Life cycle analysis of pistachio production in Greece

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Abstract

In the present paper, a life cycle assessment (LCA) study regarding pistachio (*Pistacia vera* L.) cultivation in Aegina island, Greece, was performed in order to evaluate the energy use footprint and the associated environmental impacts. In this context, a detailed life cycle inventory was created, based on site-specific and questionnaire derived data, and used for a holistic cradle-to-farm-gate (including transportation) LCA analysis using the GaBi 6.5 software package and specific related databases.

The main impact categories assessed were acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and cumulative energy demand (CED). In order to reveal the main environmental concerns pertinent to pistachio production and in turn propose measures for the reduction of environmental and energetic impacts, three scenarios were compared, namely the baseline scenario (BS) that involves current cultivation practices, the green energy (GE) scenario that involves the use of biological fertilizers i.e. compost, and the waste utilization (WU) scenario that involves the production of biochar from pistachio and other agricultural wastes and its subsequent soil application to promote carbon sequestration (CS) and improve soil quality.

Based on the results of this study, the use of compost for fertilization (GE scenario), which results in approximately 10% savings in terms of energy consumption and greenhouse gas (GHG) emissions compared to BS scenario, is considered a promising agronomic and ecological alternative strategy. Slightly higher savings (12% on average) in terms of GHG emissions, compared to the BS scenario, were indicated when the WU scenario was considered. Regarding energy consumption, the WU scenario results in minor increase, 3%, compared to the BS scenario.

Keywords

Life cycle assessment (LCA), pistachios, Aegina, waste management, compost, biochar

Introduction

Pistachios are, among the tree nuts, the richest source of heart-healthy fatty-acids, metals, phytosterols, phenolic and other compounds and therefore their consumption has become increasingly popular over the past decade [1]. The pistachio nut tree, *Pistacia vera* L., is a dioecious and deciduous native species that grows in the Mediterranean countries and the Middle East; now is expanded and is commercially grown throughout the world, from Australia to USA (California). At global scale, the pistachio production has increased from 397 MT in 1993 to 917 MT in 2013 [2]. In terms of production share, Iran is the largest producer (301 MT) followed by USA (124 MT) and Turkey (72 MT). Among the EU-28 countries, Greece has the largest production (11 MT) followed by Italy (3 MT). In Greece, pistachios are mainly produced in the regions of Attiki (Aegina island and Megara), Central Greece (Phthiotis, Viotia and Euboia), Thessaly (Almyros) and North Greece (Chalkidiki). The island of Aegina is characterized by specific pedoclimatic characteristics that promote 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. Currently, 120,000 pistachio trees are cultivated in Aegina over a total area of 3,500 acres, accounting for 11% of the total pistachio production in the country [3]. Pistachio production is of considerable importance for Aegina's economy as it is estimated that approximately 1,500 families are traditionally associated with it.

Harvested pistachio nuts are covered with organic outer pericarps (hulls) and endocarps (shells) which are removed during the processes of dehulling and shelling, respectively. Both of these pistachio waste streams account for more than 75 % of the harvested crop and in Greece around 7,000 tons are disposed annually [4]. At country level, pistachio waste is mainly subjected to open burning and dumping without any treatment. Both options may cause serious environmental problems and thus the need for the development of alternative and eco-friendly waste management practices is a major concern within the pistachio sector. To this end, production of compost and biochar from pistachio wastes has gained considerable attention over the last decade as emerged strategy for improving soil quality and productivity, sequestering carbon in soil and mitigating GHG emissions [5]. In fact, reuse and recycling of agricultural residues not only reduces the environmental footprint of the harvested crop but also provides an additional income to farmers since higher yields are achieved.

With growing environmental awareness and demand for sustainable cultivation along with proper waste management, decision-makers and other interested stakeholders are increasingly aware of the need for the development of feasible approaches to improve the eco-profile of harvested crops in the future. Among other assessment tools, LCA is considered the best available approach to identify, quantify and evaluate the potential environmental, human health and resource scarcity impacts of any product or process over its entire life cycle, from raw material acquisition to production, use, end-of-life treatment, recycling and/or ultimate disposal. To date, LCA has been extensively used to identify improvement opportunities or compare alternative farm management scenarios at farm or regional level [6].

Despite the perceived necessity towards a less GHG-intensive agriculture, very little attention has been paid in the literature to the impacts of the pistachio cropping systems. Because of their long-lived nature, cultivation of pistachios differs from that of annual crops in several aspects, including notable changes of the marketable yields, temporal variation of farm management practices as well as application of raw materials (e.g. fertilizers, irrigation water, pesticides) over the whole lifetime of the orchards [7]. As a result, the estimation of their environmental impacts is a difficult and volatile task, which requires long-term data persistence, consideration of time-changing and more detailed models for calculating direct and indirect GHG emissions and use of certain assumptions pertinent to the most site specific factors that interact with climate and resource availability.

To this context, this LCA study attempts to (i) analyze the life cycle of the pistachio production in the island of Aegina, (ii) explore two alternative scenarios, namely the GE and the WU to minimize impacts and improve sustainability, and (iii) identify critical processes that are energy intensive and cause most environmental impacts. To the best of our knowledge, no similar LCA studies are available in literature, thus this study aims to fill an important gap and propose guidelines for similar cropping systems.

Methodology

Study area

Aegina is located approximately 16.5 miles south of Athens and is the second largest island of the Saronic Gulf (after Salamis) with a total surface area of 87 km^2 (Fig.1). Aegina is a Plio-Pleistocene volcanic island with two geomorphological settings: a permeable region (34% of the total surface of the island) located in the north and covered by Neogene lacustrine along with shallow marine sediments and a less permeable region (66%) covered by andesitic lava flows, plugs and necks, as well as by large volcanoclastic dacitic flows [8]. The geological basement comprises mainly of Permian to Upper Cretaceous limestones, covered by flysch and ophiolitic thrust sheets. From a hydrogeological point of view, the mountains of the Aegina island (mainly the Oros Mountain) form four major water basins (catchment areas of Skoteini, Viros, Mesagros and Glyfada). In the rest of the island there are no significant water catchment areas or basins. Aquifer permeability increases towards the coast due to the major karstic development, while the groundwater table usually fluctuates between 10 and 60 m.

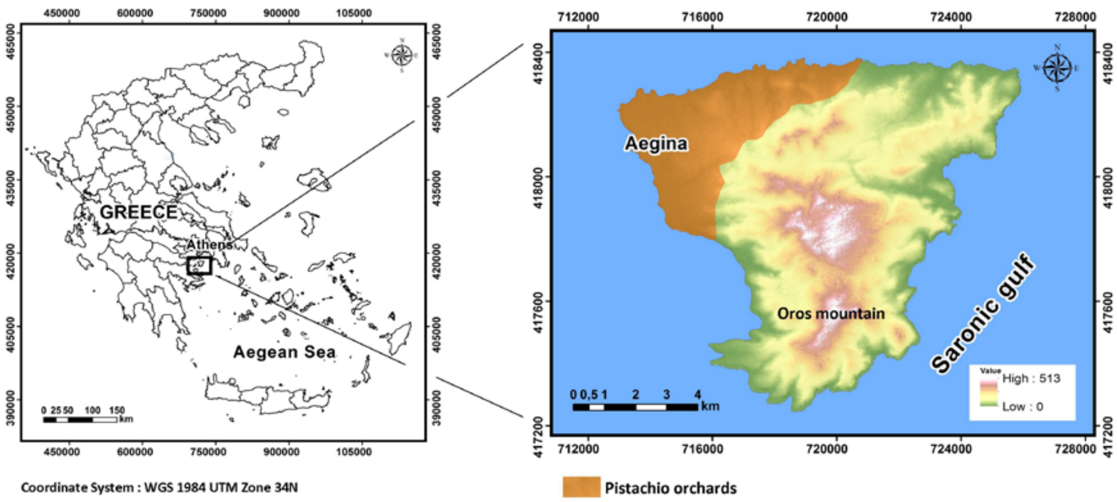

Figure 1. Location and altitude map of the study area

The island of Aegina is characterized by semi-arid Mediterranean climate, with a mean annual temperature of 19 °C and an annual rainfall of 295 mm. Almost 80% of annual rainfall is recorded in the wet period (November-April), while summers are usually dry [9]. The dominant soils in the study area are shallow Cambisols and Leptosols according to the soil taxonomy of FAO [10]. The north part of the study area is intensively cultivated and the major land uses include family orchards with pistachio trees planted in the fields and house gardens (Fig. 2). Approximately 32% of the cultivated land is irrigated while the rest is rainfed or dry. The main cultivations in the irrigated land are pistachios 63%, olive trees 20%, almonds 7%, lemon trees 4%, vineyards 2% and others 4%. Over the last three decades, agricultural activities and urban development have led to soil erosion and desertification, depletion of underground water resources availability, deterioration of irrigation water quality due to sea intrusion and significant decline in the water table of the available aquifer systems.

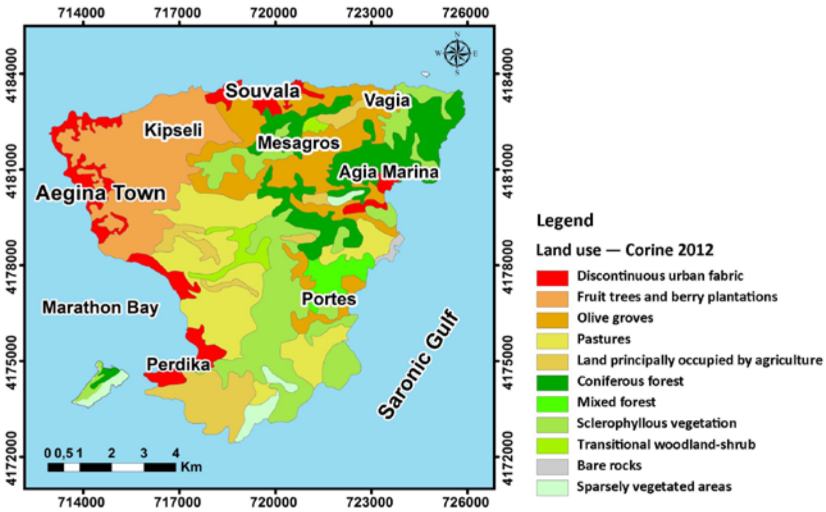

Figure 2. Land use map of the island of Aegina according to the Corine Land Cover [11]

Life cycle assessment

The LCA study was carried out to determine the consumption of raw materials i.e. fertilizers, pesticides, irrigation and processing water, energy and agricultural waste, as well as to calculate emissions of pollutants (CO_2, CH_4, VOCs, NO_x, SO_2 etc.) to air, water and soil. The study was carried out according to the guidelines and specific requirements of the International Organization for Standardization (ISO) 14040-14044 standard series [12,13]. Special emphasis was given to assess the effect of application of treated agricultural waste on crop land as compost and biochar.

Functional unit

The functional unit (FU) selected is the production of one tonne of dry in-shell pistachios (both open split and non-split). This mass-based FU is adequate in this case study since its scope is primary production. However, it is important to note that only the product suitable for sale on the market (open-split) was taken into account. This functional unit was used as reference in order to normalize input and output flows in all cultivation and waste management scenarios considered.

Modelling approach and impact categories,

The software used for life cycle impact analysis was the commercial GaBi version 6.5 [14], by taking into account the phases of classification and characterization defined by the standards of ISO 14040-14044 series. During the classification phase, each burden was linked to one or more impact categories, while in the characterization phase the contribution of each burden to each impact category was calculated by multiplying burdens with a characterization factor. The demand for energy as well as waste production was also estimated based on primary data (survey).

The impact categories calculated in the present study are shown in Table 1. Five impact categories, defined according to the CML 2001 (April 2013 version) mid-point impact assessment method reported by the Centre of Environmental Science of Leiden University [15], as well as the impact category of the cumulative energy demand as an energy flow indicator, were considered.

Table 1. Environmental impact categories with their respective units

Impact category	Acronym	Units
Acidification potential	AP	kg $SO_{2eq}\cdot FU^{-1}$
Eutrophication potential	EP	kg $PO_{4eq}\cdot FU^{-1}$
Global warming potential (100 years)	GWP	kg $CO_{2eq}\cdot FU^{-1}$
Ozone depletion potential	ODP	kg CFC-$11_{eq}\cdot FU^{-1}$
Photochemical ozone creation potential	POCP	kg $C_2H_{4eq}\cdot FU^{-1}$
Cumulative energy demand	CED	GJ eq$\cdot FU^{-1}$

FU: Functional Unit

The cumulative energy demand (CED) impact category was calculated based on the method proposed by Frischknecht et al. [16], in order to assess the energetic performance of pistachio production.

Scenario design, system boundaries and assumptions

Scenario analysis was employed to propagate the uncertainty of the sources and impacts in the current LCA study. It is considered the main method to project and analyze possible alternative future developments in a product chain in terms of emission reduction, energy conservation and sustainability [17]. Closely related to sensitivity analysis, scenario analysis has therefore been widely applied to identify potential key factors for further development and long-term sustainability in cultivations such as nut trees as well as improve decision-making by considering outcomes and their feasibility implications. The scenarios investigated take into account interactions between cultivation of pistachios and produced waste in terms of energy savings, waste reduction and reuse.

In this LCA study, the following three scenarios, one current and two alternative, were investigated:

1. Current production scenario – baseline scenario (BS). It includes common farm management and normal mode of field-work processes for pistachio production, by considering data extrapolated from the past 5 years (2011-2015). This scenario was based on the actual current cultivation and waste/by-product management practices that take place in the study area and was used as the basis for comparison with the other two hypothetical scenarios that represent alternative sustainable and plausible farm and waste management options. Table 2 shows the quantities of the main waste/by-products generated during the stages of cultivation and processing/post-harvest as well as the type of management/utilization that is currently used. It can be seen that the dominant waste management option currently used for the solid wastes (hulls and culls) is the on-farm dumping/uncontrolled disposal, which is considered an illegal activity by the Waste Framework Directive 2008/98/EC [18]. To date, pistachio farmers have traditionally adopted this inappropriate approach due to the high cost of transport, lack of adequate farm waste treatment facilities, convenience and lack of scientific knowledge and guidance.

Table 2. Key characteristics concerning waste/by-product generation and utilization during pistachio production

Stage	Output	Unit	Value	Waste/By-product Utilization (%)
Cultivation	Dead trees and orchard clearing	kg/ha	235	Burning material (100%)
	Prunings*	kg/ha	1380	Uncontrolled disposal (35%) On farm burning (65%)
Post-harvest	Hulls	kg/ha	3290	On farm dumping/uncontrolled disposal (80%) Animal feed (20%)
	Culls**	kg/ha	283	On farm dumping/uncontrolled disposal (100%)

*12% of the yielding branches are cut during pruning **Includes nuts with serious defects such as loose nutmeat (kernel) or damaged from insects, mold, disease or other decay.

2. Green energy scenario (GE). The GE scenario is based on the prevailing perception that the current pistachio farm practices are unsustainable, due to the sole use of chemical fertilizers produced from non-renewable resources that in most cases are imported and therefore are expensive. The key advantage of this hypothetical scenario lies in the partial shift to organic production with the use of local renewable resources, thus implying a more eco-friendly and economic-growth-oriented vision that promotes long-term sustainability. Therefore, in this scenario 50% (i.e 250 kg ha^{-1} per year) of the currently used N/P/K chemical fertilizers is replaced by compost (20 t ha^{-1}) produced on-site from organic solid wastes, mainly hulls and culls which are generated within the same cultivation system, along with the addition of other available raw materials such as goat and sheep manure. Thus, all composting activities that take place in the orchards such as mixing of raw materials and construction of windrows were assessed in detail. As a result, this scenario is credited with the environmental burdens of the corresponding primary production since it transforms the current solid waste into a valuable product (compost); on the other hand, it is charged with additional energy consumption and ancillary materials used for the composting process. This approach can be greatly influenced by local conditions, collection methods, as well as type of technology and scale used [6]. However, the application of 20 t ha^{-1} of compost is a substantial amount that is sufficient for several years and therefore no further application of additional nitrogen supply or re-application is required in the short term [19].

3. Waste utilization scenario (WU). This scenario includes the production of biochar [4] from the produced agricultural wastes/by-products and its soil application to improve soil properties and promote carbon sequestration (CS), mitigation of non-CO_2 greenhouse gases and reduction of nutrient leaching. More specifically, the WU scenario involves the production of biochar using 100% of the currently produced hulls and culls i.e. 3573 kg ha^{-1} per year and its use as soil amendment. However, GHG emissions related to fertilizer production and application were not totally avoided since 30% of the N/P/K chemical fertilizers used in the BS scenario are still applied to promote steady cultivation conditions in terms of continuous nutrient availability. It is important to note that biochar has recently attracted significant attention for its potential use in the agricultural sector, in an effort to enhance productivity and reduce non-renewable GHG emissions. Biochar is a carbon rich product with porous structure that can be easily produced through pyrolysis of biomass from a variety of agricultural wastes and residues [4]. Due to its relatively low production cost, wide availability and high organic content, the use of biochar is regarded as a viable option for nutrient recovery when applied to soils. However, there is currently no published data available on quantification of the effect of production of biochar from pistachio waste and its reuse to soil in pistachio orchards. This scenario is considered challenging since no landfill sites or any mechanical-biological treatment facilities exist in Aegina, apart from only one municipal waste transfer station that currently operates in Skotini (5 km south of Aegina town). To date, farm waste (plastics, organic and biowaste) is driven to the closest sanitary landfilling facility in the Municipality of Ano Liosia; this requires 18 miles of sea transport (to Piraeus) and 24 km of road transport using heavy-duty trucks of 16 t Maximum Authorized Payload (M.A.P).

In the present study, the "cradle-to-gate" approach was used, considering all production processes involved from raw materials extraction (i.e. the cradle) to the point where the final product is made available to the market (i.e. the gate) (Fig. 3).

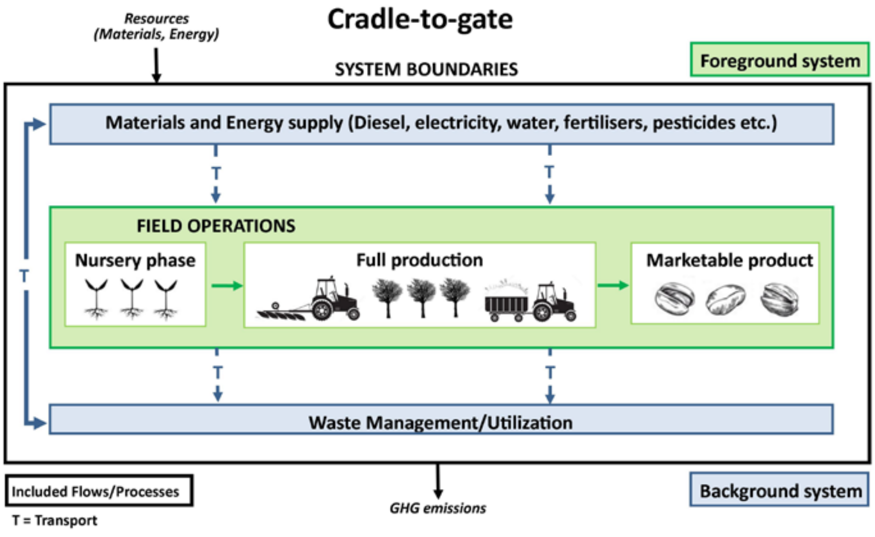

Figure 3. System boundaries adopted in this study

Two alternative scenarios investigated in this study by examining the proportional changes in terms of shifting into more eco-friendly farm practices and utilization of the waste/byproducts considered in each case, respectively. Therefore, each alternative scenario was built by substituting part or expanding the system boundaries of the BS scenario. Given the system boundaries and the associated expansion modifications, different phases were considered for each studied scenario, namely nursery production (NP) and transport (NT), waste management (WM), compost production (CP), biochar production (BP) and full production of pistachios (Fig. 4). The full pistachio production includes the phases of cultivation operations (CO), fertilizers production (FP) and transport (FT), agricultural machinery (AM), pesticides production (PP) and transport (PT), irrigation system (IS) and post-harvest (PH). All emissions, consumption of materials, water and energy during the three studied scenarios refer to the FU of 1 tonne of dry in-shell pistachios.

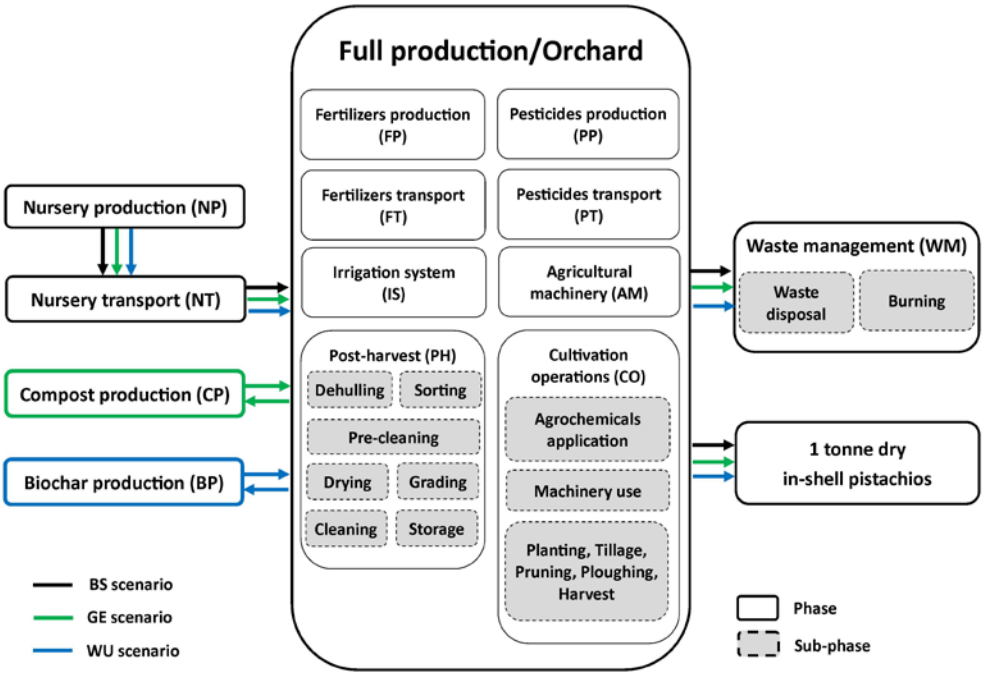

Figure 4. System boundaries for the three different scenarios

However, the following assumptions were considered in all scenarios investigated in the present LCA study, to ensure integrity, comparability and consistency of the obtained results:

Assumptions:

1. Almost two percent of the mature pistachio trees is replaced each year by nurseries. Their share is not included in the whole production cycle, since it is very low for the first 7 years of cultivation.
2. The yield of pistachio production for the two alternative scenarios (GE and WU) remains the same as in the BS scenario (250 kg ha^{-1}).
3. The grid mix of electricity power in Greece, for the year 2015, was taken into account as the main source for irrigation and post-harvest operations (drying/dehulling).
4. The lifetime of the submersible pumps used for irrigation was assumed to be 20 years. Typical shallow wells with a depth of 40 m are used for pumping about 20 $m^3 h^{-1}$.
5. The yield of pyrolysis for the temperature used (450 ^oC) is assumed constant, at 32% [4].
6. Low-horse power tractors (30 HP) were considered in this study because their use is typical for pistachio farms in Aegina to avoid soil compaction, destruction of soil structure and rutting. Diesel consumption of these small tractors was estimated depending on the task used i.e. 2.5 and 4.5 Litres/100 km for light tasks (application of fertilizers and pesticides) or heavy tasks (ploughing, transportation), respectively.
7. Transportation of agrochemicals included a full payload for outgoing transport and empty for return transport to the port of Piraeus using typical cargo vans of 3.3 t M.A.P.

Data collection and life cycle inventory

Data collection during pistachio production was enabled through a detailed voluntary survey of 11 experienced growers operating in the study area. This approach essentially aimed at increasing the credibility of LCA analysis, as well as at drafting conclusions relying on the local agricultural and economic conditions. As a result, primary site-specific data were used for operations performed at the pistachio orchards (the foreground system in Fig. 3). Where possible, based on the primary data derived from pistachio cultivations, direct field emissions from farming activities in every environmental medium (water, soil and air) were estimated using specific models [20]. To complete the life cycle inventory, data associated with the operations performed in the background system (agro-chemicals production, fertilizers production, machinery production and transportation) were drawn from literature and the available LCI databases (Professional and Ecoinvent v.3.1) of the GaBi version 6.5 software [21, 22]. In all scenarios, emissions derived from combustion of fossil fuels used by the agricultural machinery, transportation and post-harvest operations as well as heavy-metal emissions from tire abrasion, have also been included. The data for energy use which were necessary to calculate the cumulative energy demand for each unit process were obtained from the Ecoinvent v.3.1 database. Table 3 presents the main agronomic and LCI data of the pistachio production in Aegina for the BS scenario.

Table 3. Main agronomic characteristics and LCI data of the baseline scenario (BS)

Characteristics	Unit*	PDO Pistachios
Cultivar	-	Aegina
Orchard age	years	40
Density	trees ha^{-1}	250
Yield**	t ha^{-1}	2.5
Harvest period	-	1st week of September
Irrigation technique	-	Furrow, drip and sprinkler irrigation
Irrigation period	-	April to September
Fertilizers application rate		
N (as N)	kg ha^{-1}	230
P (as P_2O_5)	kg ha^{-1}	70
K (as K_2O)	kg ha^{-1}	200
Pesticides application rate		
Fungicides	kg ha^{-1}	3
Insecticides	kg ha^{-1}	2.4
Irrigation water	m^3 ha^{-1}	4450

*Mean values refer to the period 2011-2015; ** refer to FU (functional unit)

Data for the compost production were taken from Doula et al. [23], while the preparation and operating conditions used for the production of biochar were taken from Moussavi and Khosravi [24] and Komnitsas et. al. [4], respectively. In brief, composting was assumed to be carried out in outdoor windrows aerated by periodic turning for 5 months. Windrows were prepared by mixing solid pistachio waste i.e. hulls and culls (53%), goat manure (37%), straw (5%) and clinoptilolite (5%) on a weight basis. Composting temperature maintained within the range of 55–70^o C. Regarding biochar production, a small-scale low cost (approx. 6700€) pyrolysis unit with a ring kiln operating in batch mode at 450°C was considered. This unit allows the production of 100 kg/batch of biochar with 30% process efficiency. It is important to note that since compost and biochar are produced at farm level and other raw materials, such as manure and straw, are obtained from nearby agro-facilities, their transportation distance is considered negligible and therefore the associated emissions were not included in the system boundaries for GE and WU scenarios, respectively.

Results and discussion

Overall scenario comparison

The comparative environmental characterization results obtained for the different impact categories, by considering the three scenarios analyzed, namely BS, GE and WU, are summarized in Table 4. The results represent the absolute values obtained for each scenario and are expressed per FU (1 tonne of dry in-shell pistachios). For all selected impact categories, the environmental characterization impacts decrease when pistachio wastes are reused either as compost or biochar. More specifically, the calculated environmental impacts caused by scenarios GE and WU are lower, from 4% to 17% depending on the impact category assessed, than those derived by the BS scenario.

Table 4. Impact for each category and cumulative energy demand of the three scenarios investigated

Impact Category	Scenario		
	BS	GE	WU
Acidification potential (AP) [kg SO_2-eq·FU^{-1}]	8.59E+00	7.95E+00	7.68E+00
Eutrophication potential (EP) [kg PO_4-eq·FU^{-1}]	3.69E+00	3.42E+00	3.29E+00
Global warming potential (GWP) (100 years) [kg CO_2-eq·FU^{-1}]	2.04E+03	1.86E+03	1.78E+03
Ozone depletion potential (ODP) [kg CFC-11-eq·FU^{-1}]	1.19E-04	1.06E-04	9.97E-05
Photochemical ozone creation potential (POCP) [kg C_2H_4-eq·FU^{-1}]	3.24E-01	3.01E-01	2.91E-01
Cumulative energy demand (CED) [GJ·FU^{-1}]	28.05E+00	25.39E+00	28.76E+00

FU: Functional unit : 1 t of dry in-shell pistachios

According to Table 4, the GE scenario caused the lowest impacts per tonne of dry in-shell pistachios among the different scenarios assessed for almost all categories, except for CED, while the highest impact was assigned to the BS scenario. Under the BS scenario, the production of 1 t of dry in-shell pistachios consumes 28.05 GJ and releases 2041 kg CO_2-eq, 8.59 kg SO_2-eq, 3.69 kg PO_4-eq, 1.19E−04 kg CFC-11-eq and 0.32 kg C_2H_4-eq., respectively. GWP of the BS scenario is 20% lower than the respected value estimated by Marvinney et al. [25] for irrigated pistachio orchards in the Central Valley of California (2.53 kg CO_2-eq/kg pistachio nut). However, differences between studies are mainly related to methodological approaches, definition of boundaries, yield and type of FU used and therefore their accurate comparison is often a difficult task.

As anticipated, the two alternative scenarios provide more benefits compared to the BS, both in terms of energy savings and reduction of GHG emissions. In particular, the lowest impacts derive from the WU scenario, except for CED, wherein the production of 1 t dry in-shell pistachios consumes 28.76 GJ and releases 1784 kg CO_2-eq, 7.68 kg SO_2-eq, 3.29 kg PO_4-eq, 9.97E−05 kg CFC-11-eq and 0.29 kg C_2H_4-eq., thus confirming the anticipated environmental benefits as a result of carbon sequestration by the biochar application to soil. Results suggest that the WU scenario is less, 13% in terms of GWP, GHG intensive than the BS scenario as currently practiced in Aegina when viewed from an equal crop yield basis. This conclusion is consistent with previous research findings, which state that addition of biochar in cropping systems increases growth and yield, while it reduces carbon dioxide, methane and nitrous oxide emissions, which are significant contributors to GHG emissions in terms of GWP and AP/EP, respectively [5]. Therefore, converting solid pistachio waste into biochar and mixing it with soil decreases AP and EP by 7% and 11%, respectively. However, even though the CO_2-eq. emissions from pyrolysis contributed only 6% to the cumulative impact for GWP, energy needs increased by only 3% compared to BS scenario. This unfavorable result derived by the WU scenario for CED was mainly due to the temperature (450°C) used for pyrolysis of the pistachio waste and the use of wood as fuel. However, a considerable amount of biomass consisting of annual prunings and dead trees/orchard clearings, as shown in Table 2 (1615 kg/ha), can be reused as fuel feedstock for the production of biochar.

In the case of the GE scenario, the production of 1 t of dry in-shell pistachios consumes 25.39 GJ and releases 1860 kg CO_2-eq, 7.95 kg SO_2-eq, 3.42 kg PO_4-eq, 1.06E−04 kg CFC-11-eq and 0.3 kg C_2H_4-eq., respectively. The LCA scores for the GE scenario are slightly lower compared to the BS scenario, ranging from 7 to 11%. The greatest reduction compared to the BS scenario, by 11%, was achieved for ODP, mainly because of the lower requirements of mineral fertilizers in terms of production and application. The significant reduction in GWP by 9% is related to the reduction of chemical fertilizers used, by 50%, and the associated decreased consumption of fossil fuels and electricity. This leads to lower CO_2 emissions during combustion, which have a remarkable effect on the impact categories of GWP and CED. However, considerable GWP and CED savings in this scenario were also obtained as a result of carbon sequestration achieved due to composting of the organic material instead of dumping it on the farm. The reduced impact on AP and EP, by 7% is due to the avoided SO_2 and NO_x emissions from the baseline scenario, respectively. Among all three scenarios considered, GE has the lowest impact in terms of CED due to the lowest on-farm energy requirements for the composting process and off-farm fossil fuel consumption for the transport of the related feedstocks.

It is obvious that both alternative scenarios reduce almost all calculated impacts when compared to the BS scenario. This suggests that the possible reduction of GHG emissions in the life cycle of pistachio production, along with the increased yield from long-term application of compost and biochar, could increase the relative importance of raw materials, production and waste management practices. To this context, increase in the use of pistachio waste for the production of both soil amendments (compost and biochar) can generate significant GHG offsets. In order to elucidate the origin of environmental and energy burdens and relate them with specific phases, an in-depth contribution analysis was carried out and the results for each scenario studied are presented in the following sections.

Contribution analysis for BS scenario

According to Fig. 5, several processes are responsible for important contributions, up to 39% depending on the impact category, to the environmental and energy profiles associated with the BS scenario. Among studied phases and in agreement with Marvinney et al. [25], fertilizers production (FP) is the major contributor, ranging from 23% to 29%, to the total single score for the impact categories of AP, EP, GWP and CED. This result is not only attributed to the high rate of commercial N/P/K fertilizers applied per hectare (500 kg ha^{-1} on total), but it is also influenced by the production process itself in terms of energy consumption and emissions derived from raw materials (ammonium nitrate and sulfate, potassium chloride, single superphosphate, fossil fuels) extraction and processing during their entire life cycle. Production, especially of nitrogen containing fertilizers via the ammonia synthesis process, is energy intensive accounting for approximately 1% of the total global annual energy consumption [26]. As a result, 54% of the cumulative impacts for GWP were due to direct N_2O emissions, followed by CO_2 (29%), CH_4 (6%), and indirect N_2O emissions (11%).

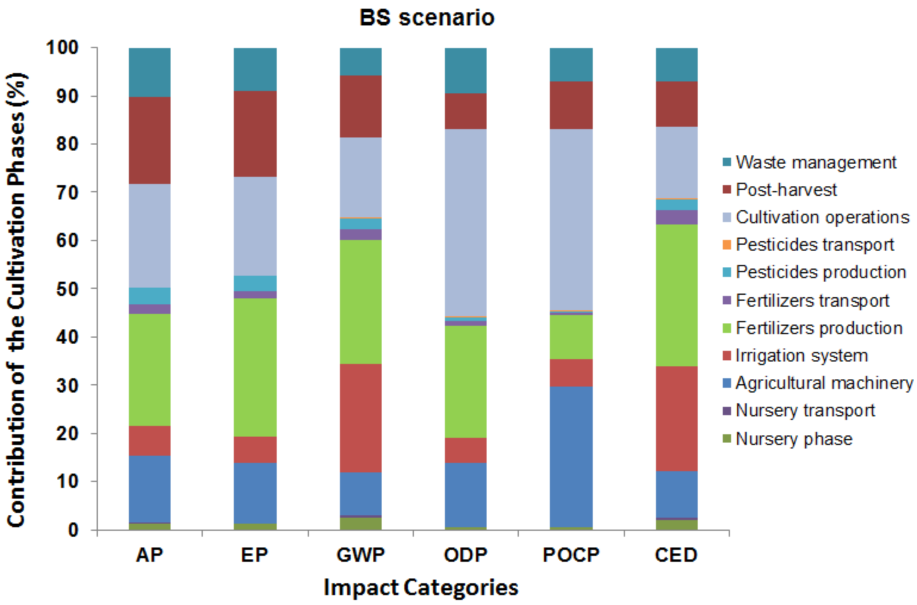

Figure 5. Contribution of each cultivation phase to each impact category for the current BS scenario of pistachio production in Aegina (AP: Acidification potential; EP: eutrophication potential; GWP: global warming potential; ODP: ozone depletion potential; POCP: photochemical ozone creation potential and CED: cumulative energy demand).

The sub-phase of cultivation operations (CO) had the second highest contribution to all impact categories, except for GWP and CED. Cultivation operations such as planting, ploughing, tillage, pruning, agrochemicals application and harvesting were the main sources of GHG emissions. In particular, the sub-phase of CO created the major burden for ODP (39%) and POCP (38%) impact categories and had the lowest share (15%) for CED. Regarding carbon-based emissions, the irrigation system (IS) was responsible for 23% and 22% contribution to GWP and CED impact categories, accounting for 460 kg of CO_2-eq. and 6.08 kg of GJ eq., respectively. These impacts were due to the high water requirements for irrigation of the pistachios orchards, i.e. 4450 m^3 ha^{-1}, along with the high energy consumption (3.79 MJ m^{-3}) required for its pumping from groundwater sources. The AM sub-phase contributed between 9% and 13% to the cumulative impacts of each impact category except for POCP, for which the contribution was considerably higher (29%) due to carbon monoxide emissions. The impacts associated with the sub-phase of AM derived from production, maintenance and repair activities as well as from end-of-life management of used equipment and other input materials (tires, lubricant oils etc.).

The phase of post-harvest (PO) operations had a critical contribution, varying between 10% and 18%, to the cumulative impacts for all impact categories, apart from ODP. These impacts were mainly related to emissions associated with the energy use for dehulling and those linked to wastewater produced during pre- and cleaning of pistachio nuts. Lower impacts but of critical importance were ascribed to waste management, ranging between 6% and 10% to all impact categories. These impacts were mainly attributed to the uncontrolled disposal of the pistachio waste and the unavoidable surface runoffs to ground- and/or surface water.

All other phases included in the BS scenario exhibited low contributions to the impact categories. The contribution of pesticides was generally low (always less than 3%), due to their very limited use, namely 5.4 kg ha^{-1}, and therefore the contribution of their transportation was negligible. Finally, the nursery phase contributed between 0.4% and 1.9%, except for GWP for which the contribution was 2.4%, while its transport had an even lower contribution varying between 0.08% and 0.65%.

Contribution analysis for GE scenario

The highest contribution to impact categories GWP, ODP and CED for the GE scenario derived from compost production (CP), which contributes 10–75% to the cumulative impacts, as shown in Fig. 6. This result can be attributed to the high CH_4 and NH_3 emissions given off during the composting process; however, the reduction of fertilization rate (by 50%) along with the avoided burdens of not dumping pistachio wastes uncontrolled, resulted in greater reduction of GHG emissions, which offset the extra input materials and machinery used for composting operations at farm level.

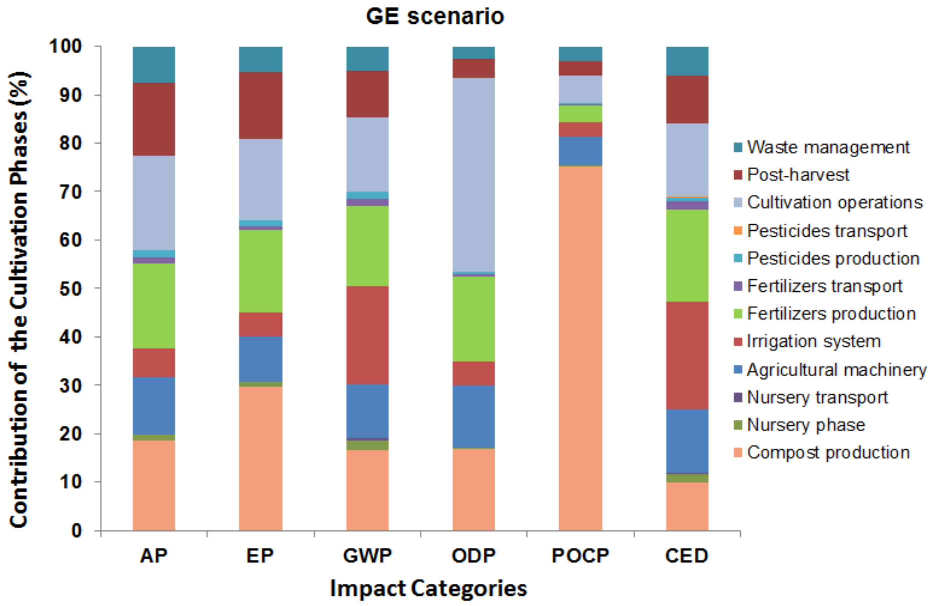

Figure 6. Contribution of each cultivation phase to each impact category for the alternative GE scenario of pistachio production in Aegina (AP: Acidification potential; EP: eutrophication potential; GWP: global warming potential; ODP: ozone depletion potential; POCP: photochemical ozone creation potential and CED: cumulative energy demand).

More specifically, the phase of compost production (CP) was responsible for approximately 75% of the cumulative impacts for POCP, due to the emission of VOCs (mainly aliphatic and aromatic compounds), NOx and aldehydes. Apart from VOCs, the 50% decreased fertilizer application compared to BS scenario and its substitution with compost (20 t ha^{-1}) resulted in 63% and 34% less N_2O and CH_4 emissions, respectively. Recent studies have shown that the environmental impacts of compost applied in combination with chemical fertilizers are lower than those of chemical fertilizers or compost alone, when avoided burdens as result of composting and not dumping organic waste are subtracted [6, 27]. However, composting on farm is highly dependent on factors such as availability of organic waste and raw materials, type of collection methods, climate, farm conditions or other temporal variations. Therefore, the emissions resulting from the biological stabilization of pistachio waste can change over time, causing uncertainty of the obtained results when assessed for short periods. To avoid this, survey data from pistachio cultivators were taken and analyzed for the period 2011-2015, including the unproductive year of 2013.

The fertilizers production (FP) phase represented the second highest burden, varying between 17% and 19% for all impact categories, except for POCP, for which its contribution was almost 4%. The highest burdens to the GWP and CED for the GE scenario were caused by the energy intensive phase of irrigation system (IS), which contributed 20% and 22% to the cumulative impacts, respectively. However, significant energetic impacts were calculated in terms of fossil fuel and electricity consumption for the phases of CO, AM and PH, accounting for 15%, 13% and 10% of the total score of CED, respectively. In the case of ODP, the CO phase was responsible for 40% of the cumulative impacts due to the application of fertilizers and pesticides. Fertilizers production represented also a significant burden for the ODP impact category, contributing 18% in the cumulative impacts, followed by the phases of CP (17%) and AM (13%), respectively. In a much lower level compared to BS scenario, waste management (WM) contributed 8% to acidification potential (AP), while its burdens varied only between 3% and 5% for all other impact categories assessed.

Finally, as in the BS scenario, the pesticides production and nursery phases as well as their transportation accounted for very low (<2%) contributions to all impact categories.

Contribution analysis for WU scenario

Among life cycle phases considered for the WU scenario, biochar production (BP) was the main source of emissions, ranging from 23 to 76%, to all impact categories, except for POCP (Fig. 7). The main environmental burdens were due to energy consumption for thermal conversion (pyrolysis), contributing 31% to CED and the uncontrolled release of high-GWP off-gases, i.e. 30% of the single impact score.

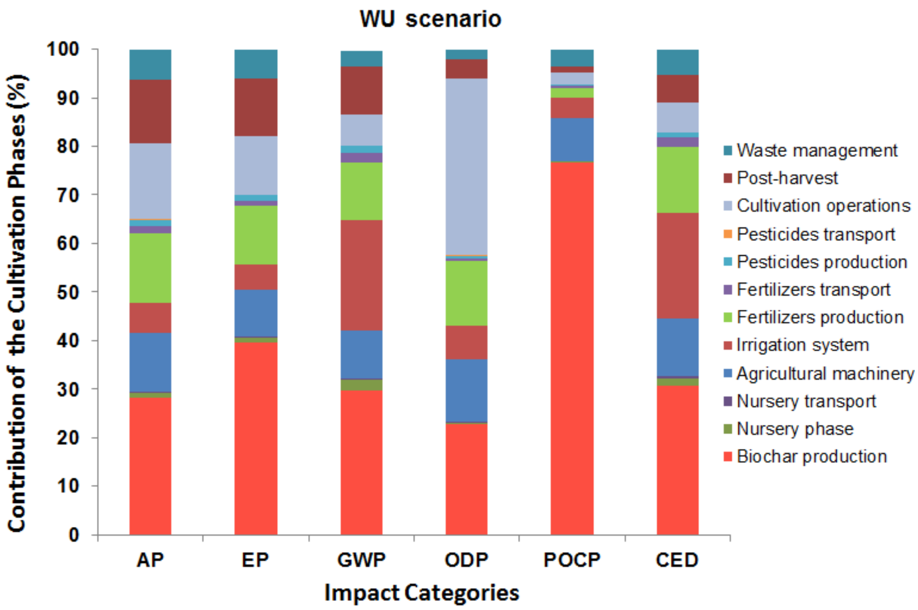

Figure 7. Contribution of each cultivation phase to each impact category for the alternative WU scenario of pistachio production in Aegina (AP: Acidification potential; EP: eutrophication potential; GWP: global warming potential; ODP: ozone depletion potential; POCP: photochemical ozone creation potential and CED: cumulative energy demand).

However, the benefits of producing biochar from agricultural residues are closely related to the lower contributions of the CO and WM phases in contrast to current commercial fertilization practices. The CO phase resulted in significantly lower impacts compared to BS scenario for all categories, with contribution values ranging from 2% (POCP) to 36% (ODP). The largest positive contributor to GHG mitigation was the direct sequestration (54%) of carbon in soil and the associated reduced emissions of CO_2. As a result, for every tonne of biochar produced via slow pyrolysis of pistachio waste and other orchard residues, a 4.4 t abatement of CO_2 eq. is anticipated, in agreement with results reported in literature for biochars produced through slow-pyrolysis of crop residues and other waste streams [28, 29]. Since biochar was applied on the pistachio orchards using the same equipment for chemical fertilization, there was only a small increase in energy use (3%) and the associated CO_2 emissions (2%) attributed to the CO phase, which is outweighed by the achieved offsets, as previously mentioned. Substitution of fertilizers with biochar also reduced direct N_2O soil emissions in terms of AP and EP that could result from N-fertilizer application along with smaller GHG benefits associated with the elimination of open burning of solid pistachio waste. The latter credit was represented by the low contributions calculated for waste management, ranging between 2% and 6%, to all impact categories.

The impact of IS phase was quite moderate in the WU scenario (4-7%), being only relevant for the energy-intensive impact categories of CED and GWP and accounting for 22% and 23% of the total scores, respectively. The phase of post-harvest had variable impact contributions, ranging from 1% (POCP) to 13% (AP). Dehulling and nut cleaning operations were the main impact contributors in this phase. Moreover, the share of agricultural machinery for most impact categories ranged between 9% and 13%, while the burdens of FP phase were between 12% and 15%, except for POCP, which exhibited an almost negligible contribution (2%). The substitution of chemical fertilization with biochar and the associated reduction of emissions is the main factor that results in lower impacts from the FP phase in this scenario compared to BS scenario. On the other hand, the contribution analysis also highlighted the relatively minor impact (>2%) of pesticides production and nursery phases on the impact categories assessed.

Conclusions

The present study determined the environmental profile of pistachio production in Aegina island, Greece, through a detailed life cycle analysis using mostly primary data obtained from local surveys. As a result, five environmental impact categories as well as one indicator concerning energy use were assessed to (i) identify the cultivation activities, which cause the highest impacts during the production of 1 tonne of dry in-shell pistachios, and (ii) explore more environmentally friendly management practices at farm scale.

To this context, a BS scenario representing the current cultivation operations and two alternative ones (GE and WU scenarios) aiming at GHG emissions reduction, waste utilization and sustainability improvement were investigated. It has been demonstrated that the environmental impacts associated with the current production of pistachios in Aegina are mainly due to the life cycle phases of fertilizers production (FP), irrigation system (IS) and cultivation operations (CO).

According to the LCA results, the production of 1 tonne of dry in-shell pistachios using the WU scenario, involving combined use of biochar and chemical fertilizers, exhibited the best overall environmental performance, with lower contributions for most impact categories, except for CED, compared to the BS. Slightly lower environmental benefits were also derived from the GE scenario, when 50% of the currently used chemical fertilizers was replaced by compost produced on-site from organic solid wastes generated within the same cultivation system.

Based upon the findings of this study, it can be concluded that application of compost and biochar, instead of chemical fertilizers, offers significant environmental benefits. However, the accurate assessment of the magnitude of these benefits is a complex issue since several local factors may affect long term credits in terms of energy savings and GHG emission reduction. Therefore, more data obtained from additional field studies, pertinent to production and application of soil amendments would be extremely useful in order to minimize uncertainty of the obtained results.

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