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Hydroponic system and desalinated seawater as an alternative farm-productive proposal in water scarcity areas: Energy and greenhouse gas emissions analysis of lettuce production in southeast Spain

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ABSTRACT

In south-eastern Spain, alternative water sources, such as desalinated seawater, and technologies for irrigation, such as hydroponic systems are required, as agriculture is currently using 80% of water resources. The present manuscript assesses the energy consumption and greenhouse gas emissions associated to two lettuce production systems, conventional soil cultivation and hydroponic system, with three desalinated seawater and freshwater blends scenarios (i.e. 0%–50%–100% of desalinated seawater). The implementation of a hydroponic system improved yield, water productivity and specific greenhouse gas emissions with respect to soil cultivation. However, specific energy consumption increased by 17% compared to soil cultivation (3.61 MJ kg^{-1} versus 4.23 MJ kg^{-1}) production. Specific greenhouse gas emissions were notably lower for the hydroponic system (0.11 kg CO_{2eq} kg^{-1}) compared to those in the soil cultivation (0.23 kg CO_{2eq} kg^{-1}). The progressive replacement of conventional water resources by desalinated seawater linearly increased energy consumption and greenhouse gas emissions in both production systems. However, the hydroponic system was less sensitive to such replacement than the soil cultivation. The results indicated that, under the expected scenarios of water limitation for agriculture, desalinated seawater coupled with hydroponic system could be a valuable strategy to sustain a high productive agriculture; albeit also highly dependent on energy. Using renewable energy could reduce emissions by 9% in hydroponic and by 2% in soil cultivation systems.

1. Introduction

The current demographic growth rate will lead to a world population of 9.1 billion people by 2050, which will require increasing food production by 70% (Faurès et al., 2013). Agriculture in semi-arid and arid regions is highly dependent on water for irrigation; however, water availability is already problematic in many regions with imbalances between renewable resources and total demands, which jeopardise irrigated agriculture and its resilience. Moreover, global climate models predict that available water resources will diminish under arid and semi-arid climates, exacerbating water scarcity problems in the near future in many areas around the world (IPCC, 2006). In this context, the required increase in food production should be met without a proportional increase in freshwater use (FAO, 2011). South-eastern (SE) Spain is one of the regions with the largest water deficit in Europe (EU) and the first in Spain, with a structural water deficit of around 400 hm^3 per year (CHS, 2015). However, given edaphoclimatic conditions, it has excellent aptitudes to achieve very competitive agriculture, which is mainly devoted to exports and to domestic food supplies (Jiménez-Martínez et al., 2016). In fact, it is one of the basic pillars of the regional economy's growth, and exports to EU countries exceed 70% of the total production of horticultural crops ($\approx$ 1 MT = 3570 M€) (IFRM, 2016). This complex scenario is putting pressure on SE Spain agriculture, which cannot meet current or future food demands from irrigated agriculture by relying solely on

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conventional water sources. Therefore, it has thus become necessary to explore new agricultural water supply options as food demand and water scarcity intensify (Barron et al., 2015). In this sense, seawater desalination for sustaining agricultural production is being reported as an alternative water source in some Mediterranean countries. It represents an abundant and steady water source which effectively removes the climatological and hydrological constraints. However, the high energy requirement of desalinated seawater (DS) ($\approx$4.45 kWh m^{-3}) in comparison with other conventional water sources (from 0.06 kWh m^{-3} for surface water to 1.21 kWh m^{-3} for desalinated brackish water) remains the main limiting factor for its incorporation into crop irrigation under current irrigated agriculture (Martin-Gorriz et al., 2014; Martínez-Alvarez et al., 2017). In addition, the high greenhouse gas emissions linked to the intensive use of energy could exacerbate climate change. Farmers must therefore look for other alternatives to the current techniques that allow water use efficiency and productivity to be increased without harming the environment. In this sense, a step forward over the traditional state of the art in irrigated agriculture is the implementation of closed soilless systems (i.e. hydroponic systems), and beyond, Nutrient Film Technique systems (NFT), in which water and nutrients flow through channels where plants have their root system in direct contact with the nutrient solution. In addition, these systems allow drainage recirculation, hence minimising harmful environmental effects on the soil-water-plant system. In Spain, about 5500 ha are devoted to hydroponic systems; most of them in the southeast (Urrestarazu, 2013); i.e. 2.3% of the total vegetable crops area, of which about 200 ha are NFT systems. By adopting these systems, in which the irrigation water can be recirculated, the amount of effluent can be reduced by up to 90% (Raviv, 2007) with significant fertilisers reduction, thus protecting the environment.

Accordingly, this system, together with the use of DS, could reduce not only the overexploitation of aquifers and degradation of soils but it can also increase water use efficiency and productivity and ensure food security. In spite of this, and to the best of our knowledge, no studies have evaluated the potential of NFT systems against soil cultivation from an agronomic, energetic and Greenhouse- Gas (GHG) emissions perspective in commercial farms.

In this context, the specific aims of this study are: (i) to assess the energy consumption and the GHG emissions due to the agricultural practices in conventional soil cultivation (SC) production against high technology NFT, and (ii) to quantify the effect of incorporating DS for irrigation into the energy consumption and GHG emissions, due to the current and expected limitation of the water availability in this basin. For this purpose, lettuce was selected as it is the winter vegetable with the highest production and area in the region, and in addition it can be grown in soil cultivation and in soilless culture.

2. Materials and methods

2.1. Study area and water supply scenarios

The study was performed in the Segura River Basin (SRB), which is a semi-arid basin located in SE Spain. Since 1979, the basin has complemented its own water resources with water transferred from central Spain through the inter-basin Tagus-Segura aqueduct (CHS, 2015); this canal periodically supplies from the Tagus basin a large part of the surface water used in SE Spain for both human consumption and irrigation practices. Such a water transfer has allowed the net surface devoted to irrigation to be increased from about 170,000 ha to 263,000 ha in last 40 years (CHS, 2015). This situation, together with the effects of climate change, has caused a chronic structural water deficit in the basin, estimated at 400 hm^3 $year^{-1}$ (CHS, 2015). In this context, in order to maintain farming systems despite the aforementioned water supply limitations, seven seawater desalination plants have been constructed to complement water supplies to more than 60 irrigation communities covering 147,255 ha within the SRB (SCRATS, 2017). Among them, the Campo de Cartagena Irrigation District has been selected as the target area for the present study as it: (i) is representative of the intensive export-oriented horticulture of the SRB; (ii) is frequently subjected to water supply shortages; (iii) uses a wide range of water sources; and (iv) is the largest irrigation district in the SRB (Soto-García et al., 2013b). The selected irrigation district provides its farmers with water by means of a collective pressurised network on rotational scheduling, and then farmers store the allocated water in on-farm artificial ponds. Under these conditions, farmers need to re-pressurise the irrigation system with their own pumping systems for drip irrigation.

Focusing on the water scarcity circumstances outlined above, the following three water supply scenarios (WS) have been considered in the study. They are based on the water availability forecasts estimated in (CEDEX, 2011) and considering the Segura river basin water balance (Martínez-Alvarez et al., 2017):

1. WS-1. It represents the current baseline scenario in which the use of DW is marginal, only 9% of the water demand, and hence we assume that all water resources for irrigation come from surface and ground water resources (854 Mm^3 y^{-1}), irrigation returns (124 Mm^3 y^{-1}), reclaimed water (144 Mm^3 y^{-1}), desalination (158 Mm^3 y^{-1}), inter-basin Tagus-Segura water transfer (322 Mm^3 y^{-1}) and overexploitation of aquifers and deficit irrigation (400 Mm^3 y^{-1}).

2. WS-2. We assume 0 Mm^3 y^{-1} of water transfer from the Tagus basin, no overexploitation of underground water resources and no deficit irrigation; i.e. 722 Mm^3 y^{-1} that are supplied by DW (about 50% of the water demand).

3. WS-3. We assume 0 Mm^3 y^{-1} of water transfer from the Tagus basin, no overexploitation of underground water resources and no deficit irrigation and 0 Mm^3 y^{-1} from surface and ground water; i.e. 1576 Mm^3 y^{-1} that are supplied by DW (about 100% of the water demand).

2.2. Farming systems description

In this study, the lettuce crop (*Lactuca sativa* L. cv. "Little Gem") was selected for two reasons: (i) lettuce production is the principal winter vegetable in the SRB, with 364 thousand tonnes in 2016, (of which 14% were Little Gem) out of which 71% were exported (BSCH-UCAM, 2017), and (ii) this variety of lettuce and those with similar characteristics can be grown both in SC and in hydroponic systems.

This study allowed the comparison of two lettuce farms from the energy and GHG emissions point of view; one lettuce plot under SC, and one lettuce plot under hydroponic system based on the NFT system. Fig. 1 summarises all processes that take place in the field to produce lettuce in SC and in NFT. On the one hand, for SC production, the data for the characterisation of the energy consumption and the GHG emissions were provided by farm managers in the Campo de Cartagena Irrigation District according to Martin-Gorriz et al. (2014). On the other hand, data for the NFT production were collected on two existing commercial farms currently using NFT systems for lettuce in the SRB.

In order to show the results of energy and GHG emissions, two functional units were chosen: 1 kg of lettuce and 1 ha of farmland. In addition, the following sets of inputs were considered: (i) diesel plus machinery; (ii) electricity for irrigation plus the irrigation system plus the reservoir; and (iii) fertilisers plus pesticides plus direct and indirect emissions of N_2O.

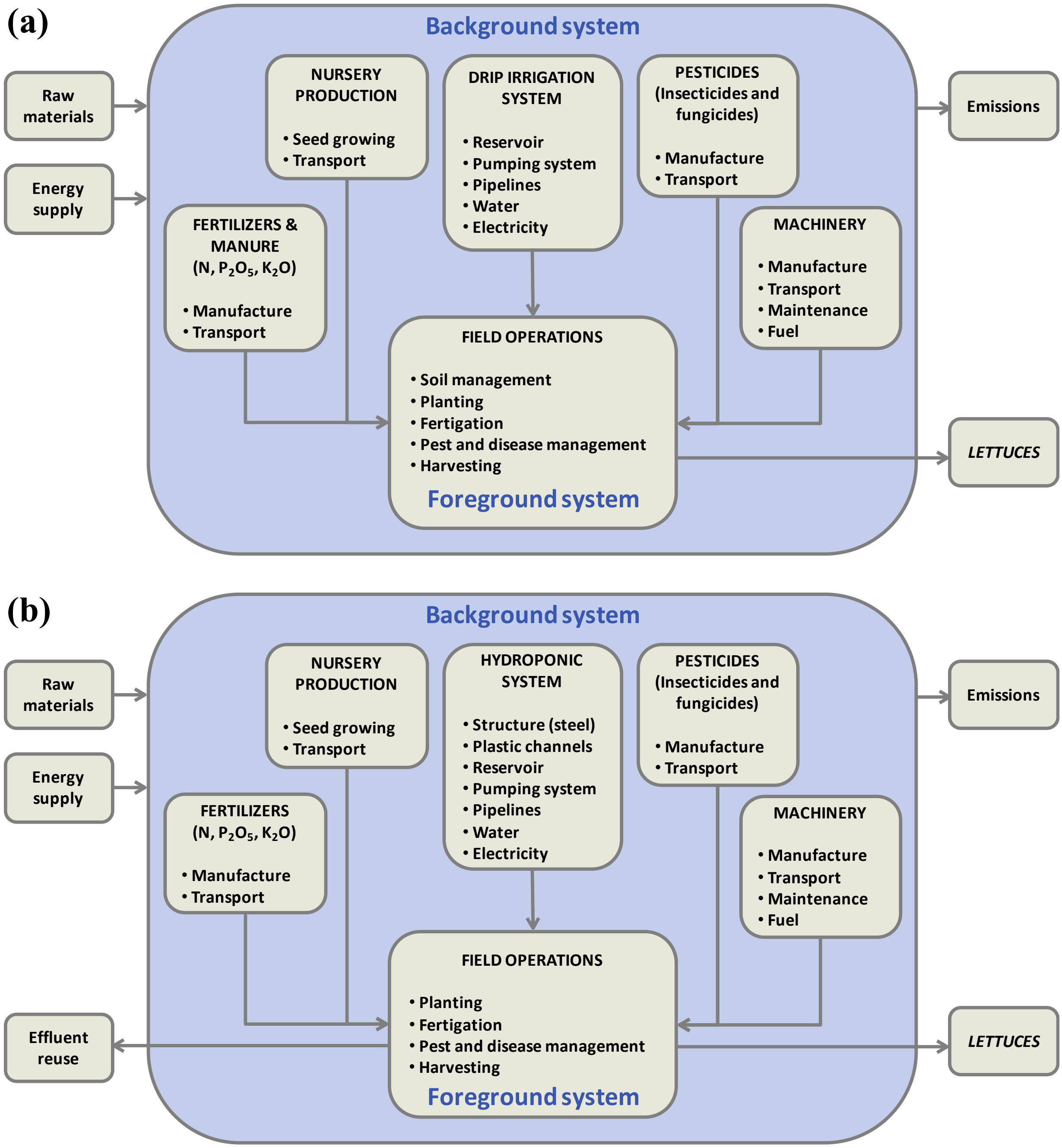


Fig. 1. Flow diagram for lettuce production in (a) soil cultivation (SC) and (b) Nutrient Film Technique (NFT).

The following CO_{2eq} indices were additionally calculated from GHG emissions and yield: specific GHG emissions (kg CO_{2eq} kg^{-1}) and areal GHG emissions (kg CO_{2eq} ha^{-1}).

2.2.1. Soil cultivation

Table 1 shows the lettuce inputs by cycle and by year for SC and NFT production. For lettuce, (*Lactuca sativa* L. cv. "Little Gem"), the growing cycle in the Campo de Cartagena Irrigation District climatic conditions (mean annual temperature of 18 °C and annual rainfall average of 350 mm) ranges between 56 and 98 days. In an agronomical year, up to three growing cycles for vegetable crops, mainly lettuce, broccoli, potatoes, melon and watermelon, are possible. A common practice among farmers is to crop lettuce-lettuce-melon in an agronomical year; consequently, lettuce is cultivated twice a year in the same field. Initially, the lettuce plantlets are produced in greenhouse nurseries and then these plantlets are transported to the main cultivation field. The plant density was 15.5 plants m^{-2}. In the plot, machinery operations involve land preparation (ploughs, cultivators, manure spreader and rotary harrow) and field cultivation (planting, row cultivation, weed control, spraying and harvesting). Fertilisers are usually applied mixed with the irrigation water; i.e. fertigation. Fig. 1a includes all processes that take place to produce lettuce in SC.

2.2.2. Soilless culture (Nutrient Film Technique)

Producing lettuce with the NFT system requires an infrastructure composed by a steel structure to support the plastic channels, pipelines, drip lines, effluent lines, pumping systems, fertilizer

Table 1
Inputs and yield in SC and NFT lettuce production in the baseline scenario.

Items	Unit	Data by cycle		Data by year	
		Cultivation system		Cultivation system	
		SC production	NFT production	SC production	NFT production
		(Unit ha^{-1} $cycle^{-1}$)	(Unit ha^{-1} $cycle^{-1}$)	(Unit ha^{-1} $year^{-1}$)	(Unit ha^{-1} $year^{-1}$)
A. Input					
A.1. Direct inputs					
Human labour	h ha^{-1}	512	768	1024	6912
Diesel	l ha^{-1}	321	15	642	135
Water for irrigation	m^3 ha^{-1}	1850	750	3700	6750
Off-farm electricity for irrigation					
External Water [100%]	kWh ha^{-1}	1572	638	3144	5742
External Water-Desalinated sea water [50-50%]	kWh ha^{-1}	5217	2115	10,434	19,035
Desalinated sea water [100%]	kWh ha^{-1}	8547	3465	17,094	31,185
On-farm electricity for irrigation	kWh ha^{-1}	315	3312	630	29,808
A.2. Indirect inputs					
Agricultural machinery	h ha^{-1}	36	23	72	207
Fertilizers					
N	kg ha^{-1}	60	162	120	1458
P_2O_5	kg ha^{-1}	50	67	100	603
K_2O	kg ha^{-1}	116	157	232	1413
Manure	kg ha^{-1}	15,000	–	15,000	–
Pesticides					
Fungicides	kg ha^{-1}	3	2	6	18
Insecticides	kg ha^{-1}	4	1.9	8	17
Herbicides	kg ha^{-1}	6.5	–	13	–
Plant material	units ha^{-1}	155,000	165,000	310,000	1,485,000
B. Output					
Yield	kg ha^{-1}	25,575	27,279	51,150	245,511
Wastewater	m^3 ha^{-1}	–	30	–	270
C. Others					
Cycles recorded	n	1	1	2	9
Cycle length	Days	77	30	154	270
Planting density	Plant m^{-2}	15.5	16.5	31	149
Water productivity	kg m^{-3}	13.82	36.37	13.82	36.37
Land productivity	kg m^{-2}	2.56	2.73	5.12	24.55

tanks and automated irrigation control systems. Table 2 shows the equipment and the total amount of material per hectare considered in an outdoor NFT system.

In NFT production labour is usually 50% higher than in SC production because most of the field work is carried out by manual workers; on the contrary, the use of machinery is very low as it is only used for pest control. It should also be highlighted that no manure is used in NFT production, which is offset by a higher dose of fertilisers. In addition, herbicides are not used because lettuce is grown in above ground structures.

It should be noted that 2 cycles per year can be achieved in SC production while 9 cycles per year can be achieved in NFT production. In NFT production, the plant density was 16.5 plants m^{-2}.

Table 2
Elements and materials considered in the NFT lettuce production.

Elements	Materials	Life spam (year)	Quantity (kg ha^{-1})
Structure			
Lattice structure, brackets steel	Steel	15	195,826
Pumping system			
Filters, pipelines, clips	PVC	10	268
Plastic channels, pipelines	PE	5	508
Probes, pumps, valves	Steel	15	166
Electric components	Copper	20	233
Irrigation and drainage network			
Drip lines, pipelines, microtubes	PVC	10	5361
Drip lines, pipelines, fertilizer tanks	PE	5	3369
Valves, pumps	Steel	15	125

The elements that represent less than 5 percent of weight have not been considered.

2.3. Processes not included in the assessment

The following assumptions have been considered to carry out the energy and GHG emissions evaluation in this work:

- CO_2 absorbed by the plants during their vegetative cycle was not taken into account; a "carbon neutral" approach has been adopted as the CO_2 absorbed by the plants has been considered to be re-emitted to the atmosphere in a short time.
- Due to a lack of information, GHG emissions of the lettuce nursery phase were excluded from the study. The nursery phase was similar in both production systems.
- Indirect energy inputs and GHG emissions involved in the raw materials of the Tagus-Segura aqueduct infrastructure have not been considered.
- Indirect energy inputs and GHG emissions related to producing water in the desalination seawater plant have not been considered.
- A greenhouse structure has not been considered because weather conditions in SE Spain allow outdoor lettuce production throughout the year.
- The storage and transport process has not been considered in the study because of the long list of destination countries involved (e.g. Germany, France, the United Kingdom, the Netherlands, etc.).

2.4. Energy consumption

Energy demand in agriculture can be divided into direct and indirect. Direct energy use covers human labour, electricity and the fuel used in the crop production while indirect energy use includes the energy inputs from material consumed to produce fertilisers, pesticides, plantlets, the irrigation system, the hydroponic system, the on-farm reservoir and agricultural machinery (Pimentel, 1992). Table 3 compiles the energy equivalences used to transform the farming inputs and outputs into energy units, which were extracted from the literature (Table 3).

Energy for human labour and diesel were calculated by multiplying the amounts required by the system by their respective energy units. Direct electrical energy used for irrigation was calculated from the irrigation water consumption and the specific energy for each water supply scenario. Losses through generation and transport of the electricity were estimated at 70%; thus 1 kWh is equivalent to 12 MJ (Ortiz-Cañavate and Hernanz, 1999). For the sake of comparing results, the specific energy values (kWh m^{-3}) for each water source were used in this study. Direct energy attributed to electricity was organised into off-farm and on-farm level. Off-farm management refers to the water allocation from the sources to the supply point of each farm (TW or DS), whilst on-farm management refers to the on-farm facilities for water application to crops. The required specific off-farm energy values used in the study are 0.85 kWh m^{-3} for TW (Martin-Gorriz et al., 2014) and 4.45 kWh m^{-3} for DS (Lapuente, 2012). The specific on-farm energy values depend on the production system, and are 0.17 kWh m^{-3} for SC production with drip-irrigation systems (Martin-Gorriz et al., 2014) and 4.42 kWh m^{-3} for NFT production (Personal communication).

Regarding indirect energy, the energy costs of fertilisers, pesticides, plant material, irrigation systems and on-farm reservoir construction were evaluated by multiplying their amounts by their respective energy units. Indirect energy for on-farm irrigation systems was calculated following Batty and Keller (1980), although considering updated energy input conversion factors of raw materials. Energy inputs associated to the on-farm agricultural water reservoir were computed by considering the volume of earth movement and the area of the PVC sheet used for seepage prevention (Ayres et al., 1974; ELCD, 2017).

Fertilisers and pesticides energy units were calculated based on Helsel (1992), which included the packaging and transportation of the raw materials and product, and excluded the application cost, since in the case of fertilisers they were added into the irrigation water. Energy associated to plant material was determined according to the methodology proposed by Bojaca and Schrevens (2010) which considers a greenhouse cultivation system using a heating system, irrigation, fertilisation, and transport burdens. Indirect energy for the machinery was calculated following the methodology proposed by Bowers (1992), by adding the values set for raw materials (86.77 MJ kg^{-1}) and the manufacturing process (8.80 MJ kg^{-1}). An additional 55% was added on top of the manufacturing process in order to consider the average energy required for machinery maintenance during its life cycle (Fluck, 1985).

Finally, the energy content of the crops; i.e. energy outputs, was taken from the Spanish national nutrient database for standard reference (BEDCA, 2014).

The following energy indices were additionally calculated from energy input, yield and energy output to analyse the efficiency of lettuce production: energy use efficiency as the ratio of energy output to energy input (dimensionless) (Eq. (1)), and specific energy (MJ kg^{-1}) (Eq. (2)) as energy of inputs per unit mass of crop production:

$$\text{Energy use efficiency} = \frac{\text{Energy output } (\text{MJ ha}^{-1})}{\text{Energy input } (\text{MJ ha}^{-1})} \tag{1}$$

$$\text{Specific energy} = \frac{\text{Energy input } (\text{MJ ha}^{-1})}{\text{Yield } (\text{kg ha}^{-1})} \tag{2}$$

Table 3
Energy equivalences of inputs and outputs.

Type	Unit	Energy equivalent (MJ $unit^{-1}$)	Reference
A. Direct energy input			
Human labour	h	2.2	Fluck, 1992
Diesel	l	38.68	Bowers, 1992
Electricity	kWh	12.0	Ortiz-Cañavate and Hernanz, 1999
B. Indirect energy input			
Machinery	kg	95.57	Bowers, 1992
Fertilizers			
N	kg	76.5	Helsel, 1992
P_2O_5	kg	15.9	Helsel, 1992
K_2O	kg	12.7	Helsel, 1992
Manure	kg	0.30	Helsel, 1992
Pesticides			
Fungicides	kg	199	Helsel, 1992
Insecticides	kg	92	Helsel, 1992
Herbicides	kg	239	Helsel, 1992
Plantlets	unit	0.2	Bojaca and Schrevens, 2010
Reservoir			
PVC sheet	m^2	20.22	Ayres et al., 1974
Earth work	m^3	25.4	ELCD, 2017
Irrigation system			
Pump system	kg	73.5	Batty and Keller, 1980
Pipeline PE	kg	52.45	Ayres et al., 1974
Pipeline PVC	kg	10.64	Ayres et al., 1974
Hydroponic system			
Structure steel	kg	24.4	Hammond and Jones, 2008
Plastic channels PE	m	0.5	Ayres et al., 1974
Copper	kg	140	Mantoam et al., 2016
C. Output			
Lettuce	kg	0.6	BEDCA, 2014

2.5. GHG emissions

According to Lal (2004) and the IPCC (2006), the assessment of GHG emissions in agricultural production can be structured into three major groups: (i) GHG emissions due to the use of fossil fuels and electricity; (ii) GHG emissions due to the production, transportation, storage and transfer of agricultural chemicals; and (iii) GHG emissions of N_2O from soils due to N-fertilizer application. GHG emissions were managed as CO_2 equivalent produced (CO_{2eq}), which was calculated by multiplying the input application rate for diesel, fertilisers, pesticides and electricity used for irrigation by its corresponding CO_{2eq} emission factor (Table 4).

Emission factor for electricity included indirect emissions attributable to the extraction, production and transport of electricity, and to the electricity lost in delivery in the network. For these calculations, it was assumed that the electricity in Spain is generated by several sources and the electricity mix factor was 0.210 kg CO_{2eq} kWh^{-1} (Iberdrola, 2017).

In order to compare the amount of GHG emissions from SC production with NFT production, areal GHG emissions (kg CO_{2eq} ha^{-1}) (Eq. (3)) and specific GHG emissions per unit weight of product (kg CO_{2eq} kg^{-1}) (Eq. (4)) were proposed to be calculated as follows:

$$\text{Areal GHG emissions}\left(\text{kgCO}_{2\text{eq}}\ \text{ha}^{-1}\right)=\frac{\text{Total GHG emissions}\left(\text{kgCO}_{2\text{eq}}\right)}{\text{Farmland(ha)}} \quad (3)$$

$$\text{Specific GHG emissions}\left(\text{kgCO}_{2\text{eq}}\ \text{kg}^{-1}\right)=\frac{\text{Total GHG emissions}\left(\text{kgCO}_{2\text{eq}}\right)}{\text{Yield}\left(\text{kg ha}^{-1}\right)} \quad (4)$$

3. Results

3.1. Soil cultivation versus nutrient film technique systems

3.1.1. Water and energy consumption

Table 5 summarises the energy equivalents of SC and NFT lettuce production (data by year). Overall, the total energy inputs for NFT (1,039,319 MJ ha-year^{-1}; 43.3% attributed to direct energy inputs) were notably higher than those for the SC system (184,900 MJ ha-year^{-1}; 39.3% attributed to direct energy inputs). Direct energy inputs for NFT production were 6.2 times higher than those calculated for SC production. In the case of indirect energy inputs that value was 5.2 times higher.

In term of specific energy the results shown 4.23 MJ kg^{-1} for NFT production and 3.61 MJ kg^{-1} for SC production. The specific energy was 17% higher in NFT production than in SC production. However, energy use efficiencies were 0.17 for SC production and 0.14 for NFT production; *i.e.* SC production was 21% more efficient in the use of energy than NFT production.

Concerning SC production, the main energy consumption share was attributed to plantlets. This result was also observed for horticultural crops in Bogotá (Bojaca and Schrevens, 2010); i.e. about 46% of the total energy inputs. After plantlets, electricity for irrigation, diesel and the irrigation system accounted for 24.7%, 13.4% and 10.2% of total energy inputs. In the case of electricity, it was mainly due to off-farm electricity (20.6%) used to transport the water from the sources to the supply point of each farm.

In NFT production, energy consumption was mainly attributed to electricity for irrigation (41.4%), followed by plantlets (28.6%), the hydroponic system (13.8%) and fertilisers (13.3%). This was due to the continuous operation of the electric pumps to supply water through the NFT channels.

In terms of land productivity by cycle, the results were very similar for the SC and NFT production (2.56 kg m^{-2} in SC and 2.73 kg m^{-2} in NFT) (Table 1). However, regarding land productivity by year, the NFT production (24.55 kg m^{-2} year^{-1}) was 4.79 times greater than that of the conventional SC (5.12 kg m^{-2} year^{-1}). It should be noted that the plant density was similar for SC and NFT production; 15.5 plant m^{-2} and 16.5 plant m^{-2} (Table 1). This

Table 4
Greenhouse gas (GHG) emission factor of inputs.

Activity	Gas	Emission factor	Unit	Source
A. GHGs emissions due to the use of fuel and electricity				
- Diesel	CO_2	74.1×10^{-3}	kg CO_{2eq} MJ^{-1}	IPCC, 2006
	CH_4	21×10^{-5}	kg CO_{2eq} MJ^{-1}	
	NO_2	19×10^{-5}	kg CO_{2eq} MJ^{-1}	
- Electricity	CO_2	0.210	kg CO_{2eq} kWh^{-1}	Iberdrola, 2017
B. GHGs emissions from farm machinery and irrigation systems				
- PVC sheet	CO_2	5.7	kg CO_{2eq} m^2	Berge, 2009
- Steel	CO_2	1.76	kg CO_{2eq} kg^{-1}	Hammond and Jones, 2008
- PE	CO_2	2.2	kg CO_{2eq} kg^{-1}	Berge, 2009
- PVC	CO_2	3.0	kg CO_{2eq} kg^{-1}	Berge, 2009
- Copper	CO_2	6	kg CO_{2eq} kg^{-1}	Berge, 2009
C. GHG emissions due production, transportation, storage and transfer of agricultural chemicals				
Fertilizers				Lal, 2004
- N	CO_2	1.3	kg CO_{2eq} kg^{-1} N	
- P_2O_5	CO_2	0.2	kg CO_{2eq} kg^{-1} P_2O_5	
- K_2O	CO_2	0.15	kg CO_{2eq} kg^{-1} K_2O	
Pesticides				Lal, 2004
- Fungicides	CO_2	3.9	kg CO_{2eq} kg^{-1}	
- Insecticides	CO_2	5.1	kg CO_{2eq} kg^{-1}	
- Herbicides	CO_2	6.3	kg CO_{2eq} kg^{-1}	
D. GHG emissions of NO_2 from soils due to N-fertilizer application				
Direct N_2O from N inputs (fertilizers and manure)	NO_2	4.87	kg CO_{2eq} kg^{-1} N input	IPCC, 2006
Direct N_2O from N leaching or runoff	NO_2	1.096	kg CO_{2eq} kg^{-1} N input	
Indirect N_2O from atmospheric decomposition of N volatilised as NH_3 and NO_x				
- Synthetic fertilizer	NO_2	0.487	kg CO_{2eq} kg^{-1} N input	
- Manure	NO_2	0.974	kg CO_{2eq} kg^{-1} N input	

Table 5
Energy conversion (MJ ha^{-1} $year^{-1}$) for the farming inputs and yield in the SC and NFT lettuce production in the baseline scenario.

Items	Cultivation system			
	SC production		NFT production	
	MJ ha^{-1} $year^{-1}$	%	MJ ha^{-1} $year^{-1}$	%
A. Energy input				
A.1. Direct energy inputs				
Human labour	2253	1.2	15,206	1.5
Diesel	24,798	13.4	5119	0.5
On-farm electricity for irrigation	7611	4.1	360,677	34.7
Off-farm electricity for irrigation	38,055	20.6	69,424	6.7
Total direct energy	**72,717**	**39.3**	**450,426**	**43.3**
A.2. Indirect energy inputs				
Machinery	6834	3.7	2220	0.2
Fertilizers				
N	9180	5.0	111,384	10.7
P_2O_5	1590	0.9	9635	0.9
K_2O	2946	1.6	17,935	1.7
Manure	4545	2.5	–	–
Pesticides				
Fungicides	1194	0.6	3582	0.3
Insecticides	736	0.4	1532	0.1
Herbicides	3107	1.7	–	–
Plantlets	62,000	33.5	297,000	28.6
Reservoir				
Excavation	775	0.4	1846	0.2
PVC sheet	302	0.2	720	0.1
Drip irrigation system				
Pump system	46	0	–	–
Pipeline PE	18,892	10.2	–	–
Pipeline PVC	36	0	–	–
Hydroponic irrigation system				
PVC	–	–	5989	0.6
PE	–	–	40,552	3.9
Steel	–	–	96,266	9.3
Copper	–	–	232	0
Total indirect energy	**112,183**	**60.7**	**588,893**	**56.7**
Total energy inputs	**184,900**	**100**	**1,039,319**	**100**
B. Energy output				
Yield	**30,690**		**147,309**	
C. Indices				
Energy use efficiency	0.17		0.14	
Specific energy (MJ kg^{-1})	3.61		4.23	

higher land productivity in the case of NFT production is explained by the 9 cycles $year^{-1}$ of 30 days $cycle^{-1}$ in the NFT production compared to the 2 cycles $year^{-1}$ of 77 days $cycle^{-1}$ in the SC production (Table 1).

Finally, comparing water productivity between the NFT production and the SC production; *i.e.* the ratio between yield and areal water consumption for irrigation, the NFT production reached a higher water productivity, 2.63 times higher in the NFT production than in the SC production (36.4 kg m^{-3} against 13.8 kg m^{-3}) (Table 1).

3.1.2. GHG emissions

Table 6 shows the GHG emissions of the SC and NFT production (data by year). Overall, the total areal GHG emissions for the NFT production (25,724 kg CO_{2eq} ha^{-1} $year^{-1}$) were more than twice as high as those for the SC production (11,760 kg CO_{2eq} ha^{-1} $year^{-1}$). In the case of the SC production, the highest GHG emissions were associated to the drip irrigation system (40.1% of total emissions), followed by the nitrogen for fertilisation (16.0%; of which 1.3% corresponds to GHG emissions due to the production, transportation, storage and transfer of nitrogen, and the remainder, 14.7%, to emissions of N_2O from soils as a consequence of nitrogen fertilizer application), the reservoir (15.8%) and the diesel (15.6%). Similarly, for the NFT production, the highest GHG emissions came from the hydroponic irrigation system (40.3% of total emissions). However, in this case, the electricity for irrigation played a representative role with 29% of total GHG emissions. This makes clear sense as NFT production requires both a major infrastructure (Table 2) as well as the continuous operation of the electric pumps to supply water through the NFT channels.

3.2. Analysis of hypothetical future alternative water supply scenarios

3.2.1. Effect on energy consumption

For all the scenarios, the implementation of DS for irrigation notably increased the off-farm and on-farm electricity for irrigation (Fig. 2). These significant changes among scenarios are mainly caused by the high impact of the production of the DS on energy consumption (4.45 kWh m^{-3}).

Overall, energy inputs in WS-2 increased by 47.6% and 15.5% in SC and NFT production, compared with WS-1. Such increases were 91.2% and 29.6% when considering WS-3 results (Table 7).

In WS-2, the increase in off-farm electricity for irrigation (3.3 times higher than that in WS-1) resulted in an increase in the specific electricity consumption for irrigation from 1.02 to 2.99 kWh m^{-3} in the SC production, and from 5.26 to 7.23 kWh m^{-3} in the NFT production. In WS-3, such specific electricity

Table 6
GHG emission of inputs (kg CO_{2eq} ha^{-1} $year^{-1}$) in lettuce production in the baseline scenario.

Activity	Cultivation system			
	SC production		NFT production	
	GHG emission (kg CO_{2eq} ha^{-1} $year^{-1}$)	Percentage (%)	GHG emission (kg CO_{2eq} ha^{-1} $year^{-1}$)	Percentage (%)
A. GHGs emissions due to the use of fuel and electricity				
Diesel	1838	15.6	379	1.4
Total electricity for irrigation	792	6.7	7465	29.0
Electricity for irrigation on-farm	132		6260	
Electricity for irrigation off-farm	660		1205	
B. GHGs emissions from farm machinery and irrigation systems				
Machinery	485	4.1	158	0.6
Reservoir	1853	15.8	4412	17.2
Drip irrigation system	4715	40.1	–	
Hydroponic irrigation system	–	–	10,360	40.3
C. GHG emissions due production, transportation, storage and transfer of agricultural chemicals				
Fertilizers	211	1.8	2226	8.7
Pesticides	146	1.2	155	0.6
D. GHG emissions of NO_2 from soils due to N-fertilizer application				
Direct emissions of N_2O	1525	13.0	–	–
Indirect emissions of N_2O	195	1.7	569	2.2
Areal GHG emissions (kg CO_{2eq} ha^{-1})	11,760		25,724	
Specific GHG emissions (kg CO_{2eq} kg^{-1})	0.23		0.11	

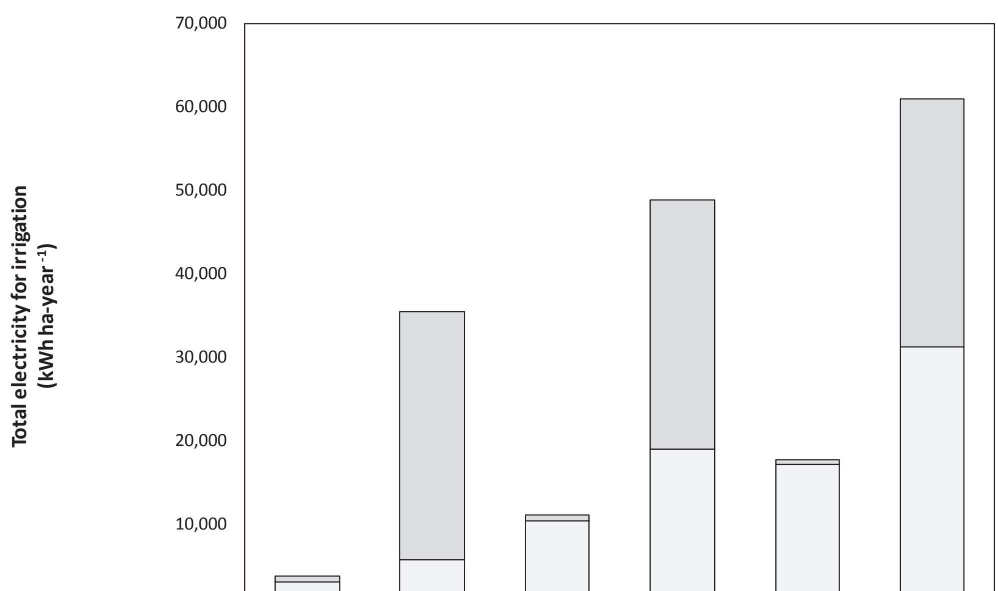
consumption for irrigation increased up to 4.79 and 9.03 kWh m^{-3} in the SC and NFT productions (data not shown).

As expected, the higher volumes of DS in scenarios WS-2 and WS-3 implied higher energy consumption and GHG emissions, with such an increase being mainly proportional to the amount of irrigation water applied in each cultivation system (Table 1).

In the WS-1, the specific energy in the NFT production was 17.2% higher (4.23 MJ kg^{-1}) than that in the SC production (3.61 MJ kg^{-1}) (Table 7; Fig. 3a). However, this trend was reversed in the hypothetical water supply scenarios WS-2 and WS-3, where the specific energy for NFT production was reduced by 8.43% and 20.55% compared with SC production, respectively. It is of note that the slope of the SC regression in Fig. 3a was much higher than that of the NFT production, which indicated the lower sensitivity of the NFT production with respect to the SC production in future water supply scenarios. In addition, the intersection point between SC and NFT trend lines showed that the NFT production began to be more energetically efficient from a percentage of DS mixing of 29.6% with a specific energy of 4.61 MJ kg^{-1}.

3.2.2. Effects of GHG emissions

In comparison with WS-1, GHG emissions increased by 13.0% and 24.9% in the SC production and by 10.8% and 20.7% in the NFT production for the WS-2 and WS-3 scenarios, respectively (Table 7). Such percentage values were notably lower than those observed for energy consumption, which indicated that energy is more sensitive to input variations than GHG emissions. In fact, regardless of the scenario, the specific GHG emissions for the NFT production were



	SC (WS-1)	NFT (WS-1)	SC (WS-2)	NFT (WS-2)	SC (WS-3)	NFT (WS-3)
Electricity for irrigation on-farm kWh	629	29,808	629	29,808	629	29,808
Electricity for irrigation off-farm kWh	3,145	5,738	10,434	19,035	17,094	31,185

Fig. 2. Total electricity for irrigation (kWh ha^{-1} $year^{-1}$) by scenario.

Table 7
Energy equivalents and GHG emission in SC and in NFT production for the three water supply scenarios.

Item	Units	WS-1 scenario		WS-2 scenario		WS-3 scenario	
		SC	NFT	SC	NFT	SC	NFT
Energy							
Total direct energy	MJ ha^{-1} $year^{-1}$	72,716	450,426	160,913	611,326	241,499	758,341
Total indirect energy	MJ ha^{-1} $year^{-1}$	112,183	588,893	112,183	588,893	112,183	588,893
Total energy inputs	MJ ha^{-1} $year^{-1}$	184,900	1,039,319	273,096	1,200,219	353,682	1,347,234
Total energy output	MJ ha^{-1} $year^{-1}$	30,690	147,309	30,690	147,309	30,690	147,309
Energy use efficiency	-	0.17	0.14	0.11	0.12	0.09	0.11
Specific energy per unit weight	MJ kg^{-1}	3.61	4.23	5.34	4.89	6.91	5.49
GHG emissions							
A. GHGs emissions due to the use of fuel and electricity	kg CO_{2eq} ha^{-1} $year^{-1}$	2630	7844	4161	10,636	5559	13,188
B. GHGs emissions from farm machinery and irrigation systems	kg CO_{2eq} ha^{-1} $year^{-1}$	7053	14,930	7053	14,930	7053	14,930
C. GHG emissions due production, transportation, storage and transfer of agricultural chemicals	kg CO_{2eq} ha^{-1} $year^{-1}$	357	2381	357	2381	357	2381
D. GHG emissions of NO_2 from soils due to N-fertilizer application	kg CO_{2eq} ha^{-1} $year^{-1}$	1720	569	1720	569	1720	569
Total areal GHG emissions	kg CO_{2eq} ha^{-1} $year^{-1}$	11,760	25,724	13,291	28,516	14,689	31,068
Specific GHG emissions	kg CO_{2eq} kg^{-1}	0.23	0.11	0.26	0.12	0.29	0.13

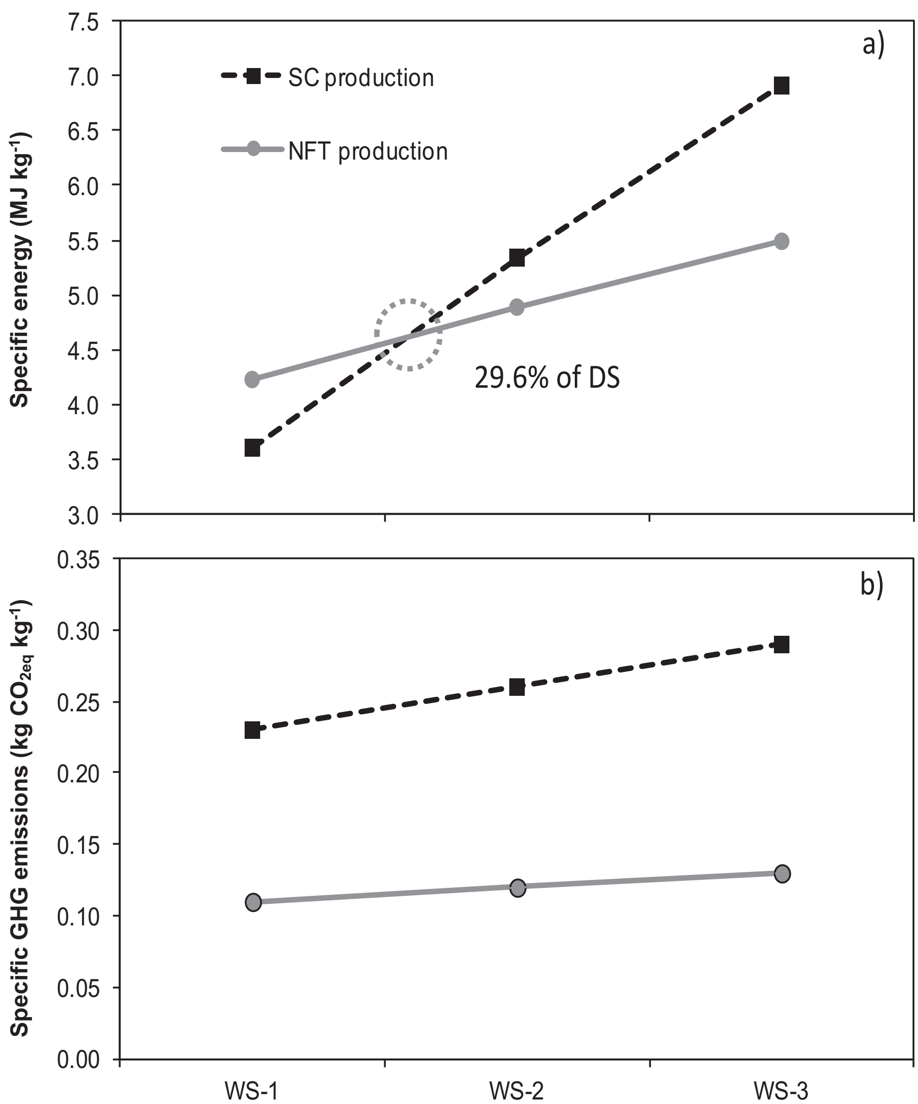


Fig. 3. (a) Specific energy (MJ kg^{-1}) and (b) Specific GHG emissions by scenario.

always lower than those observed in the SC production (Fig. 4).

As observed for specific energy consumption, the regression slope for specific GHG emissions in the SC production was higher than that for the NFT production (Fig. 4). This meant that the NFT production was less sensitive to the progressive replacement of TW by DS than the SC production. When analysing the GHG emissions for the different scenarios, based on the sets described in section 2.2, the set consisting of electricity for irrigation, the irrigation system and the reservoir accounted for 62.7% and 86.2% for SC and NFT, respectively in WS-1, 66.9% and 87.8% for SC and NFT, respectively in WS-2 and 70.0% and 88.8% for SC and NFT, respectively in WS-3.

4. Discussion

4.1. Water use efficiency

The water productivity in the SC production obtained in our study (13.8 kg m^{-3}) was similar to that found in other studies on conventional lettuce cultivation in Spain (Mila et al., 2008), which is not surprising as both studies were carried out in the same edaphoclimatic area under similar conditions. In the case of NFT, an exhaustive literature search has demonstrated the non-existence of energy quantifications associated to the NFT production in open field. Therefore, to check the reliability and representativeness of our data, our NFT results could only be compared to those observed in other hydroponic systems cultivation on substrate experiences. In this sense, water productivity values for NFT (36.4 kg m^{-3}) were slightly lower than those observed for hydroponic greenhouse lettuce production in Arizona, about 50 kg m^{-3} (Barbosa et al., 2015). In fact, this makes sense as water productivity obtained in lettuce greenhouse production can increase water productivity by 28% compared to open field cultivation (Romero-Gómez et al., 2014).

In comparison to other studies carried out on lettuce, our study showed similar results for land productivity by year to other research studies performed in the SC production in Spain (Romero-Gómez et al., 2014) and Italy (Bartzas et al., 2015) and for hydroponic system production of baby leaf varieties cultivated in greenhouse under a floating system (Castoldi et al., 2011).

4.2. Energy consumption and potential actions for reductions

In WS-1, the specific energy was 17% higher in the NFT production than in the SC production. This is an interesting result, as the excellent weather conditions in SE Spain make it possible to produce lettuce in outdoor NFT production with a slight increase of energy consumption per production unit.

Results obtained by Barbosa et al. (2015) showed a great contrast between hydroponic greenhouse and conventional lettuce production, 90 MJ kg^{-1} $year^{-1}$ against 1.1 MJ kg^{-1} $year^{-1}$. The fact was that this experiment was carried out under greenhouse conditions, which significantly increased energy consumption. In our case, NFT lettuce production was carried out outside without using a greenhouse and hence it reduced the specific energy considerably (4.23 MJ kg^{-1} $year^{-1}$).

Overall, the study showed, regardless of the cultivation system, that plantlets production and electricity were the two main energy consumptions in lettuce production in the SE of Spain. In the SC production, the electricity consumption was mainly off-farm (20.6%) used to transport the water from the sources to the supply point of each farm. In the NFT production, electricity for irrigation was mainly on-farm (34.7%). Therefore, the strategies to significantly reduce the energy consumption must be different in

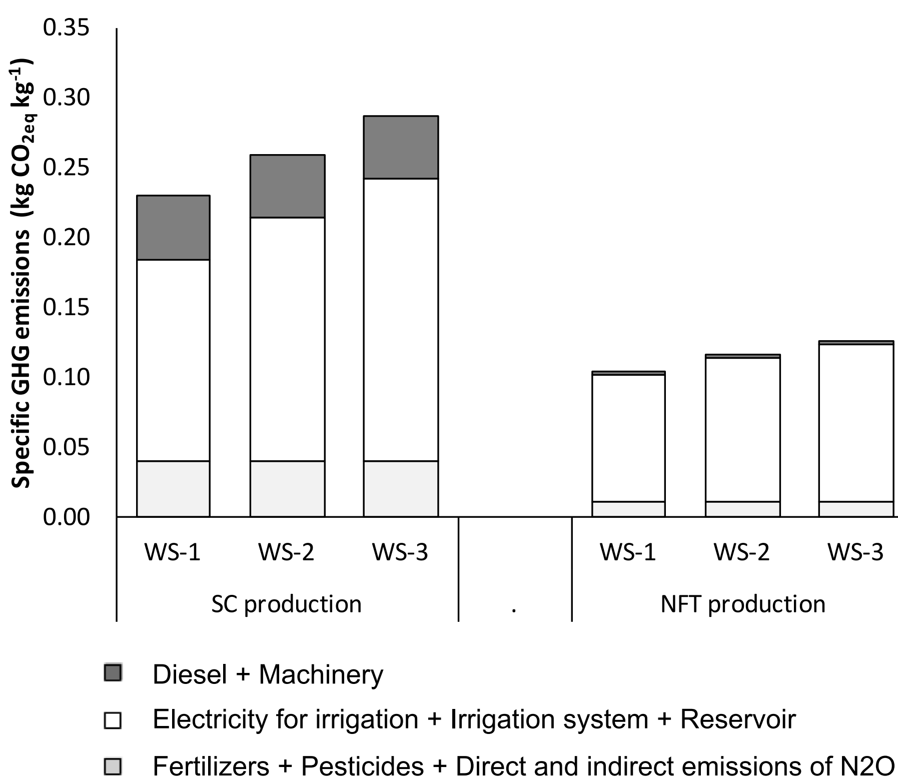


Fig. 4. Specific GHG emissions (kg CO_{2eq} kg^{-1}) for SC and NFT lettuce production in the three scenarios (WS-1, WS-2 and WS-3).

each cultivation system, since they take place in different points of the productive chain. The potential actions to significantly reduce energy consumption in SC production should therefore be performed outside commercial horticultural farms, mainly by reducing the energy associated to plantlets production as the nursery stage takes place outside the farms in the Mediterranean basin; by improving efficiency of the pumping system through real time monitoring to improve the irrigation communities water management (Soto-García et al., 2013a); and by promoting energy audits in the irrigation communities to propose corrective measures on energy savings (Rocamora et al., 2013), among others.

However, the potential actions to reduce energy consumption in NFT production can also be carried out on-farm where the electricity for irrigation was mainly associated to on-farm practices with an energy share of 83.8% of the total energy being attributed to electricity. In this case, actions to significantly reduce energy consumption should deal with the use of alternative technologies for renewable electricity generation aimed at reducing direct energy consumption. In this respect, several studies about the use of solar photovoltaic electricity have been promoted as an alternative to reduce hydroponic systems' environmental impact (Kaldellis et al., 2009; Marrou et al., 2013; Rothwell et al., 2016).

4.3. GHG emissions mitigation

Whilst yield in the NFT production was 4.8 times higher than in the SC production (Table 1), GHG emissions were only 2.2 times higher (Table 6) and specific GHG emissions were 2.1 times lower for the NFT production (25,724 kg CO_{2eq} ha^{-1} and 0.11 kg CO_{2eq} kg^{-1} against 11,760 kg CO_{2eq} ha^{-1} and 0.23 kg CO_{2eq} kg^{-1} for NFT and SC respectively). Other studies for lettuce in SC have shown a wide range of specific GHG emissions values; 0.13 kg CO_{2eq} kg^{-1} (Foteinis and Chatzisymeon, 2016); 0.19 kg CO_{2eq} kg^{-1} (Venkat, 2012); 0.20 kg CO_{2eq} kg^{-1} (Rothwell et al., 2016); 0.25 kg CO_{2eq} kg^{-1} (Maraseni et al., 2010). It should be noted that some of the references shown, as is the case of Foteinis and Chatzisymeon (2016) research, also consider the atmospheric CO_2 fixed by the crop. It is therefore noteworthy that, in our study, the CO_2 absorbed by the plants has been considered to be re-emitted to the atmosphere in a short time and hence not considered in the calculations. In the study by Maraseni et al. (2010) the high value can be explained by the consideration of post–harvesting activities such as cooling, refrigeration, cleaning and packaging vegetables in the GHG emissions analysis.

Based on our results, regardless the cultivation system, the options for reducing GHG emissions in lettuce production have to go necessarily through the irrigation set (epigraph 2.2), which included the electricity for irrigation, the irrigation system and the reservoir, accounting for 63% and 86% of total GHG emissions for the SC and NFT production, respectively (Table 6). Other studies in some regions of the Mediterranean basin (although not with NFT production) also concluded that irrigation (electricity and raw materials) is also the primary source of GHG emissions (Bartzas et al., 2015; Foteinis and Chatzisymeon, 2016). Accordingly, any attempt to improve the system efficiency in terms of GHG emissions might focus on reducing the environmental cost for the hydroponic system, for example by using recycled materials or materials with a longer service life and by promoting irrigation powered by an on-farm photovoltaic water pumping system (Moral et al., 2009; Chandel et al., 2015).

As the energy consumption and its associated GHG emissions are mainly attributed to off-farm electricity to produce DS (Fig. 3), a strategy is therefore needed to reduce GHG emissions by improving the energy efficiency of the desalination systems. In fact, the extent to which renewable energy sources progressively replace fossil fuels in the electricity supply systems (Ghaffour et al., 2015), with the consequent relaxing in the water-energy nexus, might partially mitigate the climate impact of agricultural DS use. In this sense, Shahabi et al. (2014) indicated that renewable-energy powered seawater desalination plants can achieve a GHG emissions reduction of up to 90%.

The EU 2030 Framework for Climate and Energy also sets a further binding target that at least 27% of the energy used in the EU by 2030 should be renewable (EC, 2017). Galbete (2013) concluded as a result of his doctoral dissertation that in Spain 100% of electricity generation could be achieved with renewable energy towards the year 2050. Regarding Spain, by the end of 2015 a level of 15.6% of all its energy needs came from renewable energy sources (EEA, 2017) and the contribution from renewable energy to the electric generation mix already reached 38.9% in 2016 (IDAE, 2017). The actions needed by the Spanish government to comply with the EU 2030 Framework for Climate and Energy requirements would mean reducing GHG emissions in the electricity sector by 28.4% and any effort in agricultural practices to reduce energy consumption and GHG emissions may contribute to reducing this figure. Fig. 5 shows the relative impact (%) between specific GHG emissions (kg CO_{2eq} kg^{-1}) with the current "standard" electricity mix factor (0.210 kg CO_{2eq} kWh^{-1}) and the use of renewable energy according to the following potential actions to reduce energy consumption for SC and NFT lettuce production in the three scenarios (WS-1, WS-2 and WS-3) called "low" electricity mix factor, and include: (i) a reduction of 28.4% of the electricity mix factor has been considered in the off-farm electricity to comply with the agreement of the EU 2030 Framework for Climate and Energy, and (ii) photovoltaic solar panels have been considered to produce 100% of the electricity used on-farm for irrigation. The values of specific GHG emissions (kg CO_{2eq} kg^{-1}) have been normalised by the maximum value observed in the WS-3 scenario by SC production with the "standard" electricity mix factor (0.287 kg CO_{2eq} kg^{-1}).

The results in Fig. 5 indicate that the use of renewable energy decreased the GHG emissions by 9% in the NFT production and by 2% in the SC production. It is worth noting that on-farm GHG emissions associated with irrigation in NFT production represented between 49% (WS-3) and 84% (in WS-1) of total electricity for irrigation. However, in SC production those figures only range between 4% (WS-3) and 17% (in WS-1). In the case of off-farm, GHG emissions associated with irrigation decreased 6% in both production systems and for all scenarios (data not shown).

4.4. Irrigated agriculture resilience

A new generation of agricultural system which combines seawater desalination and high-tech irrigation practices is being developed in SE Spain as an adaptive strategy to foster irrigated agriculture resilience as climate change intensifies the water scarcity.

The use of DS in NFT production instead of SC production increases yield, water productivity and energy use efficiency and reduces specific energy and GHG emissions with respect to SC production (only lower values of energy use efficiency and specific energy have been found in SC production in WS-1 (0% of DS). The turning point was found at 29.6% of DS in the blend (Fig. 3a), where all indicators were more favorable to the use of NFT production than SC production.

The paradox is therefore inevitable. If we seek to limit water resources depletion, we must necessarily use non-conventional water sources as DS. However, it should be noted that DS for irrigation is not problem-free. First, the high-energy requirement is still an essential feature of seawater desalination. Moreover, the high GHG emissions linked to the intensive use of energy could

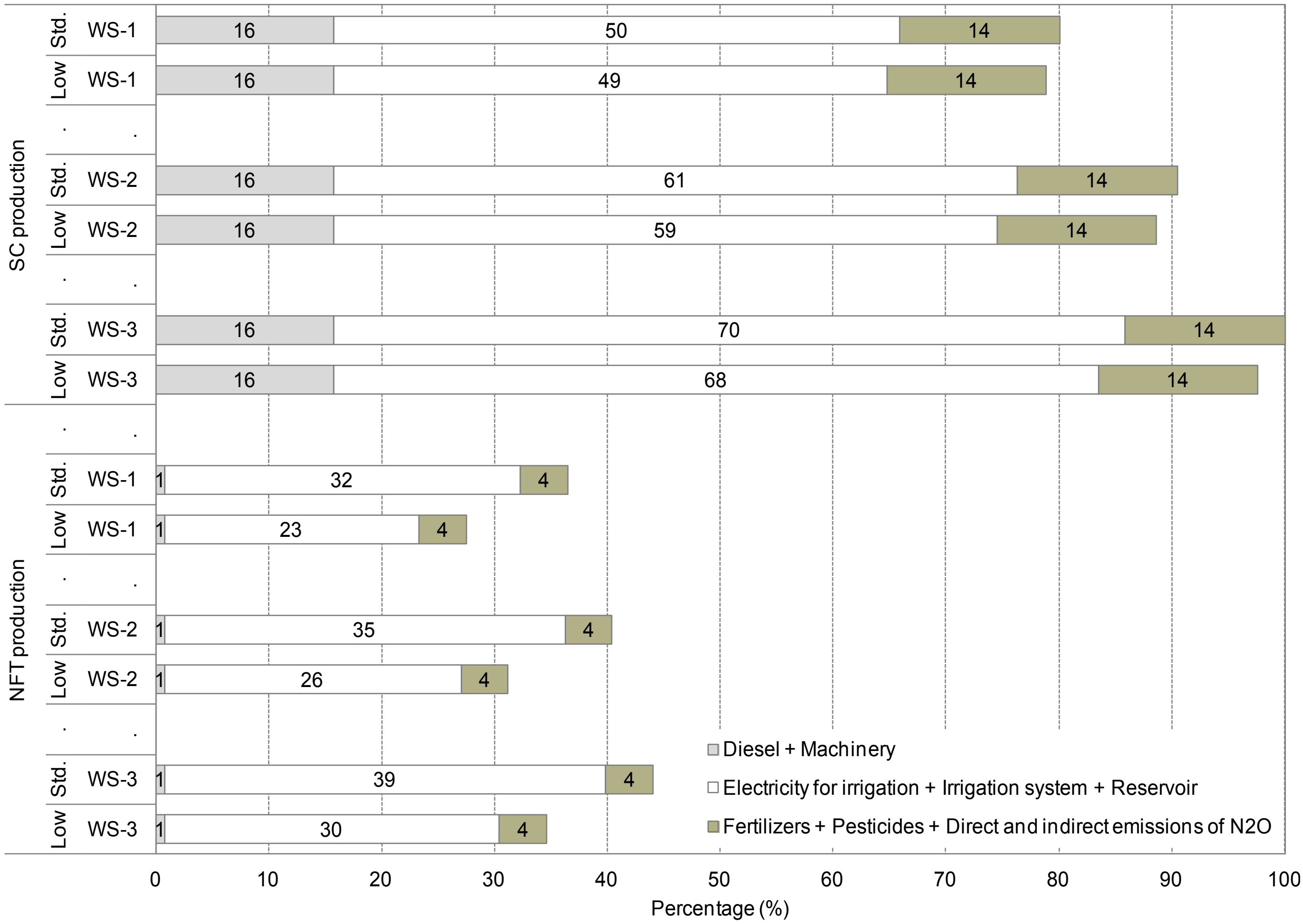


Fig. 5. Relative impact (%) between standard (Std.) and low (Low) specific GHG emissions (kg CO_{2eq} kg^{-1}) for SC and NFT lettuce production in the three scenarios (WS-1, WS-2 and WS-3).

exacerbate climate change (Martínez-Alvarez et al., 2016). In this sense, as has been indicated in the previous section, it would be possible to reduce GHG emissions through the use of renewable energy sources and improve water and energy use efficiencies.

5. Conclusions

This study analyses the water and energy consumption and Greenhouse Gas (GHG) emissions for two lettuce production systems; soil cultivation (SC) and the Nutrient Film Technique (NFT). It also examines the impact of two hypothetical future water supply scenarios (WS) where current water resources are partially or totally replaced by desalinated seawater (DS): WS-1: the current scenario in which 100% of the surface water resources are provided by the Tagus-Segura canal; WS-2: where 50% of the water resources are DS; and WS-3: in which 100% of water resources are DS.

Overall, regardless of the WS scenario, the use of NFT techniques leads to significantly higher energy consumption and GHG emissions than the SC production. However, as yield in NFT systems is also notably higher than in SC production, ratios for specific energy consumption and specific GHG emissions have allowed a more representative analysis of the results. Regardless of the WS scenario, water productivity is always higher for NFT production. However, in the case of specific energy and GHG emissions, only scenarios WS-2 and WS-3 have shown lower specific energy and GHG emissions and higher energy use efficiencies.

The results have shown that, in order to optimise energy in NFT production, efforts must be mainly directed at reducing the on-farm electricity for irrigation using alternative technologies such as renewable electricity generation with solar photovoltaic systems and increasing the efficiency in plantlets production. In the case of SC production, energy should be optimised by increasing the efficiency in plantlets production and reduction off-farm electricity for irrigation improving efficiency of the pumping system in irrigation communities.

In terms of GHG emissions optimisation for NFT and SC production, the system efficiency should be mainly increased by using recycled materials or materials with a longer service life that can reduce the hydroponic or the drip-irrigation systems environmental impact, respectively.

Consequently, DS with hydroponic technology may be a solution for the irrigated agriculture of coastal regions facing persistent water scarcity. However, in view of the high GHG emissions linked to the intensive use of energy, GHG emissions must be reduced through the use of renewable energy technologies and improved efficiency.

In short, under the expected conventional water availability limitations, the use of DS and NFT systems are thus environmentally valuable techniques that may help feed the growing world population.

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