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INFORMATION PROCESSING IN AGRICULTURE 2 (2015) 191–207

journal homepage: www.elsevier.com/locate/inpa

Information Processing in Agriculture

Life cycle assessment of open field and greenhouse cultivation of lettuce and barley

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ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form
8 October 2015
Accepted 12 October 2015
Available online 28 October 2015

Keywords:
LCA
Agricultural waste
Lettuce
Barley
Open field
Greenhouse

ABSTRACT

In the present paper, a life cycle assessment (LCA) study regarding barley and lettuce production in Spain (Barrax and Santomera regions) and Italy (Albenga region) in both open field (OF) and standard greenhouse (GH) cultivations was performed in order to evaluate energy consumption and environmental impacts. The study examines also the impact of the use of compost produced from agricultural wastes (AW). In this context, a detailed life cycle directory was created, based on site-specific experimental data, and used for a holistic cradle-to-gate LCA analysis using the GaBi 6 software package and specific related databases. In order to reveal the importance of system boundaries, factors that are often excluded from LCA studies, such as agricultural machinery manufacture, nursery production, waste management and raw materials transportation have been considered.

According to the results of this study, the use of compost for fertilization of both crops is considered a good agronomic and ecological strategy in order to maintain productivity in terms of yield, especially in the case of greenhouse cultivation, and improve overall sustainability in the agricultural sector. Moreover, the phases of compost production, irrigation system, and greenhouse construction and operation were identified as the three main "hot-spots" with the highest environmental impact and energy contribution in all studied cases. Finally, improvements to reduce those impacts were proposed.

1. Introduction

The assessment of environmental impacts in agriculture is a fundamental task towards promoting sustainability of the sector. European Union aims to integrate environmental sustainability in economic growth, thus the use of life cycle assessment (LCA) studies is considered as a decision-support tool to evaluate different scenarios and highlight the environmental hot-spots in the life cycle of a product or a system [1–3].

LCA is a standardized methodology for the assessment of the potential environmental, human health and resource scarcity impacts associated with products and services throughout their life cycle, and includes raw material extraction, transportation, processing, product development and production, use and end-of-life treatment. LCA can identify improvements on the environmental performance of products in different life cycle stages, and assist decision-making, marketing and communication activities [4–7].

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Peer review under the responsibility of China Agricultural University.

http://dx.doi.org/10.1016/j.inpa.2015.10.001

2214-3173

According to the Directive 2008/98/EC [8], waste production should be reduced while recycling and re-use should be promoted in all sectors. Composting is the most widely considered treatment option for agricultural waste (AW) management, accounting for 95% of the current biological treatment operations [9]. The use of compost produced from AW for the fertilization of crops is considered as a promising alternative waste management option. However, since minimization of environmental impacts should be always taken into account, appropriate environmental indicators, including compost and soil quality or erosion degree must be also considered [10,11]. The functional structure of an LCA framework includes all life cycle stages and in addition measures and integrates typical inputs and outputs. When several impact categories (e.g. global warming, acidification, ozone depletion, and eutrophication potential) are taken into consideration, the implementation of a thorough LCA analysis becomes a quite complex process [12,13].

A cradle-to-gate LCA approach takes into account all life cycle stages, from raw materials extraction up to the distribution of the final product, while a cradle-to-grave approach takes into account all life cycle stages from raw materials extraction up to its disposal at the end of life. It is noted that cradle-to-gate boundaries can vary according to the position of the 'gate' [14]. The magnitude of environmental impacts depends on the system boundaries and the main factors considered. Regarding agricultural systems, due to their complexity, it is very important to include in LCA studies factors such as machinery manufacture, as well as pesticide and fertilizers transport, in order to obtain more reliable results [15]. Exclusion of these factors, mainly due to lack of reliable data, may often result in over- or underestimation of the impacts and thus in wrong decision making.

LCA studies were first carried out to assess the environmental impacts of industrial processes and later they included agricultural processes. Agriculture is very intensive in terms of land use, relies on natural resources, is often seasonal and is strongly related to factors such as soil characteristics, water availability, climatic conditions and presence of weeds, insect pests and pathogens. Therefore, various adaptations and assumptions regarding system boundaries, allocation methods to partition environmental loads and impacts categories should be considered in LCA studies [16–18].

For the development of a sustainable waste management model or strategy, environmental, economic and social aspects should be considered. The model can be either simple, if aims at optimization of single flows or process parameters, or complex in order to evaluate alternative waste management strategies [19]. Various LCA studies have been carried out on waste management systems and practices or for the comparison of different management options mainly related to sewage sludge and municipal solid wastes [20–25]. However, very few LCA studies have been carried out to assess impacts related to AW management and application of compost on soils [26–28].

This LCA study attempts to (i) evaluate and compare the application of AW in three different sites in Italy and Spain during the life cycle of lettuce and barley production considering two cultivation systems, open-field and greenhouse, (ii) identify the cultivation phases/sub-phases and hotspots that are energy intensive and cause most environmental impacts, and (iii) provide suggestions for improving the environmental performance of the cultivations studied.

2. Sites and methodology

2.1. Study sites

The sites used in the present study are located in (i) Albenga, region of Liguria, province of Savona, Italy (44°04′05.54″N–8°12′45.51″E), (ii) Finca las Tiesas, municipality of Barrax, province of Albacete, Autonomous Community of Castilla La Mancha, Spain (38°06′34.3″N–1°02′16.7″W), and (iii) Finca Tres Caminos, municipality of Santomera, autonomous community of Murcia, Spain (39°3′4,68″N–2°4′46.54″W).

2.1.1. Albenga site

The location of the Albenga study site is shown in Fig. 1. The site belongs to the Center for Agricultural Experimentation and Assistance (CERSAA). It is located about 1.5 km north of the town of Albenga and belongs to the geographical zone of Ligurian Alps. A big part of the study area, namely 49%, is intensively cultivated and includes fruit orchards, olive groves, horticultural crops, vineyards, maize and wheat fields. In this experimental site, cultivation of lettuce under open-field and greenhouse conditions was investigated.

In the past, the wider Albenga area was characterized by high pond density which has now been reduced as a result of human activities (urbanization, infrastructure development and intensive agriculture). The intensive use of inorganic fertilizers, mainly ammonium sulphate and ammonium nitrate, has affected groundwater quality in the study area [29]. Finally, the study area is characterized by a notable topographic contrast. The topographic relief is flat in the central and coastal parts (elevations 0–25 m above sea level (a.s.l)), whereas the south and north parts have an undulating relief with cone landforms (elevations 50–750 m a.s.l).

2.1.2. Barrax site

The location of Barrax study site is shown in Fig. 2. The experimental farm 'Finca Las Tiesas' belongs to the "Escuela Técnica Superior de Ingenieros Agronomos" of the University of Castilla-La Mancha. The site is about 20 km away from the capital town of the region, Albacete. The area has an elevation of 700 m a.s.l and is characterized by flat morphology. In this site, open-field cultivation of cereal (barley and soft wheat) has been investigated.

The study area is intensively cultivated and the major land uses include orchards, vineyards and cropping fields. Approximately 65% of the cultivated land is dry while the rest is irrigated. Approximately 70% of the dry land is used for the cultivation of cereals while the remaining is fallow land. The main cultivations in the irrigated land include corn 75%, barley/sunflower 15%, alfalfa 5%, onions 2.9% and other vegetables 2.1%. Over the last two decades agricultural activities impose the main pressure on water-resources availability and cause significant decrease in the piezometric level of the aquifer system.

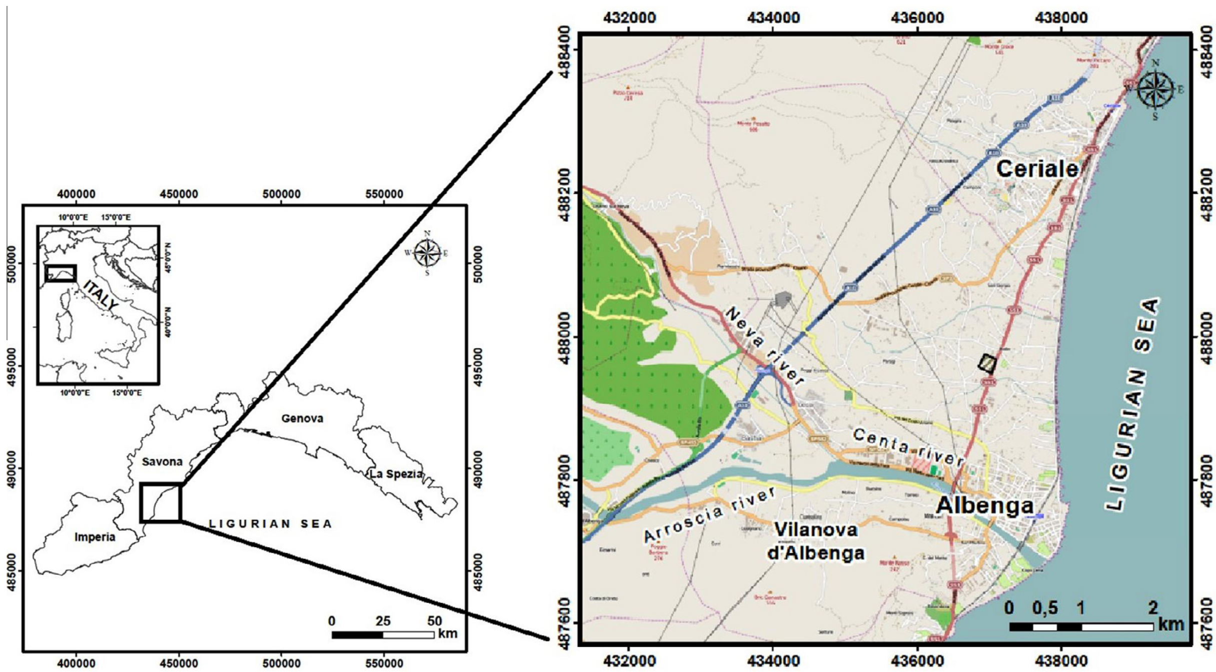

Fig. 1 – Albenga study site.

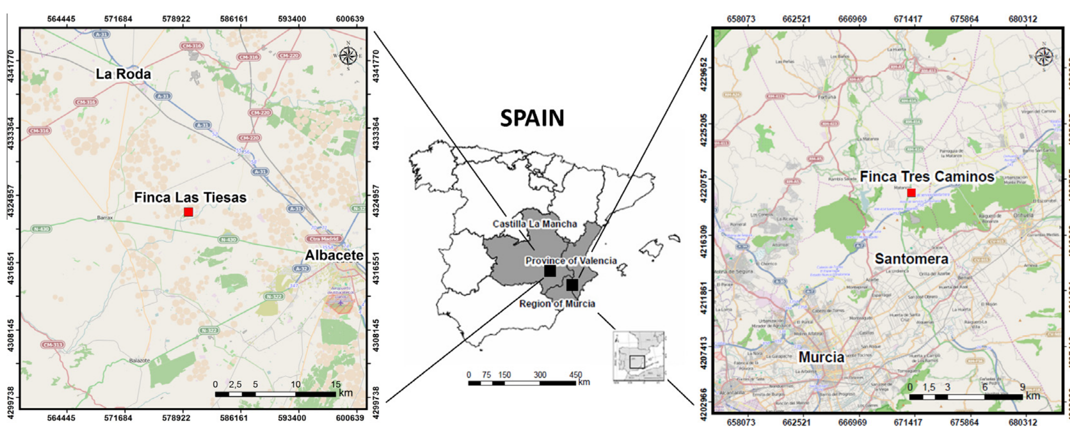

Fig. 2 – Barrax (left) and Santomera (right) study sites.

The aquifer in Barrax is part of the Mancha Oriental Aquifer that occupies about 18% of the Júcar River Basin. It comprises a regional multi-layer karstic aquifer system (Holocene, Miocene, Cretaceous and Jurassic), composed of a cyclical sequence of white to greyish marly limestones alternating with marls, which is hydraulically connected to the Jucar and the Lezuza rivers. The carbonate deposits in the region are 200 m thick [30].

2.1.3. *Santomera site*

The location of Santomera study site is shown in Fig. 2. The experimental farm 'Finca Tres Caminos' that belongs to Consejo Superior de Investigaciones Cientificas, Centro de Edafología y Biología Aplicada del Segura (CEBAS-CSIC) is located north of the town of Santomera and 18 km away from the capital town of Murcia. The site has an elevation of 50–100 m a.s.l, which is relatively low compared to nearby ridges and peaks of Sierra de Orihuela that can reach 600 m. In this site, the greenhouse field experiment of lettuce cultivation has been implemented.

The soil in the area is stony and shallow, while the soil texture ranges from sand to sandy loams and is classified as calcic xerosol. The study area is characterized by a large variety of agricultural uses, mainly involving olive and citrus groves as well as other uses, such as natural meadows and forestry. From a hydrogeological point of view, the study area displays large lithological diversity including carbonates, dolomites, conglomerates, sandstones and alluvial fans (gravel, sandy and clays) corresponding to the central zone of the Betic Cordillera [31]. The thickness of the aquifer deposits in the hydrogeological unit of Vega Media, which is part of the Segura river aquifer system, can reach 250 m.

2.2. Methodology

2.2.1. Life cycle assessment

The LCA study was carried out to determine the consumption of raw materials (agricultural waste, pesticides, fertilizers, water) and energy as well as to calculate emissions of pollutants (CO_2, CH_4, SO_2) to air and also assess the effect of application of treated or untreated AW on crop land in open field and greenhouse cultivations. The study includes the stages AW production and collection, treatment and land application, secondary waste management and disposal. The study was carried out according to the guidelines and specific requirements of the International Organization for Standardization (ISO) 14040-14044 standard series [12,32].

2.2.1.1. Goal and scope definition. The four case studies involved in the present study are:

Case 1: Cultivation of lettuce in open field in Albenga, Italy (OF_IT).

Case 2: Cultivation of lettuce in greenhouse in Albenga, Italy (GH_IT).

Case 3: Cultivation of barley in open field in Barrax, Spain (OF_ES).

Case 4: Cultivation of lettuce in greenhouse in Santomera, Spain (GH_ES).

Agricultural waste management scenarios using compost produced from treated agricultural waste and conventional fertilizers were modeled and compared in all cases.

2.2.1.2. System boundaries. In the present study, the "cradle-to-gate" approach was used, considering all the production processes involved from raw materials extraction (i.e. the cradle) to the point where the final product (lettuce or barley) is made available to the market (i.e. the gate) (Fig. 3). Based on the system boundaries, different phases were considered for each studied case, namely compost production (CP) and transport (CT), nursery production (NP) and transport (NT), waste transport (WT) and management (WM) and full production for each crop (FC) (Fig. 4). The latter phase includes the sub-phases of cultivations operations (CO), fertilizers production (FP) and transport (FT), pesticides production (PP) and transport (PT), agricultural machinery (AM) and irrigation system (IS). In greenhouse cultivations the greenhouse phase (GP) was also considered.

2.2.1.3. Data collection. In the present study, data collection and calculation procedures involved are according to ISO 14044. All relevant inputs and outputs related to crop production are identified and quantified. Table 1 summarizes the origin and the quality of the LCA data used. Ecoinvent v.3.1 [33] and Professional database [34] were also used to provide data for all transport processes included in the different phases and sub-phases. Details of the conditions and data sources are given below.

2.2.1.4. Assigned burdens. For the evaluation of environmental impacts, consideration is given to the net environmental balance between the environmental benefits and assigned burdens for each phase and sub-phase. The cut-off method, that minimizes uncertainty, was used for the management of the produced waste from all cultivation cases [35]. Landfilling of all waste materials is primarily considered for all produced wastes. No allocation criteria were used. All collected data refers to the production of the studied crops, as a function of the chosen functional unit.

Special appraisal is also given to the environmental burdens associated with compost production and transport since there is significant spatial and temporal variation in terms of quality, processing and transport in the two countries. However, in order to overcome those shortcomings, normalization of compost production characteristics was done via scale up to a reference industrial plant, as adapted from the Ecoinvent v.3.1 database [33]. The industrial scale refers to a compost

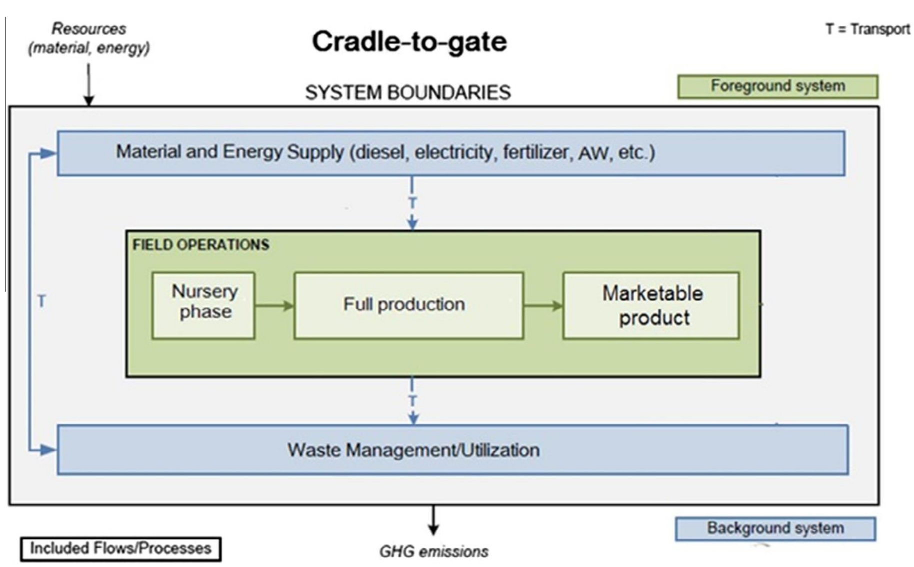

Fig. 3 – System boundaries.

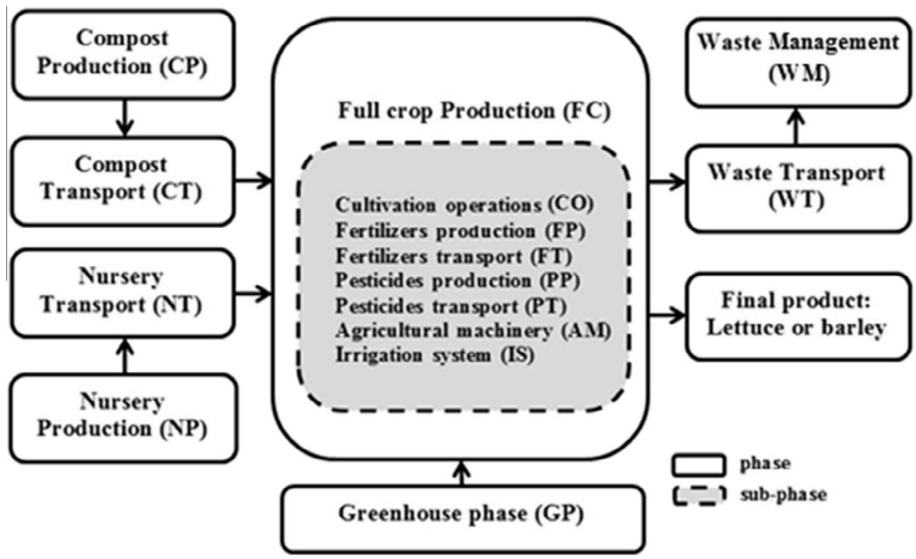

Fig. 4 – Flow diagram of the main phases and sub-phases included in the LCA study.

plant with a typical capacity of 10,000 t of treated organic waste per year and a lifetime of 25 years. In addition, comparison between composting and production of mineral fertilizers was also considered.

2.2.1.5. *Impact categories.* The software used for life cycle impact analysis was the commercial GaBi version 6 [34], by taking into consideration the classification and characterization defined by the norm ISO 14040. 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 [36]. Each of the involved production, transport and cultivation phase is separately modeled using details from mass and energy balance in each individual unit. The demand for energy as well as waste production is also estimated based on the experimental raw data.

The impact categories considered in the present study are presented in Table 2. Five impact categories, defined according to CML 2001 [36], as well as the cumulative energy demand [37], as an energy flow indicator, were estimated [38–40].

The cumulative energy demand (CED) impact category was ultimately calculated, according to the method described by Hischier et al. [41], in order to assess the energetic performance of each crop production.

2.2.1.6. *Life cycle inventory.* To complete the life cycle inventory, experimental data, bibliographical sources and the available LCI databases (Professional and Ecoinvent v.3.1) of the GaBi 6 software were used. Where possible, based on the primary data derived from open-field and greenhouse cultivations, field emissions in every environmental medium (water, soil and air) were estimated using specific models [16,42,43]. 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.

The main LCA parameters, phases and sub-phases of all agricultural cultivation practices are described below in sufficient detail.

2.2.1.7. *Functional unit.* In the present study the functional unit selected is the production of one kg of fresh (lettuce) or grain (barley) marketable product. Therefore, only the product suitable for sale on the market was taken into account as the final product. This functional unit was used as reference in order to normalize the input and the output flows in all studied systems [44,45].

2.2.1.8. *Product yield.* Different yields were obtained from each cultivation case (Table 3). Open-field and greenhouse product yields were quite similar for lettuce cultivation in Italy, whereas a slight decrease of product yield for greenhouse cultivation of lettuce was observed in Spain. It is mentioned that product yields for lettuce and barley in all studied sites were similar to those reported in literature [46,47]. Wastage (Total yield – Marketable yield), which indicates the loss due to handling and decay, varied from 1.7% to 6.0% w/w, while no wastage was observed for barley production in the open-field cultivation in Spain.

2.2.1.9. *LCI main phases and sub-phases.* Transport in the different phases and sub-phases was considered to be by road. The issue of return transport was also considered, since it is recognized that return transport plays a major role in cost unless short-distances are considered. However, in the case of transport of pesticides and fertilizers, associated environmental burdens for all impact categories were extremely high, since in both Mediterranean countries nitric acid, potassium nitrate, potassium sulfate, pesticides, herbicides and fungicides used in agriculture are transported over long-distances, mainly from north-central Europe. Truck/lorry transportation included the operation of the truck/lorry and its maintenance.

Table 1 – Origin, quality and type of data used.

Phases/sub-phases	Processes	Type	Source of data
Compost production (CP)	Organic waste collection	SD	Ecoinvent v. 3.1, 2014
	Composting process	ED	Data supplied by CEBAS-CSIC and CERSAA
	Composting facility infrastructure and machinery	SD, LD	Federici et al. [48]; Ecoinvent v. 3.1, 2014
Compost transport (CT)	Transport of raw materials	GD	Professional database, 2014
Nursery production (NP)	Greenhouse cultivation	LD, GD	Antón et al. [38]; Professional database, 2014
Nursery transport (NT)	Transport of raw materials	GD	Professional database, 2014
Waste Management (WM)	Landfill emissions	SD	Ecoinvent v. 3.1, 2014
Full crop production (FC)			
Cultivation operations (CO)	Agrochemicals application	ED	Data supplied by CEBAS-CSIC and CERSAA
	Treated AW application		
	Machinery operation		
	(Land preparation/ploughing, planting, tillage, pruning, harvest)		
	Water and energy (diesel –electricity) consumption		
	Farm waste management		
Fertilizers production (FP)	Type of fertilizers used	ED	Data supplied by CEBAS-CSIC and CERSAA
	Production of fertilizers	SD, GD	Ecoinvent v. 3.1, 2014, Professional database, 2014
	Doses of application	ED	Data supplied by CEBAS-CSIC and CERSAA
Pesticides production (PP)	Type of pesticides used	ED	Data supplied by CEBAS-CSIC and CERSAA
	Production of pesticides	SD, GD	Ecoinvent v. 3.1, 2014, Professional database, 2014
	Doses	ED	Data supplied by CEBAS-CSIC and CERSAA
Agricultural machinery (AM)	Production of Machinery	SD	Ecoinvent v. 3.1, 2014
	Waste management	SD	Ecoinvent v. 3.1, 2014
Irrigation system (IS)	Type of irrigation water supply	ED, LD	Data supplied by CEBAS-CSIC and CERSAA; Hischier et al. [41]
	System used (pumping, electricity)	SD	Ecoinvent v. 3.1, 2014
Greenhouse phase (GP)	Greenhouse building/infrastructure	SD, LD	Ecoinvent v. 3.1, 2014; Antón et al. [38]
	Operation and maintenance	ED	Data supplied by CEBAS-CSIC and CERSAA
	Waste management (plastics, steel)	SD	Ecoinvent v. 3.1, 2014

ED: experimental raw data, SD: specified database, GD: generic database, LD: literature data.

Table 2 – Environmental impact categories and respective measurement units.

Impact category	Acronym	Units
Acidification potential	AP	kg SO_2-eq FU^{-1}
Eutrophication potential	EP	kg PO_4-eq FU^{-1}
Global warming potential (100 years)	GWP	kg CO_2-eq FU^{-1}
Ozone depletion potential	ODP	kg CFC-11-eq FU^{-1}
Photochemical ozone creation potential	POCP	kg C_2H_4-eq FU^{-1}
Cumulative energy demand	CED	MJ FU^{-1}

FU: functional unit.

Table 3 – Wastage in the four different cultivation cases studied in Italy and Spain.

Parameter	Unit per cycle	Cultivation study sites	
		Italy	Spain
Open-field		OF_IT	OF_ES
Total yield	t ha^{-1}	36.6*	5.4**
Marketable yield	t ha^{-1}	33.3*	5.4**
Greenhouse		GH_IT	GH_ES
Total yield	t ha^{-1}	29.7*	23.0*
Marketable yield	t ha^{-1}	27.0*	22.6*

* Lettuce.
** Barley.

2.2.1.10. Compost production (CP). This phase included the inputs and outputs of the composting process. Since compost derives from AW, which are outputs of other agricultural systems, the raw materials for these inputs are assumed to enter the farming systems considering the environmental burdens from their processing/production as well as AW collection and transport. Data for compost production were scaled up from pilot scale to industrial plant operation in order to create a real base reference scenario. In this phase, the burdens of waste were considered using the cut-off approach (landfilling, open dumping).

2.2.1.11. Compost characteristics in Italy. The composting process was based on data derived from the LIFE05 ENV/IT/000845 TIRSAV PLUS project, in terms of energy consumption, raw materials acquisition and generation of waste [48]. Composting was carried out in a pilot plant over a period of 4 months using a trapezoidal pile of 3.5 m^3 of AW. The starting mixture included (% w/w) olive mill wastewater (OMW) (84%), waste wool (5%), olive tree leaves and twigs from the mill (5%), wheat straw (3%) and pigeon manure (3%). The water content of the initial mixture was 60% and was maintained at 40–45% during the process by watering the pile. The pile was mechanically turned twice per week to allow enable aeration and cooling. The obtained compost that used as organic fertilizer in both cultivations in Italy contained 66.4% moisture (on wet weight basis), as well as 48.1% organic carbon, 1.19% N, 0.26% P and 0.84% K on dry weight basis (Table 4).

2.2.1.12. Compost characteristics in Spain. The compost used in both cultivations in Spain is a commercial product and was purchased from Abonos Orgánicos Pedrín, Murcia [49]. It was produced from a mixture of goat and sheep manure with 39.25% moisture (on wet weight basis), 2.18% N, 28.88% organic carbon, 0.53% P and 3.78% K (on dry weight

Table 4 – Summary of selected characteristics of the composts used in Italy and Spain.

Parameter*	Unit	Cultivation study sites	
		Italy	Spain
Moisture**	%	66.40	39.25
pH	–	7.33	7.68
Electrical conductivity	μS cm^{-1}	1187	9300
Organic carbon	%	48.10	26.88
Total N	g 100 g^{-1}	1.19	2.18
Total P	g 100 g^{-1}	0.26	0.53
Total K	g 100 g^{-1}	0.84	3.78
Ammonium	g 100 g^{-1}	0.10	0.55

* On dry basis.
** On wet basis.

Table 5 – Distance for compost transportation from production sites to farm for each cultivation case studied.

Parameter	Unit	Cultivation sites	
		Italy	Spain
Open-field		OF_IT	OF_ES
Distance	km	834*	183**
Greenhouse		GH_IT	GH_ES
Distance	km	834*	50*

* Lettuce.
** Barley.

basis) (Table 4). The composting process was carried out in aerated piles. Periodically, the windrows were turned to allow heat release and were kept uniformly moistened during composting.

2.2.1.13. Compost transport (CT). All composts were transported from the composting facilities to the cultivation fields using lorries of 17.3 t of Maximum Authorized Payload (M.A.P). Table 5 shows the distance from compost production sites to farm for each cultivation case studied.

2.2.1.14. Nursery production (NP). For the efficient implementation of the LCA for each cultivation system, the phase of nursery production was considered and included in this study [50]. Data for the nursery production phase were mainly taken from the Ecoinvent v.3.1 database, and are related to greenhouse cultivation using a heating system, irrigation, fertilization, and transport burdens. In the case of barley production, data for seed production were also taken from the Ecoinvent v.3.1 database based on the fact that 400 seeds per m^2 are needed for open field cultivation.

2.2.1.15. Nursery plant transport (NT). In both open-field and greenhouse cultivations in Italy, nursery plants were transported to the main cultivation field over a short distance of 5 km. On the other hand, the distance between the nursery facility and cultivation field in Spain, is 25 and 40 km, for barley and lettuce, respectively. All transportation included a full payload for outgoing transport and empty for return transport using typical cargo vans of 3.3 t M.A.P.

2.2.1.16. Waste transport (WT). Farm waste materials (plastic, organic and biowaste) were driven to the closest landfilling facility at a distance of 9 and 17 km for Italy and Spain respectively, using lorries of 5 t M.A.P.

2.2.1.17. Waste management (WM). Various waste treatment options were considered in the whole waste-loop system. The wastes considered in the farms included wastes from the greenhouse structure (steel and glass), organic waste (crop debris) and polycarbonate mulch film [38]. All other waste streams were treated individually based on the cut-off method. Phases such as construction of the landfill site and road access, machinery operation and land use were all considered for a lifespan of 50 years [51]. During operation of the landfill site, diesel was considered to be the fuel used for activities such as waste compaction, regular covering of the waste piles and maintenance of the leachate collection system. It is mentioned that the disposal of organic waste in landfills results in generation of GHG emissions, mainly CO_2 and CH_4. Recycling of plastic and steel was not considered in the present study.

2.2.1.18. Greenhouse phase (GP). The greenhouse cultivations were studied in experimental plots of 200 m^2 (0.02 hectares) and 500 m^2 (0.05 hectares) in Italy and Spain respectively, equipped with the necessary structures. Since in greenhouse cultivations there is great variability in the type of materials used (glass cover, plastic cover, etc.), as well as in geometry (single span, multi-span, arched roof, flat roof, etc.), the specific dimensions and operating parameters considered in this study were provided by the operators in Spain and Italy. It is mentioned that on average a greenhouse structure consists of steel (15 $kg\,m^{-2}$) and glass (11 $kg\,m^{-2}$). For this study, it was assumed that the metals used for the structure were produced from virgin materials. All structural materials, such as aluminum and steel, were assumed to have a life span of 25 years. The plastic used as cover in greenhouses was assumed to have a life span of 4 years, as indicated in the Ecoinvent v3.1 database.

2.2.1.19. Full production of each crop (FC). Specific data pertinent to the cultivation practices, agricultural machinery operation, waste management, compost production, pesticides and fertilizer management were obtained from CEBAS-CSIC and CERSAA along with generic data from the databases included in GaBi v.6. The main inputs of the FC phase are given in Table 6. The quantity of commercial fertilizer applied per hectare and its composition did not vary significantly for the studied crops (lettuce and barley) in each country. N application rate for all cultivations is fairly low (58.5–80 $kg\,ha^{-1}$), except for OF_ES (118 kg N-fertilizer ha^{-1}). Among fertilizer doses, K_2O application rate (28–200 $kg\,ha^{-1}$) was higher than N (58.5–118 $kg\,ha^{-1}$) and P_2O_5 (23.8–90 $kg\,ha^{-1}$) in most cultivation cases. Commercially available fertilizers, such as ammonium sulfate, were considered in all cases. Also, the average use of the major pesticides, herbicides, fungicides and insecticides, was similar in all cases, except for OF_ES.

The supply chain for both fertilizers and pesticides, including production and transportation to the point of use, was also incorporated in the FC phase in order to assess the GHG emissions during the pre-farm cultivation stage. The management of data used and the design of the seven sub-phases included in the FC phase in all cultivation cases are described below.

Cultivation operations (CO): This sub-phase included transplanting or sowing, tillage, fertilizing, application of plant protection products and harvesting. These operations generate emissions from fuel consumption, consumption of material resources and machinery operation. Soil tillage comprises deep ripping, ploughing, disking prior to planting or sowing. Pest management is accomplished through a combination of treatment strategies such as crop rotation, interplanting and careful field spraying of pesticides. For the application of compost, pesticides and fertilizers the use of small

Table 6 – Application doses of compost, fertilizers, pesticides and irrigation water for each cultivation case studied.

Parameter	Unit	Cultivation sites	
		Italy	Spain
Open-field		*OF_IT**	*OF_ES***
Compost	t ha^{-1}	20	21
N fertilizer (as N)	kg ha^{-1}	75	118
P fertilizer (as P_2O_5)	kg ha^{-1}	80	84
K fertilizer (as K_2O)	kg ha^{-1}	200	28
Herbicides	kg ha^{-1}	4	0.9
Fungicides	kg ha^{-1}	2	0.1
Insecticides	kg ha^{-1}	3	Not applied
Irrigation water	m^3 ha^{-1}	800	2450
Greenhouse		*GH_IT**	*GH_ES**
Compost	t ha^{-1}	15	26
N fertilizer (as N)	kg ha^{-1}	80	58.5
P fertilizer (as P_2O_5)	kg ha^{-1}	90	23.8
K fertilizer (as K_2O)	kg ha^{-1}	100	105
Herbicides	kg ha^{-1}	4	0
Fungicides	kg ha^{-1}	1	3.7
Insecticides	kg ha^{-1}	1	0
Irrigation water	m^3 ha^{-1}	250	2500

* Lettuce.
** Barley.

diesel-powered tractors was assumed in the present study. For all cultivation cases, consideration was given to the transport of materials in the field via a small cargo van with a 0.6 t M.A.P.

Fertilizers production (*FP*): Data for this sub-phase, including infrastructure, transport of raw materials, type of agrochemical components (fertilizers and pesticides), and management/treatment of the generated waste were taken from the Ecoinvent v.3.1 database.

Fertilizers transport (*FT*): Concerning transport of fertilizers, a distance of 300 km from the production site to the farmland via trailer trucks (24.7 t M.A.P) was considered for both cultivations in Italy. On the other hand, a distance of 20 and 12 km from the production site to the farmland via similar trailer trucks was considered for open-field and greenhouse cultivations, in Spain, respectively.

Pesticides production (*PP*): Data for the production of pesticides was obtained from processes inventoried in the Ecoinvent v.3.1 database. As in the case of fertilizers production, this phase includes the required infrastructure, transport of primary and secondary materials to the plant, synthesis of the chemical components required and disposal or treatment of the generated waste.

Pesticides transport (*FT*): Pesticides were transported in the cultivation areas over a distance of 300 km by semi-trailer truck in Italy and 200 km by single-unit truck in Spain, respectively. Transport impacts were calculated on the basis of the amount of pesticide applied in the field as shown in Table 6.

Agricultural machinery (*AM*): This sub-phase included manufacture, transport, maintenance, repair, as well as waste management for machinery, namely tractors and ploughs, used in all four cultivation cases, while harvesting tools (harvesters) were included only in the open field cultivation of barley in Spain. Machinery that consumes less than 500 MJ ha^{-1} is regarded as light duty [52]. Data for this sub-phase regarding emissions and energy consumption were taken from the Ecoinvent v.3.1 database.

Irrigation system (*IS*): Emissions and energy consumption linked to irrigation include: (i) direct emissions related to infrastructure (power machines, conveying appliances, fittings etc), energy required for groundwater pumping and irrigation water use; and (ii) indirect emissions as a result of dispersion of agrochemical (fertilizers, pesticides). All inventory data concerning irrigation were obtained from Hischier et al. [41] and Ecoinvent v.3.1 database. The total supply of irrigation water included pumping of groundwater from nearby wells for drip and overhead irrigation using an open loop system. Rainfall was not considered in any of the cultivation cases.

3. Results and discussion

3.1. *Cumulative impacts for each cultivation case*

In the interpretation step, the results were analyzed according to the scope and goal of the study, to identify the most important aspects of the production system and determine which activities cause the most significant environmental impacts.

The absolute values of each impact category and the cumulative energy demand for the four studied crop systems are shown in Table 7. For example, the production of 1 kg of lettuce in greenhouse in Italy has an overall impact for CED of 3.15 MJ, for GWP 0.205 kg CO_2-eq, for AP 9.65E−04 kg SO_2-eq, for EP 8.54E−04 kg PO_4-eq, for ODP 2.12E−08 kg CFC-11-eq and for POCP 3.01E−04 kg C_2H_4-eq. The results show that impacts for each category were different for the open-field cultivations in the two countries, while the greenhouse cultivation of lettuce showed quite similar results in both experimental sites.

Table 7 – Impact for each category and cumulative energy demand of the studied cultivations.

Impact Category	Italy		Spain	
	Open-field* (OF_IT)	Greenhouse* (GH_IT)	Open-field** (OF_ES)	Greenhouse* (GH_ES)
Acidification potential (AP) [kg SO_2-eq FU^{-1}]	1.20E−03	9.65E−04	6.63E−04	1.13E−03
Eutrophication potential (EP) [kg PO_4-eq FU^{-1}]	1.09E−03	8.54E−04	5.62E−04	1.01E−03
Global warming potential (GWP) [kg CO_2-eq FU^{-1}]	2.43E−01	2.05E−01	1.71E−01	2.25E−01
Ozone depletion potential (ODP) [kg CFC-11-eq FU^{-1}]	2.42E−08	2.12E−08	7.17E−09	2.35E−08
Photochemical ozone creation potential (POCP) [kg C_2H_4-eq FU^{-1}]	3.98E−04	3.01E−04	8.74E−05	3.58E−04
Cumulative energy demand (CED) [MJ FU^{-1}]	2.98E+00	3.15E+00	2.11E+00	3.47E+00

* Lettuce.
** Barley; FU: functional unit.

Regarding lettuce production, the impacts for most categories were higher in the open field cultivation. More specifically, with regard to the crop production system, the open field cultivation of lettuce in Italy (OF_IT) causes bigger impacts, up to 70%, except for CED, than the same cultivation in the greenhouse (GH_IT). This is due to the fact that in the second case less organic and mineral fertilizers are used while the marketable yield of lettuce is higher. The greenhouse cultivation in Spain (GH_ES) caused bigger impacts for all impact categories, except GWP, compared to the open field cultivation. Even though different products were produced in each cultivation case, this is due to the fact that in greenhouse larger amounts of compost/mineral fertilizers were used while additional burdens, approximately more than 10%, are related to greenhouse construction and operation.

In general, the differences between the two countries for open-field (OF) cultivations were in the range of 29–48%, apart from ODP, with a difference of 70%, and POCP, with a difference of 78%. On the other hand, the differences for greenhouse cultivations were in the more narrow range of 9–14%. The difference for POCP was higher than 16% as a result of VOCs emissions. Compost production and transport, nursery production and cultivation practices were the phases that contribute more to environmental impacts.

In order to elucidate the origin of environmental and energy burdens and link them with specific phases and subphases, a contribution analysis was carried out and is presented below.

3.2. *Contribution of each cultivation phase to each impact category*

3.2.1. *Open field cultivation in Italy (OF_IT)*

The highest contribution to all impact categories considered for the open-field cultivation of lettuce in Italy, except for POCP, derives from the compost production phase (CP), which contributes 29–74% to the cumulative impacts, as shown in Fig. 5.

Regarding POCP, compost production was responsible for approximately 92% of the cumulative impacts due to the emission of VOCs. The second highest contributor was the fertilizers production phase, with a contribution varying between 9% and 25%, for all impact categories except for ODP. In the case of ODP, the field cultivation phase was responsible for 39% of the cumulative impacts due to the application of pesticides, fungicides and herbicides. Compost production represents also a significant burden for the ODP impact category, contributing 29% in the cumulative impacts, followed by the agricultural sub-phase (10%).

The transport of compost to the field is the main cause for the transport impact, contributing 2–8% to all impacts categories, except for POCP, as a result of the long distance, namely 900 km and the heavy weight of cargo required per functional unit (0.4 kg FU^{-1}). The other transport phases, including waste, fertilizers, pesticides, and nursery transport, contributed less than 1% to the cumulative impacts. The farm waste management phase contributed 6% and 4% to CED and GWP respectively, and less than 1% to the other impact categories.

On the other hand, significant energetic impacts were calculated in terms of CED for the agricultural and fertilizers production sub-phases (12% for each sub-phase), mainly due to emissions derived from raw material (ammonium nitrate and sulfate, potassium chloride, single superphosphate, fossil fuels) extraction and processing during their life cycle.

3.2.2. *Greenhouse cultivation in Italy (GH_IT)*

As in the previous case, compost production (CP) is the phase with the highest contribution to all impact categories, except for ODP, for the greenhouse cultivation of lettuce in Italy (Fig. 6). Compost production creates the major burden for POCP (88%) and EP (63%) impact categories and has the lowest share (23%) for ODP.

The sub-phase of cultivation operations (CO) has a contribution varying between 17% and 48% to the cumulative impacts for all impact categories, apart from POCP. The greenhouse phase (GP) contributed 19% to acidification potential (AP), while the fertilizers production (FP) and agricultural machinery (AM) sub-phases contributed between 6–10% and 4–7% respectively to ozone layer depletion potential (ODP), acidification potential (AP) and global warming potential (GWP). These impacts are mainly related to emissions associated with the application of mineral and organic fertilizers.

The greenhouse phase (GP) caused high impacts, especially in terms of AP and GWP categories, and its contribution was almost 19% and 10%, respectively. Concerning energy consumption, the greenhouse phase (GP) represents 9% of

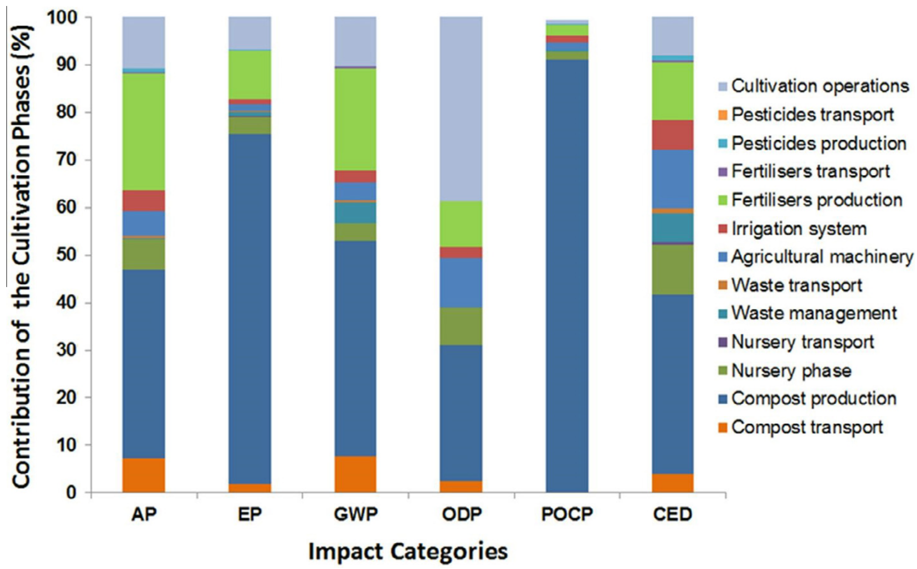

Fig. 5 – Contribution of each cultivation phase to each impact category for the open field cultivation of lettuce in Italy (EP: eutrophication potential; GWP: global warming potential; ODP: ozone depletion potential; POCP: photochemical ozone creation potential and CED: cumulative energy demand).

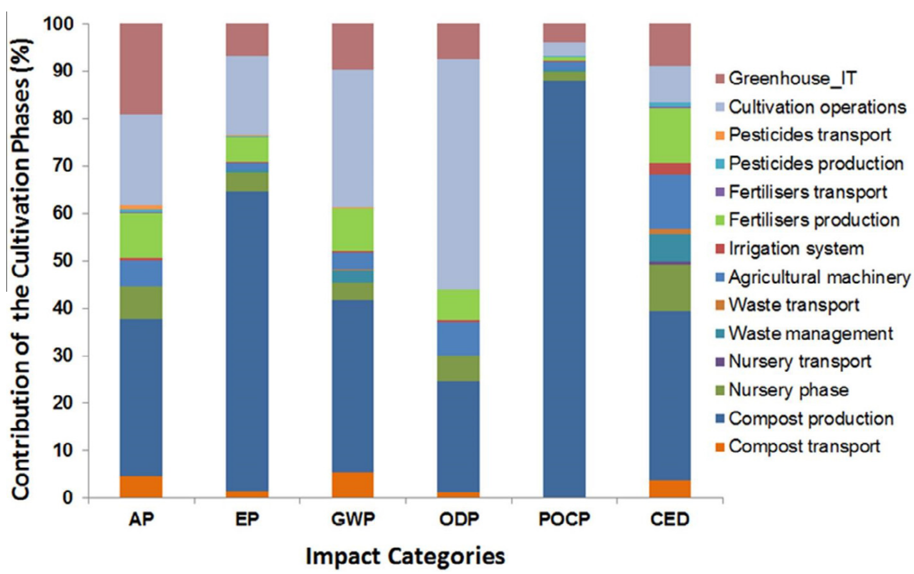

Fig. 6 – Contribution of each cultivation phase to each impact category for the greenhouse cultivation of lettuce in Italy (EP: eutrophication; GWP: global warming potential; ODP: ozone depletion potential; POCP: photochemical ozone creation potential and CED: cumulative energy demand).

the cumulative impacts for CED. Nursery production contributed 10% to the cumulative impacts for CED due to the high electricity consumption.

Agricultural machinery (AM) and fertilizer production (FP) sub-phases had similar contributions (11%) to the cumulative impacts for CED. This contribution is due to the use of fossil fuels for their manufacture/production as well as for the transport of raw materials.

3.2.3. *Open field cultivation in Spain (OF_ES)*

As in the case of open field cultivation in Italy, compost production (CP) had the highest contribution to all impact categories for the open field cultivation of barley in Spain, varying between 20% and 64%, except for POCP, for which the contribution was very high reaching 89% (Fig. 7).

This was followed by the sub-phase of cultivation operations (CO), which contributed between 13% and 37% to the impacts of each category, apart from POCP for which the contribution was only 1.2%. Agricultural operations such as tillage, agrochemical/compost application and harvesting were the main sources of GHG emissions associated with the CO sub-phase.

Furthermore, fertilizer production sub-phase (FP) contributes mainly to AP (14%) and GWP (21%) impact categories as a result of nitrous and nitrogen oxides (N_2O and NO_x) emissions. The contribution of nursery production (NP) to AP, EP,

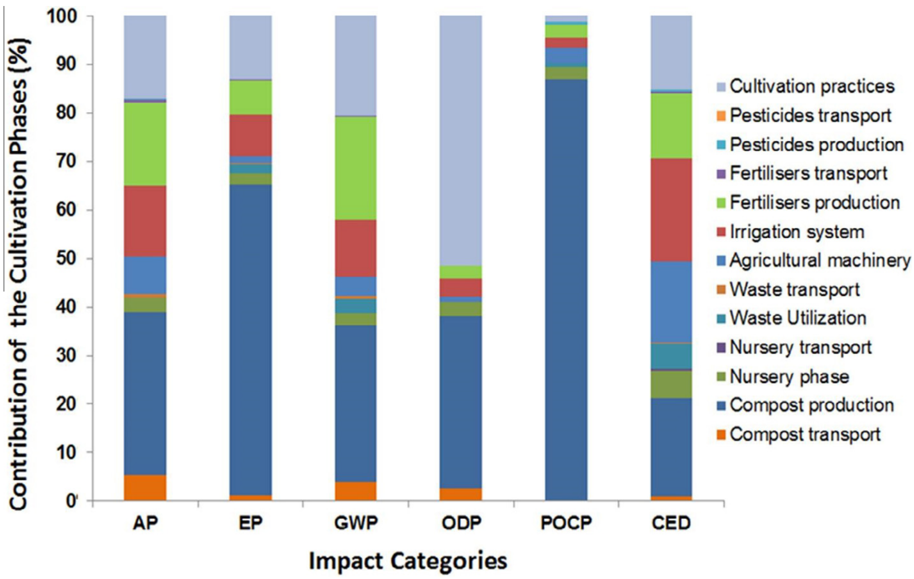

Fig. 7 – Contribution of each cultivation phase to each impact category for the open field cultivation of barley in Spain (Albacete) (EP: eutrophication; GWP: global warming potential; ODP: ozone depletion potential; POCP: photochemical ozone creation potential and CED: cumulative energy demand).

ODP and CED varied between 1% and 5%, while the agricultural machinery sub-phase (AM) contributed 17% to CED. Among sub-phases, irrigation system (IS) was responsible for 11%, 12% and 21% contribution to AP, GWP and CED impact categories due to the high energy consumption required for pumping groundwater. The contributions to the remaining categories and phases/sub-phase were limited and did not exceed 3%.

3.2.4. *Greenhouse cultivation in Spain (GH_ES)*

Fig. 8 shows the contribution of each cultivation phase to each impact category for the greenhouse cultivation of lettuce in Spain. The results show that in terms of impacts the cultivation GH_ES had many similarities with the respective cultivation in Italy (GH_IT). The only exception was the higher contribution of IS and GP sub-phases due to emissions associated with pumping of irrigation water as well as with construction and operation of the greenhouse system. As in the case of GH_IT, compost production (CP) exhibited the highest contribution, varying between 35% and 64%, for AP, EP and GWP impact categories, whereas its contribution to ODP was smaller, almost 24%. Regarding POCP, compost production was responsible for approximately 90% of the cumulative impacts, mainly due to VOCs emissions.

The cultivation operations sub-phase (CO) contributed between 20% and 36% to all impact categories, except for

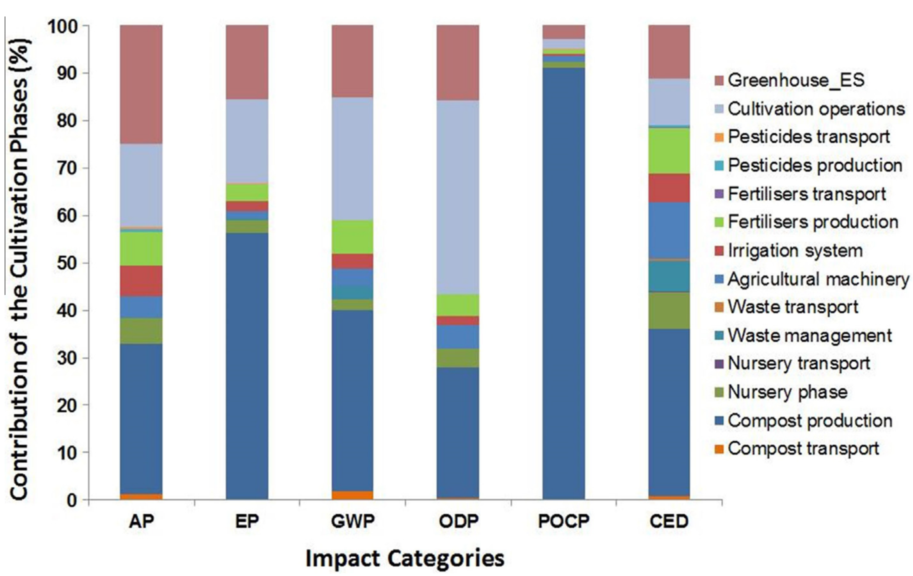

Fig. 8 – Contribution of each cultivation phase to each impact category for the greenhouse cultivation of lettuce in Spain (Murcia) (EP: eutrophication; GWP: global warming potential; ODP: ozone depletion potential; POCP: photochemical ozone creation potential and CED: cumulative energy demand).

POCP and CED, while the contribution of the greenhouse phase (GP) varied between 14% and 29%. The agricultural machinery sub-phase (AM) contributed between 2% and 5% to the cumulative impacts of each impact category except for CED, for which the contribution was considerably higher (12%). Production of fertilizers (FP) represented 8% of the cumulative contribution to AP and was the fourth major contributor to global warming, accounting for 7%. The phase of Nursery production (NP) contributed between 3% and 8% to the cumulative impacts for AP, EP, ODP and CED impact categories.

All other phases included in lettuce production had low contributions to the impact categories. Waste management contributed between 0.10% and 3%, except for CED for which the contribution was 6%, while pesticides production had an even lower contribution varied between 0.03% and 0.61%. The contribution of pesticides and mineral fertilizers transport was negligible, since very low quantities of these materials were consumed in GH_ES cultivation phase.

3.2.5. *Crucial phases/sub-phases and suggestions*

Based on the impact categories presented in Table 7, comparative conclusions can be mainly drawn for the three lettuce cultivation cases.

The impacts related to AP and EP were up to 10 times higher in OF_IT compared to GH_IT. This was mainly due to the greater use of mineral/organic fertilizers and water consumption for irrigation in OF_IT. On the other hand, the contribution of pesticides production phase (PP) in all impact categories was in general low, i.e. less than 3%, due to the very limited use of pesticides in all four cultivations.

The contribution of fertilizers production phase (FP) to GWP impact category was significant in all studied cases. Regarding this phase, the highest contribution (21%) was indicated in OF_IT cultivation case due to the greater consumption of mineral fertilizers and therefore the higher associated emissions of NH_3, SO_2 and NO_2. The lowest impact in terms of GWP was shown in OF_ES cultivation case, mainly as a result of the relatively lower energy required in the open field and thus the lower anticipated emissions. Greenhouse cultivation is characterized by high GWP values in both countries. This is due to the high emissions of CO_2 which are associated with the production of steel, plastics and glass, materials which are used for the construction of greenhouse. ODP and POCP impact categories have similar values which are associated with fertilizer production and greenhouse infrastructure, in both greenhouse cultivations.

Compost transport affects the environmental footprint of all cultivation cases to a rather limited extent, since it contributes between 1% and 4% to the fossil-affected CED impact category. This share can be reduced by shortening the distance between the composting facility and the crop field.

Based on the results of the present study, compost production (CP), irrigation system (IS) and greenhouse phase (GP) are considered as the "crucial phases/sub-phases" since their impact contributions are high in all cultivation cases. More specifically:

Compost production (CP): The contribution of the composting process to impacts was considerably high, varying from 23% for ODP to 92% for POCP. This issue has been also highlighted in other recent studies [39,53]. Reduction of its environmental footprint can be accomplished by reducing energy consumption in the composting facility, minimizing the transport distance between production areas and cultivation sites and promoting composting of locally available bio-waste [39,54,55].

Irrigation system (IS): This is another important energy-driven contribution sub-phase in all studied cases. The highest impact from irrigation, which reached 21% of the cumulative impact for CED was determined in the OF_ES case, mainly due to the high water consumption ($2500\,m^3\,ha^{-1}$). The energy consumption associated with irrigation is due to pumping groundwater, as well as for the manufacture and processing of the elements needed for the production of the irrigation system, namely steel for pumps and injectors, polyethylene for pipes and polyvinyl chloride for electro-valves. It is important to note that in the present study energy consumption for pumping groundwater is low since shallow aquifer systems (5–10 m) exist in the study areas of both countries. Reduction of the cumulative impact associated with irrigation, especially in open field cultivations, can be accomplished by (i) promoting the use of recycled materials or materials with longer service life, (ii) increasing water irrigation efficiency with the use of closed-loop irrigation systems that can achieve water savings up to 20% per m^2 and (iii) reducing irrigation rates and/or promoting mulch films [40].

Greenhouse phase (GP): This phase had a contribution between 7% and 28% to all impact categories, except for ODP, in all cultivation cases considered. This is mainly due to the manufacture of the elements required for the construction of the steel/glass frame structure and the energy consumption required to maintain temperature at the desired level, i.e. 20 °C. However, results of other LCA studies show that a prolongation of the anticipated life span of the greenhouse for five more years, to reach 30 years, can reduce impacts associated with GWP and CED up to 14% and 18%, respectively [38].

The key phases and sub-phases identified in the contribution analysis serve as the starting point for planning abatement measures that will reduce GHG emissions in the studied and other similar cultivation cases. Table 8 shows that energy and associated impacts for open field lettuce production, as derived from the present study, are much bigger compared to the impacts determined in another recent study [56]. This is mainly due to the fact that in the latter study the application of compost was not considered as fertilization management practice and therefore its impacts were not taken into account and that the impact of primary energy demand (PED) instead of cumulative energy demand (CED) was calculated.

On the other hand, the impacts pertinent to greenhouse lettuce cultivation in both countries are very similar to the impacts calculated in the same previous study [56]. In this latter study only the EP was quite smaller (0.28 kg PO_4-eq FU^{-1} instead of 0.85 and 1.01 kg PO_4-eq FU^{-1} for the cultivation in Italy and Spain, respectively). This is due to the fact that in the present study all impacts associated with the entire life cycle of compost, including collection of agricultural waste, treatment, transport, application and landfilling, instead of

Table 8 – Comparison of impacts pertinent to lettuce production in LCA studies.

Cultivation type[a]	Treatment N/P/K/C[b] ($kg\ ha^{-1}$)	CED ($GJ\ FU^{-1}$)[c]	GWP ($kg\ CO_2$-eq FU^{-1})[c]	AP ($kg\ SO_2$-eq FU^{-1})[c]	EP ($kg\ PO_4$-eq FU^{-1})[c]	Reference
OF	84/92/220/N.A	0.32*	25	0.20	0.08	[56] [Cradle to gate]
OF (Italy)	*75/80/200/20*	*2.98*	*243*	*1.20*	*1.09*	*This study [cradle to gate]*
GH	135/92/220/N.A	3.74	209	1.35	0.28	[56] [Cradle to gate]
GH (Italy)	*80/90/100/15*	*3.15*	*205*	*0.97*	*0.85*	*This study [cradle to gate]*
GH (Spain)	*58.5/23.8/105/26*	*3.47*	*225*	*1.13*	*1.01*	*This study [cradle to gate]*

[a] OF: open field, GH: greenhouse.
[b] Compost in $t\ ha^{-1}$.
[c] FU: 1 t of fresh product.
* Primary energy, N.A: not applied.

only those related to transport and application, were taken into account.

Table 9 compares the impacts pertinent to open field barley production as derived from various LCA studies. Apart from GWP, the results of the present study are in accordance with those obtained by Fallahpour et al. [57], who used the ReCiPe 2008 methodology [58]. In that study it was estimated that the cultivation of 1 t of barley in Iran has an overall impact of 419 kg CO_2-eq for GWP, 0.69 kg SO_2-eq for AP and 0.67 PO_4-eq for EP.

A second study carried out by Mogensen et al. [59] following the methodological directions of PAS2050 [60], determined that barley production in Denmark created a total GWP impact of 341 kg CO_2-eq per t of barley (seed). No other impact categories determined in this study.

A third study assessing the production of barley in Sweden, carried out by Tidåker et al. [61] showed big differences, compared to the present study, in terms of impacts for all categories. Although CED was almost 50% less, all other impacts, namely AP, GWP and EP, were much higher, varying from 57% to 195%.

The differences between the present and other relevant recent studies are due to a number of reasons, mainly related to methodological approach, definition of boundaries and type of LCA study carried out, and highlight the difficulties pertinent to comparison of LCA studies. The differences shown in Table 9, in terms of EP and AP impact categories, are mainly due to the amount and type of the fertilizers applied in the field. On the other hand, GWP is largely affected by yield, which in the present study is quite higher ($5.42\ t\ ha^{-1}$) compared to the other studies where it varied between 3.13 and $4.84\ t\ ha^{-1}$, thus resulting in a lower value for this impact category. Previous studies have shown that crop yield, which is affected by the application rate and efficiency of mineral fertilizers, and GWP are two impact categories closely related to each other [40,62]. Other factors which may affect impacts in several categories, to a lower or higher extent, are intensity of agricultural practices, level of machinery usage, type of electricity grid mix, availability of water for irrigation, as well as the site-specific conditions, namely soil and climate [63].

4. Conclusion

In the present study, a detailed life cycle assessment analysis of four cultivation cases implemented in two Mediterranean countries (Italy and Spain) has been performed. With the use of five environmental indicators as well as one indicator concerning energy, it was possible to identify the activities causing the highest impacts across and within the studied life cycle phases such as agricultural waste production and management, compost application on soil and cultivation practices applied.

The results obtained in this study show that impacts were different for the open-field cultivations, since different crops were investigated, while the greenhouse cultivations of lettuce showed quite similar results in both cultivation sites. Higher impacts have been calculated for the open-field

Table 9 – Comparison of impacts pertinent to barley production in LCA studies.

Cultivation type[a]	Grain yield ($t\ ha^{-1}$)	Treatment N/P/K/C[b] ($kg\ ha^{-1}$)	CED ($GJ\ FU^{-1}$)[c]	GWP ($kg\ CO_2$-eq FU^{-1})[c]	AP ($kg\ SO_2$-eq FU^{-1})[c]	EP ($kg\ PO_4$-eq FU^{-1})[c]	Reference
OF	3.13	>220/N.M/N.M/N.A	–	419	0.69	0.67	[57] [Cradle to gate]
OF	4.84	119/23/49/N.A	–	341	–	–	[59] [Cradle to gate]
OF	4.30	80/N.M/N.M/N.A	1.48	351	1.05	1.65	[61] [Cradle to gate]
OF (Spain)	*5.42*	*118/84/28/21*	*2.11*	*171*	*0.67*	*0.56*	*This study [cradle to gate]*

[a] OF: open field.
[b] Compost in $t\ ha^{-1}$.
[c] FU: 1 t of grain product; N.M: not mentioned, N.A: not applied.

compared to greenhouse cultivations. Compost production phase (CP), irrigation system sub-phase (IS) and greenhouse phase (GP) were the three phases/sub-phases with the highest energy and impact contributions in each impact category in the four cultivation cases.

Despite the fact that exact quantification of the related environmental impacts is not fully comparable within LCA studies, the impacts calculated in this study are significantly lower in terms of GWP, EP and AP compared to conventional cultivation of barley in the open field, thus underlining the importance of application of organic fertilizers in agriculture towards promotion of sustainability.

The present study highlights the importance of the implementation of an LCA study to evaluate environmental impacts caused by agricultural practices in open-field and greenhouse cultivations. Comprehensive documentation of system boundaries is required in order to perform meaningful assessment and reliable comparisons of environmental impacts pertinent to crop production.

Acknowledgements

The authors would like to acknowledge the financial support of the European Commission (LIFE+ Environment Policy & Governance) in the framework of the WasteReuse LIFE10 ENV/GR/594 project, www.wastereuse.eu. The authors also would like to express their sincere thanks to the journal editor and two anonymous reviewers for their constructive comments, which significantly improved the quality of the paper.

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