification potential (kg SO_2-eq. FU^{-1})	AP	8.71	8.24	0.95
Eutrophication potential (kg PO_4-eq. FU^{-1})	EP	3.84	3.62	0.44
Global warming potential (100 years) (kg CO_2-eq. FU^{-1})	GWP_{100}	2,119	2,009	89
Cumulative energy demand (GJ-eq. FU^{-1})	CED	28.05	27.33	1.21

FU: functional unit (1 tonne of fresh apples, in-shell almonds and pistachios)

impact categories, the machinery production phase was responsible for approximately 12% of the cumulative impacts in all three cultivation systems. This was mainly due to fossil fuel requirements for their manufacture/production, transport of raw materials and their associated combustion emissions, as well as due to maintenance activities from the end-of-life management of used equipment and other materials. As expected, during almond and pistachio cultivation, contrary to apples, post harvest and waste management phases has the highest contribution to all impact categories. Dehulling operations, as well as other farm activities, including also auxiliary operations such as drying, pre-cleaning, sorting, grading and dust removal, cause considerable GHG emissions (for almonds up to 17% in AP and EP impact categories) during the peak period (August–September), as their demand for electricity is high. However, around 60% of the GHG emissions of the "post harvest and waste management" phase were due to the generation of considerable waste volumes, since in most cases waste hulls and shells are disposed of in an uncontrolled site or even buried at the farm site.

3.3. *Hot spots and suggestions for environmental improvement*

Based on the results of the contribution analysis, the phases of fertilizers production, irrigation system and field operations were identified as "hot spots", since their impact contributions were the highest in all tree cultivation systems studied. More specifically, the contribution of the fertilizers production to impacts varied from 23% for CED in the apple orchards to 35% for GWP in the pistachio orchards. Reduction of the environmental footprint of this phase can be accomplished by (i) enhancing energy efficiency in the fertilizers' production facility, (ii) reducing the associated emissions with the use of de-N_2O catalyst systems, (iii) minimizing the transport distance between production sites of fertilizers and cultivation areas, and (iv) adjusting the application rate of fertilizers to the required N/P/K quantities for each cultivation system studied. A shift in the existing nutrient management plan from energy-intensive chemical to the use of eco-friendly organic fertilizers (i.e. manure, compost) or their combined application may drastically reduce emissions by 30% and energy use by half. In this context, composting/reuse of available bio-waste and crop residues (prunings, hulls and shells) at orchard level can be a feasible and low-cost approach to improve sustainability of agricultural production as well as minimize extensive use of chemical fertilizers. This is mainly associated with the high nitrogen demand of pistachios in comparison to two other crops studied [6,24].

The irrigation system was another important energy-driven and GHG-intensive phase which was identified via contribution analysis for the two nut tree cultivation systems studied. This phase is of paramount importance for Aegina, where limited water resources are available, thus requiring intense over-pumping of the shallow aquifers during the dry summer period when irrigation requirements for pistachio trees (*Pistacia vera* L.) are very high. Based on the results obtained in this study, the highest impacts from irrigation reached 22% and 24% of the cumulative impact for GWP in almond and pistachio orchards, respectively, mainly due to the higher amounts of water pumped for irrigation and post-harvest activities (4650 and 4450 $m^3\,ha^{-1}$) compared to apple orchards (3400 $m^3\,ha^{-1}$). It is important to note that even though the volume of water used for the production of pistachios is significantly lower in Aegina compared to California where 10,000 $m^3\,ha^{-1}$ [25] and Cyprus where 7500 $m^3\,ha^{-1}$ are required [26], the environmental impacts associated with pumping groundwater are higher since the electricity power grid mix in Greece is based on the dominant use (56.6%) of the GHG-intensive lignite.

Therefore, reduction of the cumulative impacts associated with irrigation, can be achieved by (i) increasing water irrigation efficiency with the use of micro-irrigation systems (mini- and micro-sprinklers) that can achieve water savings up to 40% per m^2 compared to conventional irrigation techniques (furrow/surface flooding), (ii) regular maintenance of the pumping units and their components (pipes, electro-valves) to prevent efficiency loss due to clogging and corrosion damage due to the use of saline water, (iii) monitoring the irrigation water quality on a frequent basis and (iv) using a targeted irrigation scheduling program (rates and timing) to maintain the best possible soil-water relationship for optimal crop yield.

Contribution analysis identified the phase of field management as the most impactful one during the life cycle of apple production (30–34% to all impact categories) and also clearly indicated its significant contribution (11–24%) in the life cycle of almonds and pistachios, especially for AP and EP impact categories. It is important to note that the control of insects and weeds in apple tree cultivation systems is necessary for the production of a high-quality marketable product, compared to nut tree cultivation systems that are more tolerant to natural diseases. Therefore, in the case of apple production, potential mitigation of greenhouse gas emissions can be achieved by minimizing pesticide application rates through the use of crop sanitation, application of spot treatment to improve pest efficiency, installation of protective netting and adoption of cross-protection techniques. Other possible strategies to achieve reduction of emissions related

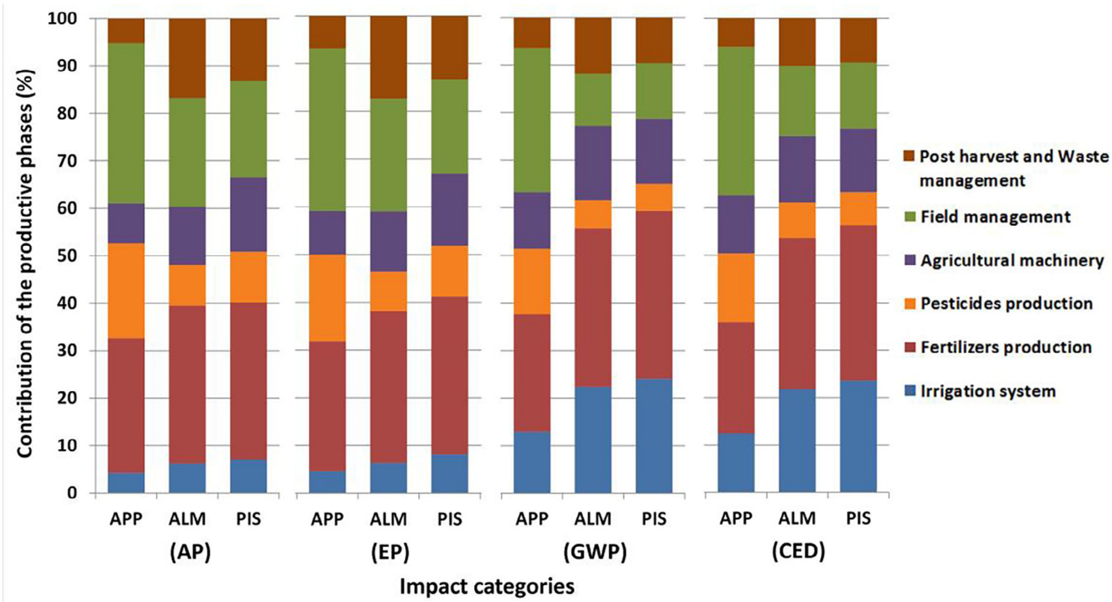

Fig. 4 – Comparative contribution of each production phase to each impact category for the three cultivation systems under assessment (APP: apples; ALM: almonds; PIS: pistachios) (AP: acidification potential; EP: eutrophication potential; GWP: global warming potential and CED: cumulative energy demand).

to farm management phase in all studied cultivation systems may include proper sizing and use of more energy efficient machinery, rational application of agrochemicals to match requirements for each crop and use of alternative cultivation practices such as conservation tillage and pruning. However, since in practice field operations depend strongly on site-specific factors such as soil quality, climate and orchard level conditions, the use of monitoring techniques (e.g. soil and leaf tissue sampling and analysis) at frequent intervals for the determination of the main agronomic characteristics is of great importance [23].

3.4. *Sensitivity analysis*

In order to elucidate the importance of the phases that exhibited the highest contribution to impact categories, namely irrigation system and fertilizers production, under different input requirements and operating conditions and thus enhance reliability and comparability of results, a sensitivity analysis was performed for all cultivation systems under study. To this context, three scenarios were taken into account and analyzed to quantify the subsequent changes in the results compared to the corresponding base case cultivations in terms of reducing the impact of the four different categories (CED, GWP, AP and EP).

The first scenario ("water desalination") assumes that all water needed for irrigation is pumped and desalinated on-site using a small scale photovoltaic-powered reverse osmosis (PV-RO) system as proposed by Jones et al. [27]. The application of this innovative autonomous system is extremely attractive for medium-sized orchards (2–5 ha) since it requires low capital cost and enables high desalinated water recovery rates (75%) in the long term. For Greece, the feasibility of this option requires in most cases the use of the system for more orchards since the average size of a typical orchard, especially for pistachios and almonds, is much smaller and does not exceed 0.5 ha. In the second scenario ("organic"), 50% of the currently used N/P/K chemical fertilizers for apples, almonds and pistachios (i.e. 175, 240 and 260 kg ha^{-1} $year^{-1}$ respectively), is replaced by an organic fertilizer (i.e. compost) produced from goat and sheep manure as mentioned in Bartzas et al. [6]. The third scenario ("renewable") explores the possibility of using renewable energy instead of electricity grid mix in order to fully satisfy the energy needs for pumping groundwater. Therefore, the inventories of Kannan et al. [28] and Ecoinvent v.3.1 [22] considering a mono-silicon roof top solar PV system of 2.7 kWp with life time of 25 years and efficiency of 10.6%, were used. Fig. 5 presents the results of the sensitivity analysis as% variation per impact category (CED, GWP, AP and EP) for each of the three scenarios analyzed in comparison to the base case.

From an overall environmental perspective, the most influential scenario for both pistachios and almonds production was the one envisaged 50% replacement of fertilizer application with compost. Based on the results of sensitivity analysis, the use of the "organic" scenario reduced CED by 17–19%, GWP by 19–21%, AP by 11%, and EP by 12%. On the other hand, considerably smaller environmental improvements for the four impact categories assessed, ranging between 2–7%, were estimated in the case of apples.

However, it is important to note that a profound effect was noticed as a result of the sensitivity analysis when the "water desalination" scenario was taken into account for the production of pistachios in the island of Aegina. More specifically, the impact on CED and GWP was reduced by 5% and 17%, respectively, while the impact on AP and EP was reduced by

9%. These results indicate that noticeable energetic and environmental improvements can be achieved during pistachio production, especially in Mediterranean islands and coastal sites where water shortage and salinization of groundwater resources is noticed. Finally, total shift from conventional energy (electricity grid mix) to renewable energy as considered in the third scenario, indicated the greatest benefits during pistachio cultivation since it reduced CED by10% and GWP by 9%.

3.5. *Comparison with previous LCA studies*

Comparison of agricultural LCA studies is in general difficult since several influential factors usually differ and affect results. These factors are mainly related to different assessment methods used for the quantification of impact categories, system boundaries, allocation approach followed and associated modeling assumptions. Furthermore, the lack of reliable assessment of site-specific variations during production, the use of extrapolated values based on outdated or incomplete primary data sets and the lack of in-depth information provided in previous studies may also create difficulties when LCA results are compared [6,29].

Table 3 compares the findings of previous LCA studies with the results of this study, in terms of GWP and CED impacts for the three cultivation systems investigated. It can be seen that most earlier studies attempt to assess GHG emissions of apple production, using data from different cultivars located mainly in Europe. On the other hand, it is difficult to compare the results of this study with earlier studies in terms of GHG emissions for almonds and pistachios, since earlier studies are solely based on primary data obtained from California, USA. However, in general terms, comparison shows good agreement with previous studies for all cultivation systems investigated.

More specifically, the results obtained in this study in terms of GHG emissions for apple production fall in the middle range, i.e. 64–200 kg CO_2-eq/t apples and 1.10–1.84 GJ-eq/t apples, respectively. In terms of GWP, Keyes et al. [29] reported the lowest value, while Sessa et al. [30] the highest one in the above-mentioned range, even though in the latter study the yield was almost 3 times higher (62.7 t ha^{-1}) than that recorded in the apple orchards of Nova Scotia [29]. However, Sessa et al. [30] have considered the production of 1 tonne of apples commercialized in plastic bags and used expanded system boundaries including packaging and transport to retailers, thus the comparison is not straightforward.

Regarding CED, this study showed that 1.21 GJ of energy is consumed for the production of 1 tonne of apples, value which is very close to the values of 1.10, 1.16 and 1.20 GJ/t apples reported by Keyes et al. [29], Alaphilippe et al. [31] and Mouron et al. [33], respectively, although in these studies expanded system boundaries (e.g., packaging, nursery stage) were considered and different calculation assessment methods were used. Keyes et al. [29] assessed impacts of apple production in Nova Scotia, Canada, based on the Eco-indicator method developed by Goedkoop [36], while Alaphilippe et al. [31] quantified the impacts of apple production in Rhone Valley, Southern France, using the Recipe method. However, the CED impact values determined in these studies are significantly lower compared to 1.84 GJ/t apples reported by Longo et al. [32]. It is mentioned that in this latter study data from only one experimental farm located in the territory of Trentino Alto Adige (North of Italy) was used, while the cultivation period considered was only one year. Thus, the high CED value can be explained by the fact that calculations were based on data taken from extremely intensive cultivation conditions, requiring extensive use of agricultural machinery and high consumption of diesel, i.e. 1470 L ha^{-1}. Another important difference between the present and earlier studies [31,32] is that in earlier studies the impacts of pesticide production and application were not taken into account, due to the lack of data and the absence of relative characterization factor in the Recipe method used, respectively. Nevertheless, in the present study such impacts accounted for 14.5% for CED impact category, while Keyes et al. [29] reported more than two-times higher contribution (32.1%), thus indicating the importance of taking into account pesticide emissions in LCA inventories of apples cultivation.

Comparisons are getting even more difficult for almonds and pistachios since very few LCA studies are available in literature. Marvinney et al. [8] carried out the only LCA study, using consistent system boundaries in California, which compared the production of almonds and pistachios. In their study, almonds presented a more favorable environmental profile than pistachios, in terms of GWP and CED, as also indicated in the present study. In absolute values, GWP results obtained in the present study, i.e. 2009 and 2119 kg CO_2-eq for the production of 1 tonne of almonds and pistachios, respectively, were significantly lower than the values of 2300 and 2530 kg CO_2-eq calculated for the same cultivation systems in California [8]. This is mainly due to the fact that additional external management phases (nursery, pollination) were included in system boundaries in the Californian study and resulted in higher impacts. However, both studies identified fertilizers production, cultivation practices and irrigation as the main contributors to the global impacts.

Regarding almonds, the GWP estimated in the present study is 14% lower than the corresponding value obtained by Venkat [34], due to the higher level of electricity consumption (1500 kW h per tonne) in the latter case. Concerning CED, only one value i.e. 35 GJ-eq t^{-1} given by Kendall et al. [35] was found in literature, which is 29% higher than the energy consumption calculated in the present study. This is mainly due to the differences in crop yield (32% higher in the present study) and modeling assumptions since Kendall et al. [35] excluded the manufacture of agricultural machinery from their LCA study.

Finally, it is underlined that the present LCA study provides valuable results for pistachio and almond production for which very limited data is available in international literature. The results of our LCA for apples production may be extrapolated to assess the impacts of other fruit cultivations in the Mediterranean region and in other regions with similar characteristics. It is mentioned that Lo Giudice et al. [37] have carried out an LCA study for citrus production in Sicily, while Ingrao et al. [38] have assessed the environmental hotspots of peach production in the same region. Both cultivations exhibit similar characteristics to apple production (e.g. in citrus farms the average tree density is 400 trees per hectare and

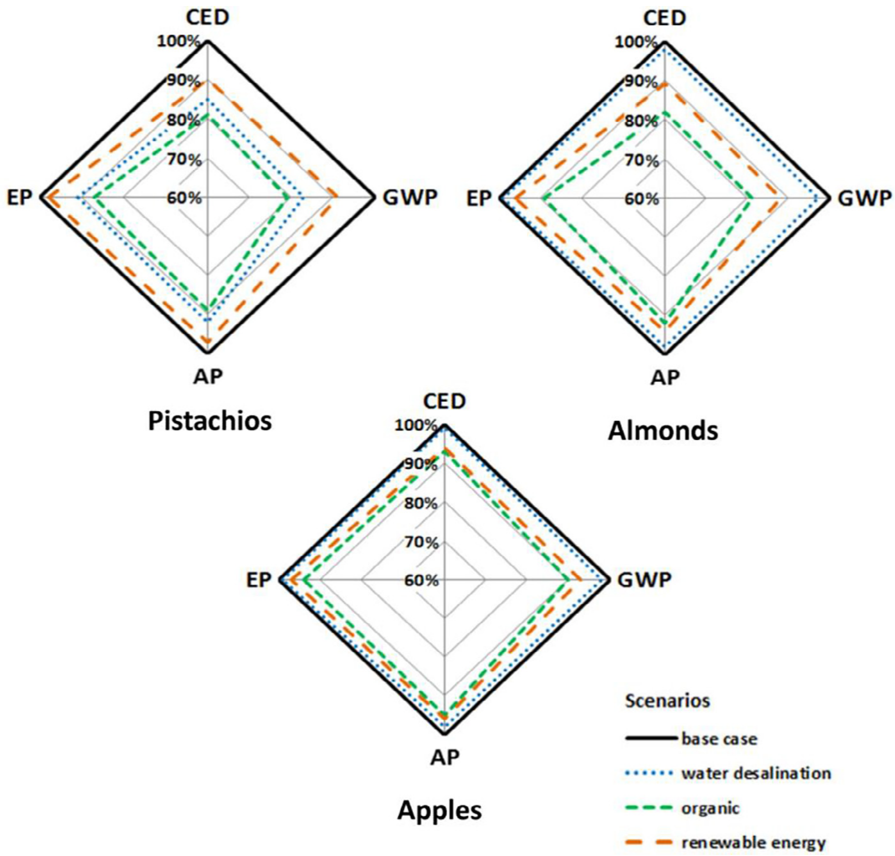

Fig. 5 – Percentage variation of the impacts categories (CED, GWP, AP and EP) for each scenario adopted in the three cultivation systems.

Table 3 – Comparison of GWP and CED impacts calculated in previous LCA studies with the respective impacts calculated in this study for the three cultivation systems under analysis.

Type of cultivation	Region/Country	Yield (t ha^{-1})	GWP (kg CO_2-eq)[a]	CED (GJ-eq)[a]	Ref.
Apples	Nova Scotia/Eastern Canada	23.7	64	1.10	[29]
Apples	South Tyrol/North Italy	62.7	200	N.R	[30]
Apples	Rhone Valley/Southern France	37.8	75	1.16	[31]
Apples	North Italy	70	112	1.84	[32]
Apples	Eastern and Central Switzerland	31.4	83	1.20	[33]
Apples	Agia/Central Greece	32.4	89	1.21	This study
Almonds	California/Western USA	2.2	2,479	N.R.	[34]
Almonds	California/Western USA	3.0	2,300	N.R.	[8]
Almonds	California/Western USA	2.5	1,630	35.00	[35]
Almonds	Agia/Central Greece	3.3	2,009	27.33	This study
Pistachios	California/Western USA	2.8	2.530	N.R.	[8]
Pistachios	Aegina island	2.5	2,119	28.05	This study

a Per t^{-1} FU (without co-products credit); N.R: Not reported.

the yield is 25 t/ha, while in peach farms the tree density is 700 trees per hectare and the yield is 31.5 t/ha). The results of these studies are almost similar to those mentioned in our study (for example the GWP of citrus production is around 20% less that the respective value for apples, while the production phases with the highest impacts were similar in all studies). This is another indication that the approach followed and the data obtained in our study are characterized by high degree of reliability.

4. Conclusions

Considering the difficulties in performing comparative LCA studies for different tree cultivation systems exhibiting variability in terms of yield, cultivation practices, post-harvest operations, waste management and other site-specific factors such as climate, irrigation water quality and availability, the present study examined the life cycle of pistachio, almond and apple production in two representative areas in Greece.

The LCA methodology has been applied in order to identify the activities causing the highest impacts across and within the studied life cycle and provide guidelines for potential improvements in order to reduce environmental impacts.

Given the fact that dissimilarities between tree cultivation systems are unavoidable, apple orchards exhibited the best overall environmental performance, with lower GHG contributions in all production phases compared to the other two cultivations (pistachios and almonds). On the other hand, the LCA indicated that the two nut tree cultivation systems, given their relatively similar agronomic characteristics, performed quite similarly with respect to all impact categories.

The results of the contribution analysis showed that the phases of fertilizers production, irrigation system and field management were responsible for the largest share of energy consumption and the associated GHG emissions. Regarding irrigation phase, it was shown that its importance is very high in semi-arid and arid Mediterranean areas, such as Aegina island, which suffer from water shortage and are prone to salinization. The sensitivity analysis highlighted the variations between the three cultivation systems and proposed feasible ways to decrease impacts and enable energy conservation through the implementation of more environmentally sustainable and eco-friendly practices. In particular, the transition to organic production by replacing 50% of mineral fertilizers with compost, produced from agricultural wastes/by-products, was the most influential scenario that generated significant GHG offsets for both pistachios and almonds.

The present LCA study incorporated important aspects (e.g., contribution analysis, sensitivity analysis) into one robust approach that integrated data pertinent to specific site conditions as well as generic data from reliable databases. The results obtained can be used by several end-users (i.e. farmers, agronomists), policy makers and other stakeholders. They can also be applied in similar arid and semi-arid environments, in the Mediterranean region and elsewhere.

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