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Environmental impact assessment of local decoupled multi-loop aquaponics in an urban context

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ABSTRACT

Fresh vegetables available on Northern European markets usually originate from a high number of sources. Environmental impacts for these goods typically arise from the resources used in production and the long-distance transport in air-conditioned trucks. As such, environmental impacts are mainly attributed to direct energy consumption, water use and nutrient supply. The aim of this paper was therefore to investigate and evaluate possible solutions to reduce the environmental impacts of vegetables available on urban markets in Northern Europe. We hypothesise that for the production of lettuce and tomatoes in Northern Europe, a 4-step solution, i.e. 1) local production, 2) climate-controlled efficient greenhouses, 3) decoupled aquaponics, and 4) combined building architecture with waste heat and green waste reuse, will enable a low environmental impact. We defined the metropole Berlin as case example, and used simulation results from a proven greenhouse simulator as input to a comparing life cycle assessment of fresh lettuce and tomato. The assessment included a list of 12 midpoint environmental impact categories, e.g. global warming potential with 100 year horizon (GWP_{100}; kg CO_2 eq.), depletion of fossil fuel reserves (FRS; kg oil eq.), and water use (WCO; m^3 water). Most impact categories decreased systematically when increasing the complexity of the local vegetable production. Compared to the mix of vegetables from different locations available on the market, the complete 4-step solution reduced WCO from water consumption to water saving: i.e. from 14.2 L or 3.3 L to −10.1 L or −0.21 L per package of 500 g tomatoes or 150 g lettuce, respectively. GWP_{100} and FRS were below the values of the available market mix, e.g. GWP_{100} decreased with 8.7% in tomatoes and 49.9% in lettuce. In conclusion, with the right set-up, local vegetable productions in urban regions can surpass the imported mix on environmental performance in Northern Europe.

1. Introduction

Aquaponics is the combined cultivation of fish in recirculating aquaculture systems (RAS) and plant hydroponics (HP). In these combined systems, two products are produced simultaneously with almost the same amount of resource input when the system is optimally balanced (Goddek and Körner, 2019). Additional advantages are synergistic effects with substantially increased crop production that have been observed in some crops (e.g., in lettuce) (Delaide et al., 2016; Goddek and Vermeulen, 2018), decreased energy use (Körner et al., 2017), and a lower environmental impact compared to production in independent systems (Ghamkhar et al., 2020). However, common single-loop aquaponic systems (CAPS) often fail to provide the necessary quantity and composition of nutrients to the HP system (Goddek et al., 2019). Significant amounts of crop produced in CAPS are also often of lower quality or gain only a reduced yield. The improvements of various environmental impacts, such as eutrophication, water usage, and geographic footprint (Cohen et al., 2018), are commonly quantified for CAPS in a given environment. Compared to CAPS, where RAS water is directly recirculated via the HP subsystem, decoupled aquaponic systems treat the water by adjusting the quantity and quality to the actual crop demands. Since not all nutrients required by the crop are available from the RAS subsystem (Kloas et al., 2015), decoupled aquaponic

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Abbreviations

ALU	agricultural land use
AP	aquaponics
CAPS	coupled single-loop aquaponics systems
DAPS	decoupled multi-loop aquaponics system
DLI	daily light integral control
CLCA	Consequential life cycle assessment
FRS	fossil resource scarcity
FEP	freshwater eutrophication
GWP_{20}	global warming potential with a 20-year horizon
GWP_{100}	global warming potential with a 100-year horizon
HP	hydroponic cultivated plants
HCT	human carcinogenic toxicity
HNT	human non-carcinogenic toxicity
LCA	Life cycle assessment
MRS	mineral resource scarcity
MGS	moving gutter system
NFT	nutrient film technique
ODP	ozone depletion
RAS	recirculating aquaculture system
TAP	terrestrial acidification
WCO	water consumption
WSC	Water scarcity

Table 1
Simulation model scenarios used for the comparing LCA study with hydroponics (HP), decoupled multi-loop aquaponics (DAPS); letter code in scenario: T (tomato); L (lettuce); R (rooftop, combined building); + (active energy transfer).

Scenario	Crop	Location	System	Climate Control	Building situation	Usage	Type
T_HP_ES	Tomato	ES	HP	Semi	Self-contained	Benchmark	HP
T_HP_IT		IT					
T_HP_NL		NL		Full			
T_HP_DE		DE					
T_HP_MIX		ES, IT, DE, NL					
$T\_HP\_DE_{local}$		DE Berlin	DAPS			Case	
T_AP_DE							DAPS
T_HP-R_DE			HP		Roof-top		HP-R
T_HP-R+_DE							HP-R+
T_AP-R_DE			DAPS				DAPS-R
T_AP-R+_DE							DAPS-R+
L_HP_ES	Lettuce	ES	HP	Semi	Self-contained	Benchmark	HP
L_HP_IT		IT					
L_HP_NL		NL		Full			
L_HP_DE		DE					
L_HP_MIX		ES, IT, DE, NL					
$L\_AP\_DE_{local}$		DE Berlin	DAPS			Case	
L_AP_DE							DAPS
L_HP-R_DE			HP		Roof-top		HP-R
L_HP-R+_DE							HP-R+
L_AP-R_DE			DAPS				DAPS-R
L_AP-R+_DE							DAPS-R+

systems, showing great advantages, have been developed (Goddek, 2017) and can be economically viable (Baganz et al., 2020). In modern decoupled aquaponic systems (DAPS), multiple loops are used for water treatment, and additional nutrients are dosed into the HP system to maintain high-quality crop production (Goddek and Keesman, 2018). Closed loop systems tend to accumulate salts; thus, a periodic refreshing of the HP system and an environmentally harmful discharge of the used nutrient solution is needed (Savvas et al., 2008). On the other hand, an improved nutrient balance in HP increases the production amount and the share of high-quality produce, e.g., lettuce with a higher dry weight fraction (Goddek and Vermeulen, 2018) or tomato with less blossom-end rot (Delaide et al., 2019; Schmautz et al., 2016). Since the environmental impact assessment allocates the total resource use to the total quantity of products, this in turn reduces the total environmental impact of a product unit.

In aquaponics, some resources can be allocated to both vegetables and fish. The major environmental burden of fish production in RAS consists of fish-feed and wastewater and is largely independent of location. For greenhouse-produced vegetables (i.e., LCA-term: farm), the most significant environmental impact of the products available in the supermarket (i.e., LCA-term: gate) is often fossil fuel use either in the form of heating or transport, depending on the location of the farm (cradle) and the distance to the consumer (gate) (Pluimers, 2001).

In the European Union market, Spain, the Netherlands and Italy are the three largest exporters of fresh vegetables (De Cicco, 2019). Despite the long distances of Southern European produce to the market, the high heating load in Northern European greenhouses greatly overshoots the energy-related environmental footprints of greenhouse produce. However, modern and highly insulated greenhouse systems have greatly reduced the environmental impact of fossil energy consumption (Cuce et al., 2016). The modernisation of greenhouses with a package of high-tech equipment, such as combined heat and power units, heat pumps, underground seasonal and daytime energy storage systems, and air treatment units, such as those used in the closed or semi-closed greenhouse concepts (Opdam et al., 2005), has strongly reduced energy consumption (Cuce et al., 2016; Gruda et al., 2019). These new technologies enable local production of vegetables all year round in almost all climatic zones (Ntinas et al., 2020).

The objective of this study was to investigate and evaluate possible solutions to reduce environmental impacts of vegetables produced in greenhouses in Northern Europe (Germany, the Netherlands) to or below the levels in Southern Europe (Italy, Spain). For the given case of Berlin (Germany), with a mild temperate climate, i.e., Cfb after the Köppen classification, the environmental impact of local, year-round produced greenhouse vegetables such as lettuce or tomatoes can be reduced by technology alone (Vadiee and Martin, 2012). The installation of modern DAPS can further improve the environmental impacts per unit of production, while additional roof-top farming can yield in

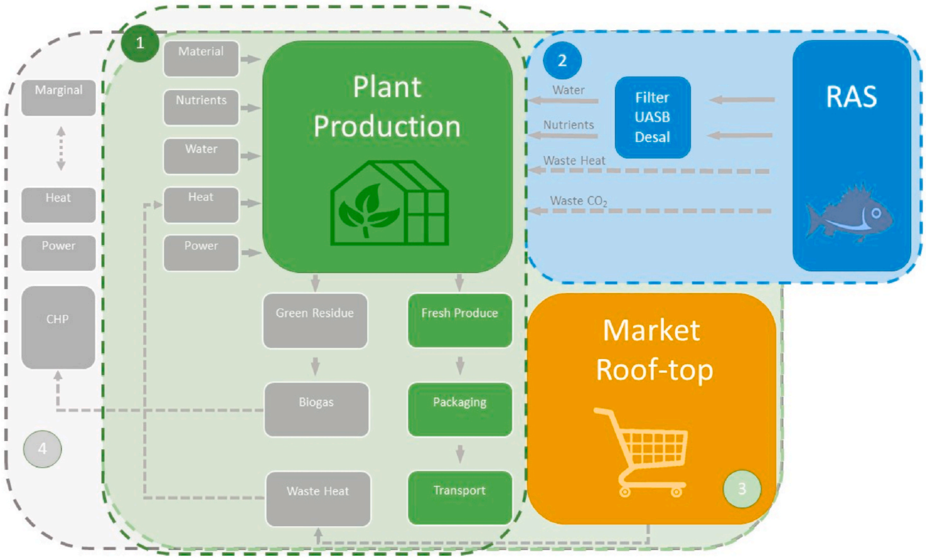

Fig. 1. Overview of the life cycle system and its borders, with main plant production (1), RAS system with aquaponics combination (2), combined market-roof (3) and system expansion (4).

Table 2
Core cultivation settings for lettuce and tomatoes in greenhouse production in Germany (DE), Netherlands (NL), Italy (IT) and Spain (ES).

	Lettuce				Tomato			
	DE	NL	IT	ES	DE	NL	IT	ES
Set-point heat; °C	16–17				18–19			
Set-point vent; °C	17–18				19–20			
Set-point RH; %	80				80			
Set-point DLI; mol day^{-1}	10		–		10		–	
Cultivation; months year^{-1}	11.5		9		11.5		9	

energy savings (Torres Pineda et al., 2020). The combination of DAPS in an urban environment such as Berlin with the broad possibilities of reusing waste heat from industrial or private households is thus likely to outperform imported products in some categories of the environmental impacts, such as climate change. Therefore, it was hypothesised that a 4-step approach with 1) local production systems, 2) high technology greenhouses, 3) DAPS, and 4) waste heat re-usage and biogas will allow an environmentally friendly production of greenhouse vegetables such as lettuce and tomatoes in Northern Europe. Therefore, for the first time this study examines the environmental impact of fresh lettuce and tomato from cradle to gate with these preconditions. Three main scenarios were analysed for both crops: 1) produced locally in HP, 2) produced in DAPS, and 3) produced in rooftop DAPS using waste heat. All cases were compared to benchmark scenarios. As a benchmark, mixtures of lettuce or tomato available in Germany were used, which were produced in and imported from Spain (El Ejido, Almería), the Netherlands (Westland region), Italy (Rome area) or in different locations in Germany. The products were transported to the gate, defined as a supermarket in the centre of Berlin. An extended greenhouse and aquaponics simulator was used as the data source for the four scenarios (Goddek and Körner, 2019; Körner and Hansen, 2012). The simulation results were then used as part of the input for a follow-up study on life-cycle assessment (LCA).

2. Materials and methods

2.1. Functional unit and LCA scope

A comparative LCA of tomato or lettuce produced in DAPS or produced in HP was performed with different benchmark scenarios (Table 1). Four producing countries of both tomato and lettuce (Spain, Italy, the Netherlands and Germany), including their transports to the final gate, were analysed. The main benchmark was calculated from a mix of data from these four countries present on the German market (see T_HP_MIX, L_HP-MIX; Table 1). For HP tomatoes or lettuce, separate analyses were conducted. Eventually, a normalised mixture of tomatoes or lettuce, available in the supermarket in Berlin (i.e., the gate) and based on the lettuce/tomato origins from years 2009–2018 (Behr, 2019), was analysed. German imports of fresh tomatoes came mainly from the Netherlands (58% of value) and Spain (25% of value) (Workman, 2020a), and then from Belgium, Morocco and Italy (Behr, 2019). Lettuce was imported from Spain (39% of value), Italy (25% of value), and the Netherlands (16% of value) (Workman, 2020b). For tomatoes, the production in Belgium and Morocco, with 5.0% and 6.6% of the fresh tomatoes consumed in Germany, was attributed to the Netherlands and Spain, respectively. The remaining 3.7% was distributed evenly among the four countries of origin. The four countries of Italy, Spain, the Netherlands and Germany accounted for 90% of the lettuce consumed in Germany. The remaining 10% were distributed among these four countries at parity.

In this study, the combination of two fully functional food production systems with RAS and HP greenhouse production was modelled. The aquaponic system was designed as a DAPS four-loop system (Goddek, 2017). The size of the HP greenhouse was set at 5000 m^2. The RAS system was predicted for tomatoes and lettuce for a location in Berlin using the method presented by Goddek and Körner (2019) that resulted in 180 m^3 or 112 m^3 for tomato and lettuce, respectively.

When allocating the environmental impacts in complex systems between products and co-product, according to the ISO standards (ISO14044; ISO14049), the first option is to avoid allocation by making use of a subdivision or to expand the systems investigated (Fitwi, 2012). Therefore, in this paper system expansion was used (Weidema, 2003; Weidema and Schmidt, 2010). System expansion as part of consequential LCA (CLCA) is often used in complex systems with co-products, as it is the case in modern greenhouse horticulture and in aquaponics (Boxman et al., 2017). In food systems, CLCA is increasingly used as favourite method (Brandão et al., 2017; Gava et al., 2018).

Capital goods (e.g., roads and maintenance) were included in the majority of the background data (i.e., data for processes that are not part of the immediate product chain, such as electricity production, and packaging), while infrastructural processes were excluded. The functional units were 0.5 kg of packed tomatoes or 1 bag of sliced lettuce

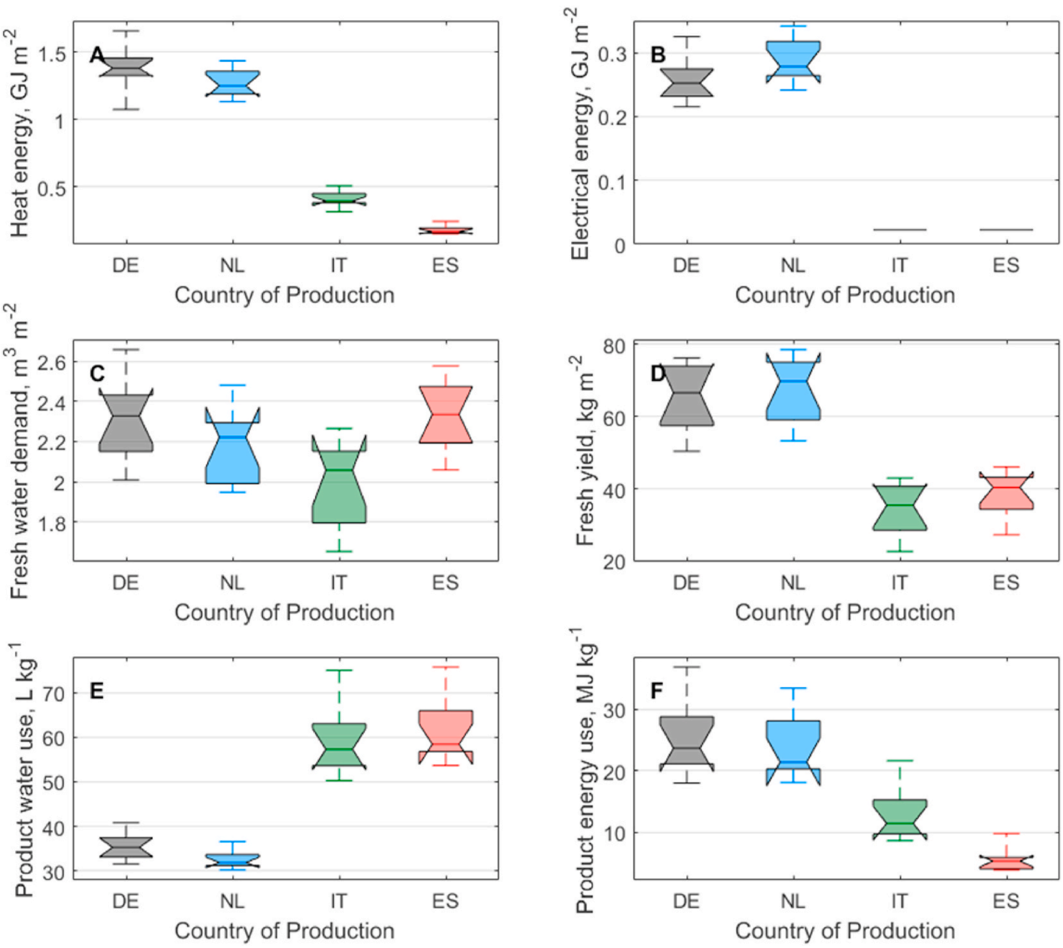

Fig. 2. Simulation results for hydroponically produced tomatoes in four locations (Germany, DE; the Netherlands, NL; Italy, IT; Spain, ES) for one year simulated over 10 years (2009–2018) with heat energy consumption (A), electrical energy consumption for supplementary lighting (B), fresh water demand (C), fresh crop yield (D), product water use (E), and product energy use (F).

(150 g), available on the supermarket shelf in the centre of Berlin, which was defined as the gate. In this analysis, the cradle-to-gate principle was used; i.e., no complete life cycle including waste management was performed.

2.2. Process boundaries

The boundaries are shown in Fig. 1. The lower boundary of the analysis was the production of raw material, such as the production of seeds. The upper boundary was the delivery of products (tomato, lettuce) to the gate. System expansion was used to include the consequences of, e.g., the green waste by transformation to biogas. Unless otherwise stated in the Inventory section, data from the Ecoinvent 3 database (ver 3.6; consequential approach; Ecoinvent, 2019) were used and, if necessary, adapted to the specific case.

This LCA ended at the environmental impact midpoint categories, i.e. no weighing or normalisation was performed. To address the major impacts of horticultural crop production with its known high consumption of energy, nutrients and water, we selected the most suitable LCA midpoint impact categories from three sources. The ReCiPe 2016 method (Huijbregts et al., 2017; ver. 1.1, H for Europe) was used for resource scarcity (FRS; kg oil eq.), water consumption (WCO; m^3), freshwater eutrophication (FEP; kg P eq.), mineral resource scarcity (MRS; kg Cu eq.), stratospheric ozone depletion (ODP; kg CFC-11 eq.), land use (ALU; m^2a crop eq.), human carcinogenic toxicity (HCT; kg 1,4-DB eq.), human non-carcinogenic toxicity (HNT; kg 1,4-DB eq.), and terrestrial acidification (TAP; kg SO_2 eq.). Global warming potential (GWP; kg CO_2 eq.) was analysed with two different time horizons of 20 and 100 years (GWP_{20} or GWP_{100}, respectively) based on the latest IPCC method (climatechange2013.org) relevant for Greenhouse Gas Protocol, ISO14067 and PAS2050. Water scarcity (WSC, m^3) published by Berger et al. (2014) was applied. Calculations were performed with the software tool SimaPro (ver. 9.1.1, PRé_Consultants, Amersfoort, Netherlands).

2.3. Inventory

The investigations included the three main components of the system: RAS and HP, as well as roof-top installation where applicable (see Table 1). Technical processes of both HP lettuce and tomato production where included, with seed production, plant cultivation, harvest and packaging, internal and external transport, plastic for wrapping, the production of plastic foil for packaging and of cardboard packaging boxes, etc. The life cycle inventory of the main processes is provided in Supplementary Table 1. Sources of data and the main processes are summarised in Supplementary Table 2.

To better compare the main environmental burden of greenhouse HP production, a natural gas driven heat-power co-generation unit with 200 kWe (allocation exergy) was used for heating according to the global approach (Ecoinvent, 2019) and was independent of the greenhouse location. In the DAPS-R, HP-R, DAPS-R+ and HP-R+ scenarios (see Table 1), heat demand was partly covered by the waste heat of the connected industrial supermarket building. The energy consumed in the supermarket was completely attributed to the supermarket. The biogas produced from tomato green waste was burned in a combined

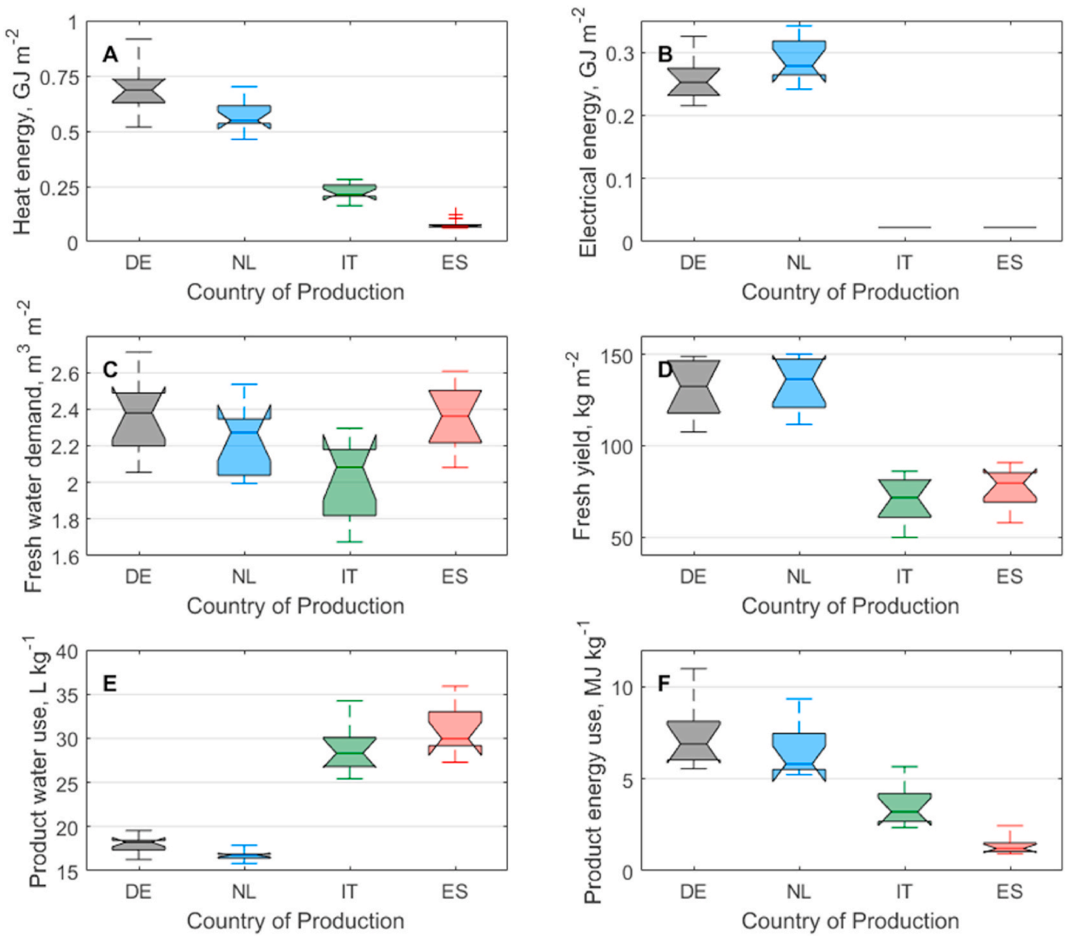

Fig. 3. Simulation results for hydroponically produced lettuce in four locations (Germany, DE; the Netherlands, NL; Italy, IT; Spain, ES) for one year simulated over 10 years (2009–2018) heat energy consumption (A), electrical energy consumption for supplementary lighting (B), fresh water demand (C), fresh crop yield (D), product water use (E), and product energy use (F).

heat-power co-generation unit (Jenbacher GE, Type 2) with an electricity share of 39.1% and a thermal share of 46%. Heat production was used as input for the energy mix, while replacing coal energy that was identified as a marginal heat resource according to the consequential LCA theory. These shares were then attributed to HP tomato production as an avoided product (see Fig. 1). For lettuce production, no green waste was assumed. In the Netherlands and Germany, the production of biogas from system waste was modelled using Ecoinvent 3.6 processes, where the leakage of methane and dinitrogen monoxide was reduced to 0, i.e., a 100% sealed biogas reactor was assumed. No biogas production was assumed for Spain and Italy. For electricity, country-specific energy mixes with medium voltage were used (Ecoinvent, 2019). For HP, fertiliser with NPK plus micronutrients was used, which is a typical mix used for tomatoes (De Kreij et al., 1997), and the Hoagland solution was used for lettuce. N was modelled as ammonium nitrate, P as triple superphosphate, and K as potassium chloride.

For tomatoes and lettuce in greenhouse cultivation, a production system either in a modern greenhouse heated with biogas and exhaust heat for Berlin, or in a semi-climate-controlled greenhouses in Spain and Italy was used. For both crops, the CLCA data based on the studies of Stoessel et al. (2011) was used and adjusted to the specific conditions of each system (yields, energy consumption, etc.) of the current study. Crop production in Germany and the Netherlands was assumed to proceed throughout the year with ongoing planting of lettuce and replanting of young tomato plants in weeks 51 and 52 of the year (Table 2). In Spain and Italy, a summer break of 92 days for HP greenhouse production was assumed. During this period, the German product mix was covered from Germany and the Netherlands. For all scenarios, lettuce in hydroponics was produced using nutrient film technique (NFT) and moving gutter systems (MGS) with data reported by Körner et al. (2018).

As a substrate for hydroponic production in tomatoes in Spain and Italy, expanded perlite was used. For tomato production in the Netherlands and Germany, stone wool was used and calculated similar to stone wool insulation material (Schmidt et al., 2003). For DAPS, tomatoes were grown in NFT in a stone wool cube with an inert fleece underneath (Ramírez et al., 2019). Fleece was modelled as viscose fibre from the global market. Dinitrogen monoxide (N_2O) was added as a direct supplement of 0.127 g kg^{-1} in both DAPS and HP cultivations (Aigner, 2003). It has been assumed that transplant production is performed locally within countries using greenhouses. Seed production was implemented as regular plant production of tomato and lettuce up to the seed-bearing stage, and transplants were produced in nursery greenhouses for 21 and 14 days for tomato and lettuce, respectively.

For local transport, location-independent standard values for tractors and trailers (including diesel consumption, construction, maintenance, shed, etc.) were used. The same technology was used in all countries. Transport was included using standard values for a EURO5 transport truck of 7.5–16 t for short-distance transport (<50 km), of 16–32 t for medium-distance transport (50–200 km), and EURO5 >32 t for long-distance transport, including international transport (>200 km). For all trucks, cooling was realised by means of a combined electricity/diesel driven engine (TS600e, Thermo King). The transport and packaging losses of the products (tomato and lettuce) were considered to be

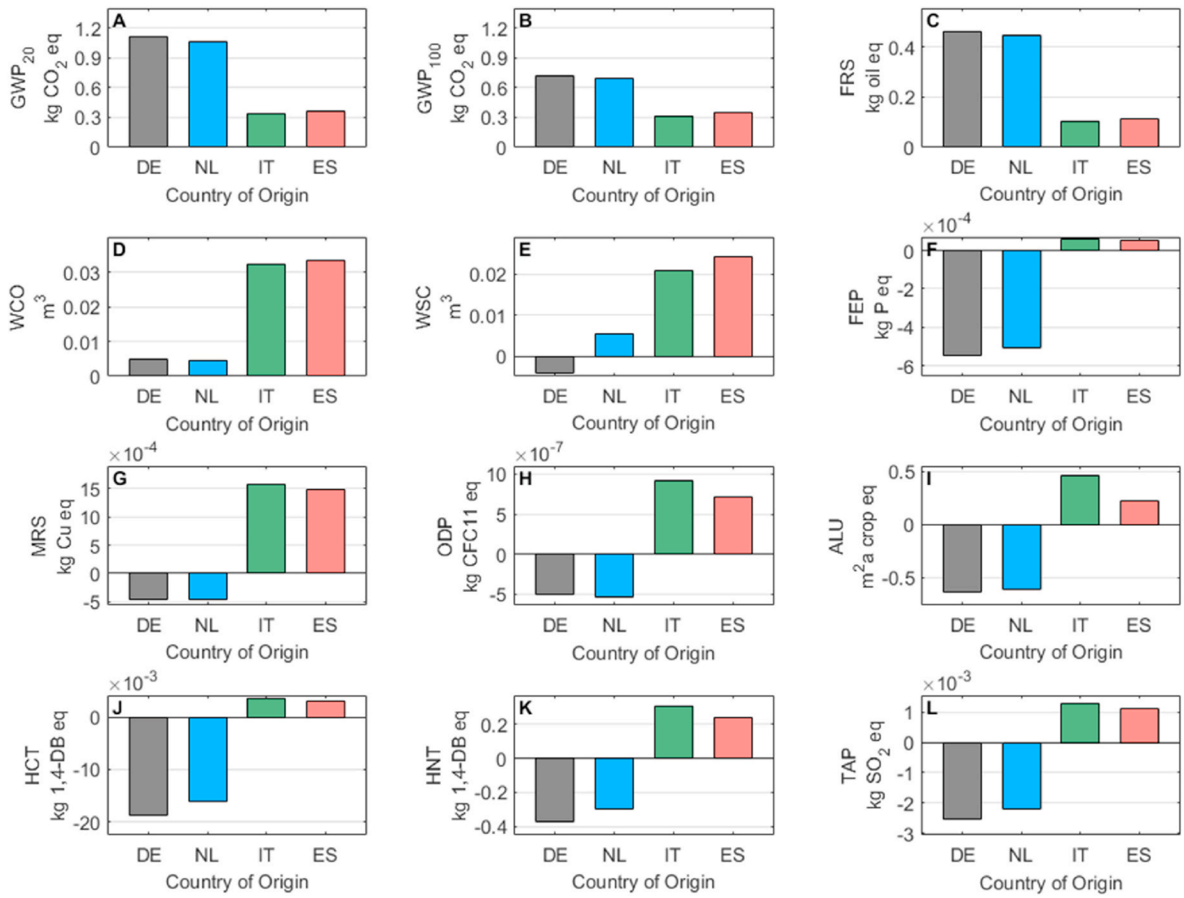

Fig. 4. Comparing LCA for 500 g of packed tomatoes as available at the Berlin supermarket with different origins as Germany (DE), the Netherlands (NL), Italy (IT) and Spain (ES) for 12 LCA impact categories with their indicators.

7.5% in long-distance transport from Italy and Spain to Berlin, 3.5% from the Netherlands to Berlin, and 2% within Germany. Waste management was included in the modelling for processes demanding waste treatment.

3. Theory and calculation

3.1. Simulator

A numerical simulation model of HP and DAPS systems in greenhouses (Goddek and Körner, 2019; Körner and Hansen, 2012) was used to compare virtual production of lettuce or tomato for all scenarios. Simulations were performed with 5-min time-step and average over 1 h for 10 independent yearly scenarios for the years 2009–2018. Location specific hourly climate data were used as model input (MeteoBlue.com). For direct comparison between locations and cultivation systems (i.e., HP and DAPS), basic theoretical greenhouse structures were created. Multi-span glass greenhouses configured according to commercial practice with passive heating and ventilation (Körner et al., 2008), and climate set-points as used in commercial practice were used (Table 2). Supplementary lighting was installed in Germany and the Netherlands (no supplementary lighting in Italy and Spain) with LED lamps installed under the roof above the crop with an installed capacity of 80 W m^{-2} power and an output of 192 μmol m^{-2} s^{-1}. Light was controlled dynamically with set points generated using a daily light integral (DLI, mol m^{-2} d^{-1}) (Körner et al., 2006).

3.2. Crop growth

Crop growth and yield were simulated with a photosynthesis-driven growth model based on a large collection of studies found in the literature and summarised by Körner (2004). A commonly applied biochemical-based leaf photosynthesis model was used as a basis (Yu et al., 2020), while crop-specific parameters for lettuce and tomatoes were used. Fresh mass and yield were calculated from simulated dry weight with a fraction dry matter of 6.0% and 4.8% for lettuce and tomato, respectively. The standard model incorporated the higher fresh yield of DAPS in lettuce with a conservative approach using an increase fraction of 0.25, while fractions of 0.1 and 0 were also tested in a sensitivity analysis. The ratio of discarded tomato fruits due to quality problems was set to 5% and 1% in HP and DAPS, respectively. Sensitivity analysis on the influences of crop production efficiency in each of the four producer countries was done for tomato as example. For each producing country, the total influence on the market available tomato mix was analysed with 25%, 50%, 75% and 100% production efficiency.

3.3. Urban context scenarios

The greenhouses were either placed on the ground or on the roof of a supermarket. When set on the ground, energy exchange to the floor was calculated from the temperature difference between the soil and greenhouse floor. For roof-top placement, two scenario options were used: passive and active thermal energy transfer (denoted with 'R' or 'R+' in Table 1). In the passive scenarios, heat exchange was calculated according to the supermarket roof, while with active heat transfer, the exhaust heat from refrigerated cooling rooms in the supermarket was used as supplementary air heating in the greenhouse when needed. For

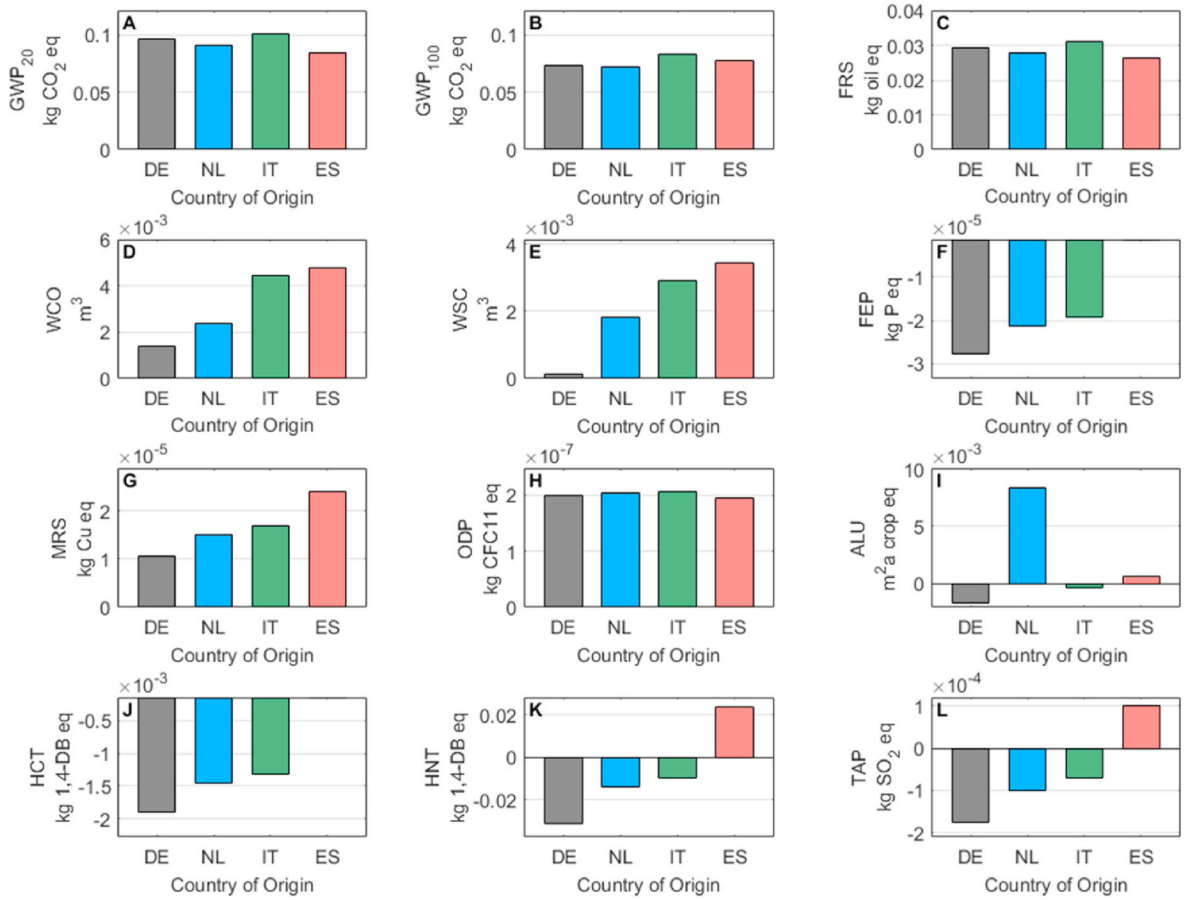

Fig. 5. Comparing LCA for 150 g of packed lettuce as available at the Berlin supermarket with different origins as Germany (DE), the Netherlands (NL), Italy (IT) and Spain (ES) for 12 LCA impact categories with their indicators.

Table 3
Comparison between 150 g lettuce at production site in DAPS with yield increase of 0%, 10% and 25% (i.e. standard) compared to local produced lettuce in HP with the main influenced impact indicators.

	Cultivation Method				DAPS to HP Reduction (%)		
	DAPS			HP	–		
DAPS related yield increase →	0%	10%	25%	0%	0%	10%	25%
GWP_{20}	0.083	0.075	0.066	0.089	6.8	15.3	25.4
GWP_{100}	0.060	0.055	0.048	0.066	8.4	16.7	26.7
FRS	0.025	0.023	0.020	0.027	5.9	14.4	24.7
WCO	−0.400	−0.364	−0.320	1.309	188.1	177.0	164.8
MRS	−0.005	−0.005	−0.004	0.010	309.3	273.7	238.5
ODE	0.138	0.126	0.111	0.189	26.8	33.4	41.4

the latter case, 10% of the supermarket floor area was assumed with refrigerated chambers with a constant temperature of 6 °C. The rooms were controlled with an active cooler based on the ANSI/AHRI Standards 1200 (I-P) using R410A as the refrigerant and an isentropic compressor efficiency of 65%. The energy released in the condenser was obtained and led to the greenhouse via isolated pipes, i.e., no transport heat losses were assumed.

Single components of DAPS, i.e., RAS, desalination unit, and sludge bioreactor, were modelled and optimally sized (Goddek and Körner, 2019). The RAS system was physically located in the same air system as HP, which enabled heat and CO_2 exchanges between the two main sub-systems of aquaponics (Körner et al., 2017).

4. Results and discussion

4.1. Differences in production origin

The market available fresh produce originates from various geographical sources. Production in Northern Europe usually uses more energy for heating while South European vegetable production is highly water consuming (Fig. 2, Fig. 3). For instance, for tomatoes produced in Germany, heating has a total consumption of 1.38 GJ m^{-2} per year, which is more than eight times higher than that in Spain. Electrical energy in Spain and Italy only uses general electrics, such as pumps, while a minimum DLI is maintained for electrical lighting in the Netherlands and Germany. Hence, product energy use in Northern Europe was more than four times higher than that in Spain and Italy, which is in agreement with earlier reporting (Antón et al., 2012; Körner et al., 2008; Torrellas et al., 2012). In contrast, water consumption is relatively higher in Southern Europe. Consequently, Spain and Italy have lower product energy use, despite the lower yields, but a higher product water use of 70–90%.

The main differences between Northern and Southern European greenhouse production can thus be identified by higher energy use for heating and supplementary light in the North (using the current carbon-bound energy mix) and higher water consumption in the South, where desalinated sea water or unsustainably exploited groundwater often is used (Custodio et al., 2019). Substantially higher use of energy for tomato production in Northern Europe leads to a lower global warming potential and fossil resource scarcity potential for Spain and Italy (Fig. 4,

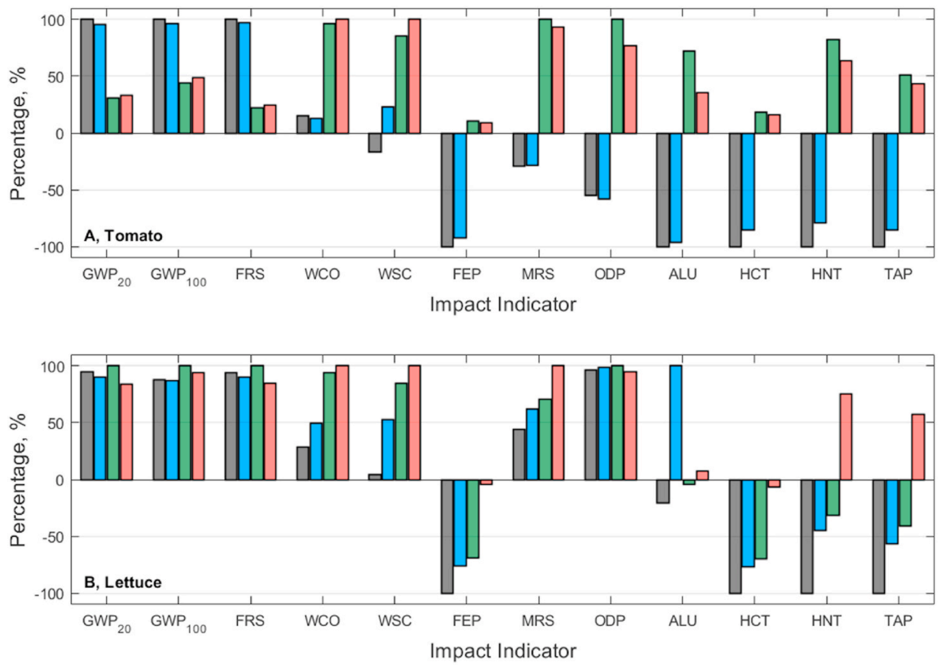

Fig. 6. Percentage from absolute maximum case (100%) of 12 LCA impact categories with their indicators for availability of (A) 500 g of packed tomatoes or (B) 150 g of lettuce in Germany (DE) with different origins as Germany (DE, black), the Netherlands (NL, blue), Italy (IT, green) and Spain (ES, red).

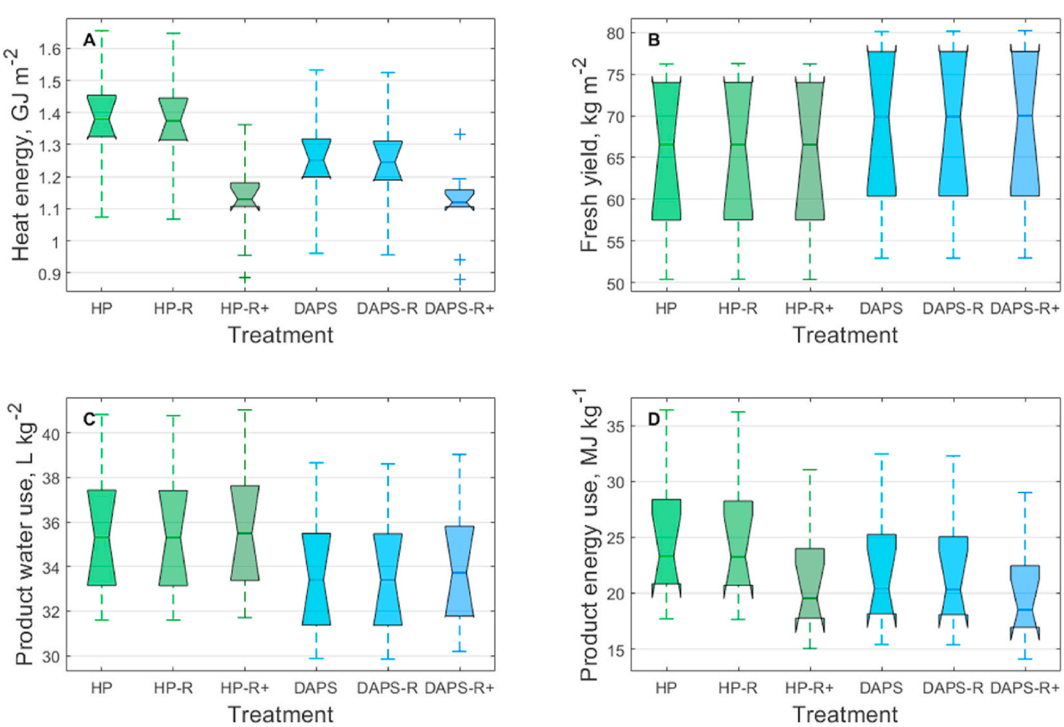

Fig. 7. Simulation results for one-year tomato fruit production in four production systems of hydroponics (HP), decoupled aquaponics (DAPS), decoupled aquaponics on a roof with passive energy exchange (DAPS-R), decoupled aquaponics on a roof with active energy exchange (DAPS-R+) in Berlin (Germany, DE) with heat energy consumption (A), fresh crop yield (B), product water use (C), and product energy use (D).

Fig. 5). As such, e.g. GWP_{100} for Spanish or Italian packed tomatoes in German supermarkets is approximately 44% and 48% of local produce, respectively.

4.2. Combined systems

One advantage of DAPS is the recycling of nutrients, and environmental impact reductions can partly be attributed to this (Monsees et al., 2019). A significantly higher lettuce yield of 25% compared to HP was incorporated in DAPS, which was below reported increase possibilities of 35% and more (Delaide et al., 2016; Goddek and Vermeulen, 2018). This had a clear impact, while the general picture does not change (Table 3). Thus, in terms of environmental impact, locally producing greenhouse vegetables with DAPS is the best method,

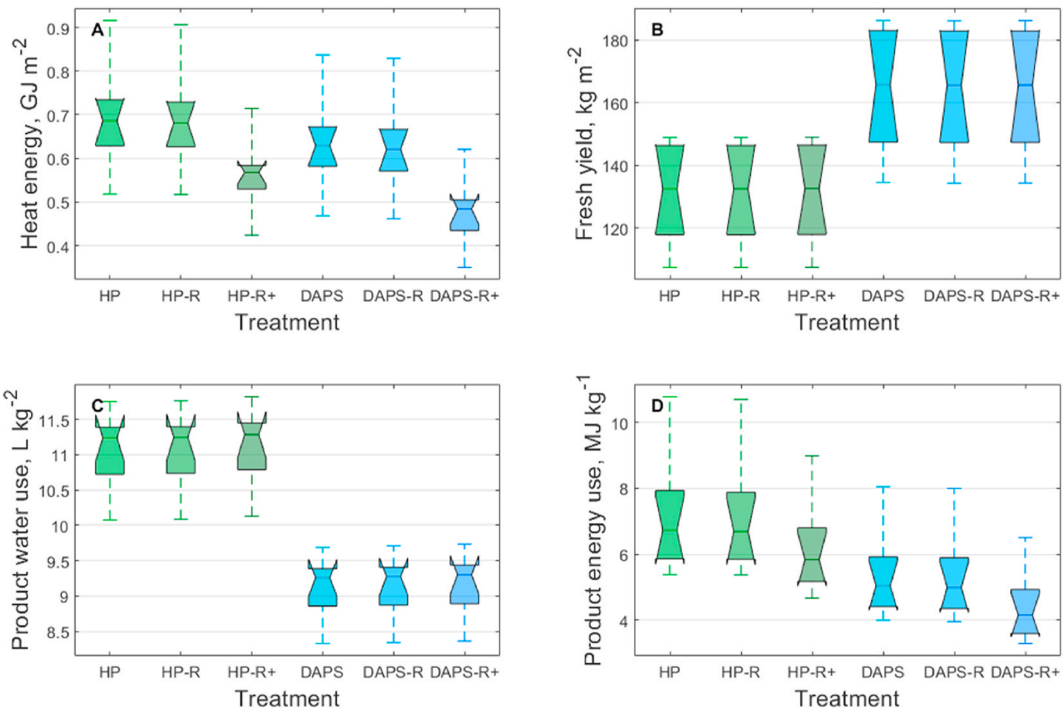

Fig. 8. Simulation results for one-year lettuce production in four production systems of hydroponics (HP), decoupled aquaponics (DAPS), decoupled aquaponics on a roof with passive energy exchange (DAPS-R), decoupled aquaponics on a roof with active energy exchange (DAPS-R+) in Berlin (Germany, DE) with heat energy consumption (A), fresh crop yield (B), product water use (C), and product energy use (D).

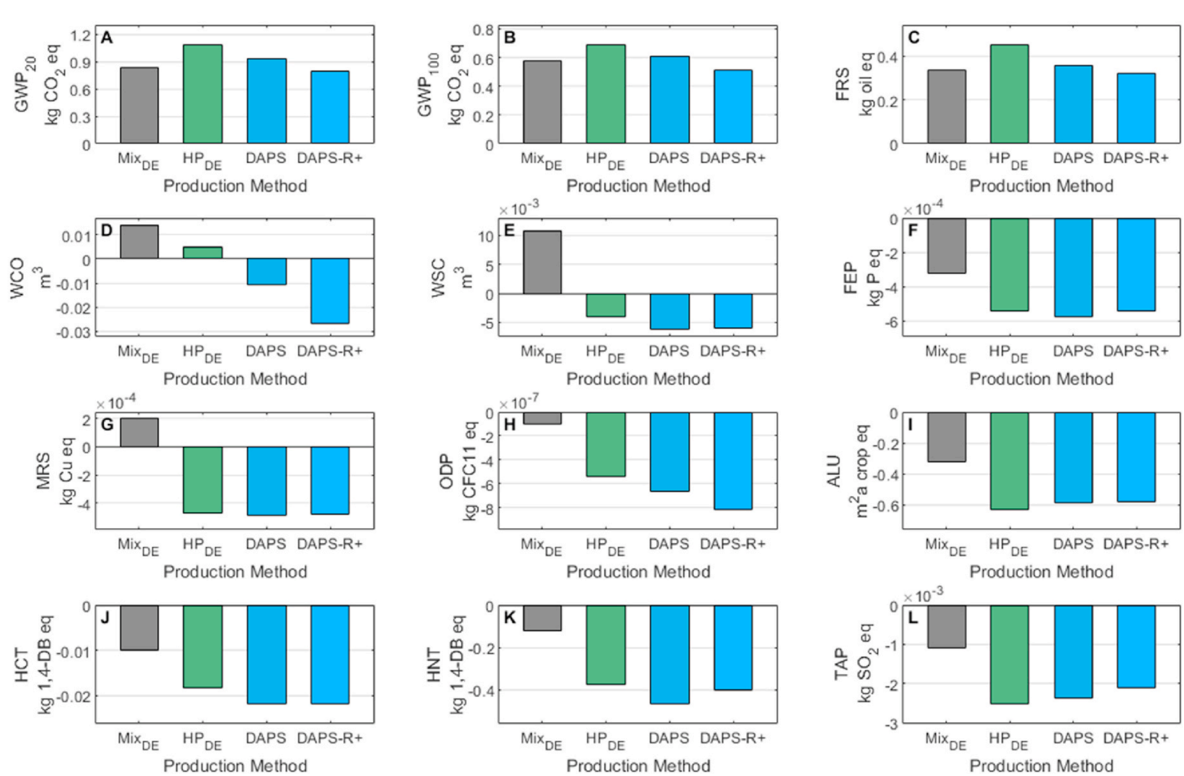

Fig. 9. Comparing LCA for 500 g of packed tomatoes from import mix (MIX), local hydroponics (HP), decoupled aquaponics (DAPS), and decoupled aquaponics on a roof with active energy exchange (DAPS-R+) for 12 LCA impact categories with their indicators.

preferably in combination with waste heat usage (Fig. 6).

DAPS mainly reduce the water- and energy-related midpoint categories compared to HP, and all the DAPS scenarios showed the same trend. Mainly four key issues lead to these reductions. First, the fish tanks in the current study, which were kept at 30 °C (assuming tilapia culture), were located within the plant production area and released low energy heat to the greenhouse environment. Consequently, the DAPS used less greenhouse heating energy (Körner et al., 2017). Second, most

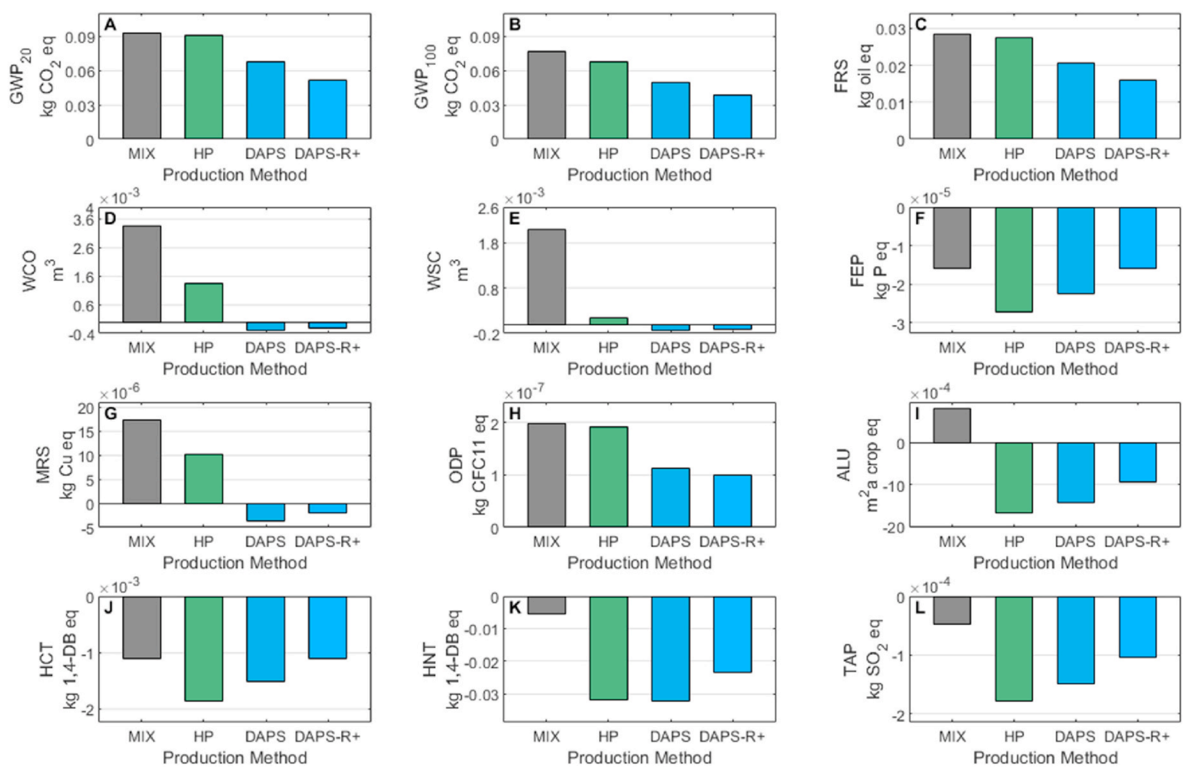

Fig. 10. Comparing LCA for 150 g of packed and sliced lettuce from import mix (MIX), local hydroponics (HP), decoupled aquaponics (DAPS), and decoupled aquaponics on a roof with active energy exchange (DAPS-R+) for 12 LCA impact categories with their indicators.

Table 4
Percentage saving on impact indicators of different production methods compared to the market available bag of cut lettuce of (150 g) or a box of 500 g tomatoes at a local market in Berlin.

		Local Production Method			
		HP	DAPS	DAPS-R	DAPS-R+
Lettuce	GWP_{20}	2.2	27.3	29.8	44.0
	GWP_{100}	11.8	35.6	37.8	49.9
	FRS	3.5	27.6	30.1	44.2
	WCO	59.9	108.8	108.4	106.1
	WSC	93.4	106.6	106.3	104.7
	FEP	72.3	41.8	35.9	1.4
	MRS	40.9	121.9	120.3	111.3
	ODE	4.2	43.7	44.6	49.8
	ALO	311.1	281.0	271.9	218.6
	HCT	69.3	38.4	32.8	−0.1
	HNT	491.9	501.4	477.0	333.7
	TAP	275.7	214.9	200.9	117.5
Tomato	GWP_{20}	−30.0	−11.6	−8.3	2.1
	GWP_{100}	−19.6	−5.3	−2.0	8.7
	FRS	−34.3	−5.7	−3.2	4.7
	WCO	66.1	175.8	174.7	171.1
	WSC	137.6	157.3	156.7	154.6
	FEP	68.4	79.9	76.4	65.1
	MRS	330.0	339.5	337.9	332.9
	ODE	442.1	568.6	590.0	657.9
	ALO	99.1	83.8	83.5	82.7
	HCT	86.6	122.0	114.6	90.2
	HNT	210.2	289.5	276.6	234.1
	TAP	131.2	116.5	109.3	85.3

plant nutrients originate from the fish system. Hence, the energy needed to produce a considerable amount of fertiliser can be significantly reduced (Baganz et al., 2020; Goddek, 2017). Third, all the DAPS were located close to the market, and thus transport was minimised. Fourth, in DAPS, no water is spoiled, and besides the power needed for irrigation pumps, no additional water supply is needed for the plants when the system is optimally balanced (Keesman et al., 2019).

Thermal energy consumption in the different systems under consideration shows a similar behaviour for tomato and lettuce production (Fig. 7, Fig. 8). The highest energy use was calculated for regular HP, while energy reductions of 8% and 10% (lettuce and tomato) were possible replacing HP with DAPS. Additional reduction of energy consumption were achieved when combining DAPS with active waste heat transfer from a connected building, hence under scenarios HP-R+ and DAPS-R+ (for both tomato and lettuce). Combining greenhouses with buildings has a high potential on energy savings, which depends on individual set up and location (Nadal et al., 2017). In our case, the total energy consumption could be reduced by 18% from regular HP to HP-R+ in both crops and by 19% and 30% with DAPS-R+ in tomato and lettuce, respectively. Energy savings of 13% were earlier reported for roof-top greenhouses in humid continental climates and roof-adjusted structures (Torres Pineda et al., 2020), while the actual settings and climate conditions strongly influence the possible impact reductions. In our case, the passive reuse of waste heat reduced energy consumption only marginally; i.e., ca. 1% in HP and 3% in DAPS.

4.3. Impact of DAPS on environmental impact categories

In aquaponics, heat, electricity, equipment, and fish feed are reported as the four main environmental impact hotspots (Ghamkhar et al., 2020). However, in the current LCA, a sharp line was drawn between the two main sub-systems of DAPS, i.e., HP and RAS. As such, RAS was used as a provider of water, nutrients, heat and, to a lesser extent, CO_2 for hydroponic crop production. For both lettuce and tomato, moving from regular HP to DAPS reduced the global warming potential (and fossil resource scarcity) and hence the emissions of greenhouse gases to the atmosphere. Water consumption (WCO, m^3) was highest for available market mixes (Fig. 9, Fig. 10), with a high contribution of imported products. Product water use in Figs. 2 and 3 illustrates that,

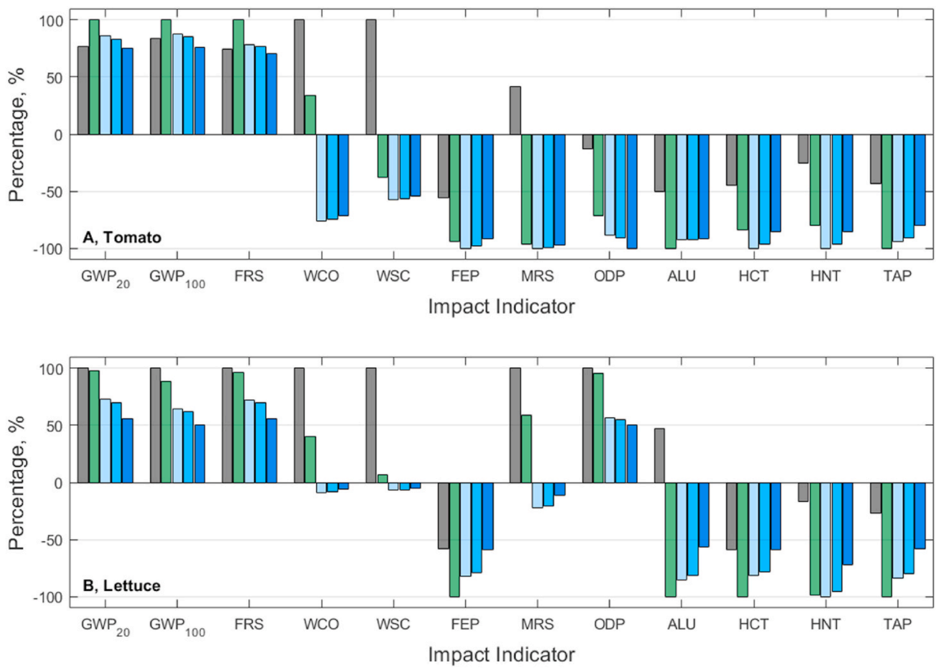

Fig. 11. Percentage from absolute maximum case (100%) of 12 LCA impact categories with their indicators for availability of (A) 500 g of packed tomatoes or (B) 150 g of lettuce in Germany with five scenarios (from left to right in the column clusters): available market mix (grey), local hydroponics (green), decoupled multi-loop aquaponics (DAPS, light blue)), decoupled multi-loop aquaponics on a roof with passive energy exchange (DAPS-R, blue), decoupled multi-loop aquaponics on a roof with active energy exchange (DAPS-R+, dark blue).

and it is in agreement with earlier results of tomatoes produced in Mediterranean greenhouse (Payen et al., 2015). The general picture is evident: Local Northern European produced lettuce and tomatoes have strong influence on the energy related impact categories (GWP_{20}, GWP_{100}, FRS); while water based impacts (WCO, WSC) are mainly a problem in Southern Europe. Some environmental impacts could improve by solely shifting from import to 100% local production (Table 4). However, the combination of local production and DAPS (in particular DAPS-R+), can strongly reduce all environmental impact categories, with strongest effect on those related to energy, water and mineral resources (Table 4). Using the complete programme of roof-top decoupled aquaponics in DAPS-R+ compared to the available market mix, WCO dropped from water consumption to water saving: i.e. from 14.2 L or 3.3 L to −10.1 L or −0.21 L per package of 500 g tomatoes or 150 g lettuce, respectively. GWP_{100} and FRS were below the values of the available market mixes, e.g. GWP_{100} decreased with 8.7% in tomatoes and 49.9% in lettuce (Table 4, Fig. 11).

4.4. Methods and data

In LCA, data quality and choice of method are key issues. Given the complexity of the system with various co-products, CLCA with system expansion was defined as best method for our scenarios (Weidema and Schmidt, 2010). While CLCA was earlier used in aquaponics (Boxman et al., 2017), only few LCA studies have been done on this topic (Ghamkhar et al., 2020). The data situation is limited (Boxman et al., 2017), while it even worsens with aquaponics in urban environments (Wu et al., 2019). We have addressed that problem incorporating the output from a model-simulation study to LCA. For the first time, a simulation study with a widely validated aquaponics simulator (Goddek and Körner, 2019) was combined with LCA. Through that, production data from various geographical locations and individual production systems could be used for real market scenarios. While the composition of the market available mixes of lettuce and tomatoes where a result of the present fresh market situation in Berlin (Behr, 2019; Workman, 2020a, b), production efficiency influences the contributions on environmental impacts from each producing country. In addition, the larger the share of a certain origin country on any impact category, the stronger is its influence on the total impact (Table 5). For instance, a change in production efficiency in 25% of the Netherlands would have a total impact of 22.4% on GWP_{100}; the same change in Spain results in a higher GWP_{100} of only 3.4%. Focusing on water turns that picture around. With the same scenario, the WCO for 500 g packed tomatoes on the Berlin market would increase by 5.6% or 17.7% due to the Netherlands or Spain, respectively. Thus, although the reported results are valid in the current situation, any adjustments in the complex global producer market will have an impact. However, with the here presented methodology, also future market scenarios could be analysed.

5. Conclusions and future prospective

Choosing the right set-up, local vegetable productions in urban regions can surpass the import mix on environmental performance in Northern European centres. Production in Northern European countries uses more energy (mostly carbon-bound, currently), while product water use is significantly higher in Southern Europe (inter alia desalinated seawater). When replacing HP with aquaponics, some resources could be attributed to RAS, which partly reduces the global warming potential for plant production and water-related environmental impacts can be strongly reduced. Placing the DAPS in a local urban context using the rooftop of an existing industrial building further reduces GWP and other environmental impact through reduced transport, area re-usage and a combined possibility for waste heat usage. In this scenario, active reuse of waste heat was the most effective method of environmental impact reductions. Our results clearly illustrate the strong positive effect of both local food production in combined production systems. Increase in complexity and technology as shown in the top solution analysed here, decrease environmental impact. In the next step, additional co-products need to be added to the system, further increasing its complexity. Here, we expect increasing synergy and further improvements of environmental impacts of the produce. Then, to decrease the error in LCA studies, system expansion becomes increasingly important (Weidema and Schmidt, 2010).

CRediT authorship contribution statement

Oliver Körner: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft,

Table 5
Sensitivity analysis on the effects of the yields mixes with individual reductions per country of 25%, 50%, and 75% yields in Germany (Mix DE), The Netherlands (Mix NL), Italy (Mix IT), and Spain (Mix ES) compared to local production and the market available mix (MIX).

		Local			MIX	Mix DE			Mix NL			Mix IT			Mix ES		
		HP	DAPS	DAPS-R+													
	Prod. Efficiency (%) →	100	100	100	100	25	50	75	25	50	75	25	50	75	25	50	75
GWP_{20}	kg CO_2 eq	1.08	0.93	0.81	0.83	1.09	0.92	0.86	2.62	1.43	1.03	0.88	0.85	0.84	1.08	0.91	0.86
GWP_{100}	kg CO_2 eq	0.69	0.61	0.53	0.58	0.74	0.63	0.59	1.74	0.96	0.71	0.62	0.59	0.58	0.81	0.65	0.60
FRS	kg oil eq	0.45	0.36	0.32	0.34	0.44	0.37	0.35	1.09	0.59	0.42	0.35	0.34	0.34	0.41	0.36	0.35
WCO	m^3 (10^{-3})	4.8	−10.7	−10.1	14.2	15.3	14.6	14.3	21.6	16.7	15.0	19.0	15.8	14.7	36.8	21.7	16.7
WSC	m^3 (10^{-3})	−4.1	−6.2	−5.9	10.9	9.9	10.6	10.8	20.1	14.0	11.9	13.9	11.9	11.2	27.3	16.3	12.7
FEP	kg P eq (10^{-3})	−0.54	−0.58	−0.53	−0.32	−0.45	−0.36	−0.33	−1.17	−0.60	−0.41	−0.31	−0.32	−0.32	−0.29	−0.31	−0.32
MRS	kg Cu eq (10^{-3})	−0.47	−0.49	−0.47	0.20	0.10	0.17	0.19	−0.56	−0.05	0.12	0.44	0.28	0.23	1.21	0.54	0.32
ODE	kg CFC11 eq (10^{-6})	−0.54	−0.67	−0.75	−0.10	−0.22	−0.14	−0.11	−0.99	−0.40	−0.20	0.04	−0.05	−0.08	0.38	0.06	−0.05
ALO	m^2a crop eq	−0.63	−0.58	−0.58	−0.32	−0.46	−0.37	−0.33	−1.35	−0.66	−0.43	−0.25	−0.30	−0.31	−0.17	−0.27	−0.30
HCT	kg 1,4-DB (10^{-3})	−18.3	−21.8	−18.7	−9.8	−14.2	−11.3	−10.3	−36.9	−18.9	−12.8	−9.3	−9.7	−9.8	−7.8	−9.1	−9.6
HNT	kg 1,4-DB	−0.37	−0.47	−0.40	−0.12	−0.21	−0.15	−0.13	−0.62	−0.29	−0.18	−0.07	−0.10	−0.11	0.04	−0.07	−0.10
TAP	kg SO_2 eq (10^{-3})	−2.52	−2.36	−2.02	−1.09	−1.68	−1.29	−1.16	−4.76	−2.31	−1.50	−0.90	−1.03	−1.07	−0.34	−0.84	−1.01

Visualization. **Mehdi B. Bisbis:** Writing – original draft, Writing – review & editing. **Gösta F.M. Baganz:** Investigation, Data curation, Writing – review & editing. **Daniela Baganz:** Writing – review & editing, Supervision, Funding acquisition. **Georg B.O. Staaks:** Writing – review & editing. **Hendrik Monsees:** Writing – review & editing. **Simon Goddek:** Software, Writing – review & editing. **Karel J. Keesman:** Validation, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Aigner, H., 2003. Denitrification in Cultures of Potted Ornamental Plants. Universität Hannover, Hannover, Germany, p. 133.

Antón, A., Torrellas, M., Montero, J., Ruijs, M., Vermeulen, P., Stanghellini, C., 2012. Environmental impact assessment of Dutch tomato crop production in a Venlo glasshouse. Acta Hortic. 927, 781–791.

Baganz, G., Baganz, D., Staaks, G., Monsees, H., Kloas, W., 2020. Profitability of multi-loop aquaponics: year-long production data, economic scenarios and a comprehensive model case. Aquacult. Res. 2020 (51), 2711–2724.

Behr, H.C., 2019. The Market for Fresh Tomatoes in Germany Global Tomato Congress. Rotterdam, The Netherlands.

Berger, M., Van der Ent, R., Eisner, S., Bach, V., Finkbeiner, M., 2014. Water accounting and vulnerability evaluation (WAVE): considering atmospheric evaporation recycling and the risk of freshwater depletion in water footprinting. Environ. Sci. Technol. 48 (8), 4521–4528.

Boxman, S.E., Qiong, Z., Doland, B., Trotz, M., 2017. Life cycle assessment of a commercial freshwater aquaponic system. Environ. Eng. Sci. 35 (5), 299–311.

Brandão, M., Martin, M., Cowie, A., Hamelin, L., Zamagni, A., 2017. Consequential life cycle assessment: what, how, and why? In: Abraham, M.A. (Ed.), Encyclopedia of Sustainable Technologies. Elsevier, pp. 277–284.

Cohen, A., Malone, S., Morris, Z., Weissburg, M., Bras, B., 2018. Combined fish and lettuce cultivation: an aquaponics life cycle assessment. Procedia CIRP 69, 551–556.

Cuce, E., Harjunowibowo, D., Cuce, P.M., 2016. Renewable and sustainable energy saving strategies for greenhouse systems: a comprehensive review. Renew. Sustain. Energy Rev. 64, 34–59.

Custodio, E., Sahuquillo, A., Albiac, J., 2019. Sustainability of intensive groundwater development: experience in Spain. Sustain. Water Resourc. Manag. 5 (1), 11–26.

De Cicco, A., 2019. The Fruit and Vegetable Sector in the EU - a Statistical Overview Eurostat.

De Kreij, C., Voogt, W., Van den Bos, A.L., Baas, R., 1997. Nutrient Solutions for the Growth of Tomato in Closed Systems (In Dutch). Brochure VG 3. Proefstation voor Bloemistrij en Glasgroenten, Naaldwijk, The Netherlands.

Delaide, B., Teerlinck, S., Decombel, A., Bleyaert, P., 2019. Effect of wastewater from a pikeperch (Sander lucioperca L.) recirculated aquaculture system on hydroponic tomato production and quality. Agric. Water Manag. 226, 105814, 1-9.

Delaide, B.P.L., Goddek, S., Gott, J., Soyert, H., Jijakli, M.H., 2016. Lettuce (Lactuca sativa L. Sucrine) growth performance in complemented aquaponic solution outperforms hydroponics. Water 8, 467.

Ecoinvent, 2019. Version 3.6. Simapro Database Swiss Centre for Life Cycle Inventories.

Fitwi, B.S., 2012. Environmenta evaluation of aquaculture using life cycle assessment (LCA), Agrar- und Ernährungswissenschaftlichen Fakultät. Christian-Albrechts-Universität zu Kiel, p. 145.

Gava, O., Bartolini, F., Venturi, F., Brunori, G., Zinnai, A., Pardossi, A., 2018. A reflection of the use of the life cycle assessment tool for agri-food sustainability. Sustainability 11 (71), 1–16.

Ghamkhar, R., Hartleb, C., Wu, F., Hicks, A., 2020. Life cycle assessment of a cold weather aquaponic food production system. J. Clean. Prod. 244, 118767.

Goddek, S., 2017. Opportunities and Challenges of Multi-Loop Aquaponic Systems. Wageningen University, p. 170.

Goddek, S., Bläser, I., Reuter, M., Wuertz, S., Körner, O., Joyce, A., Keesman, K.J., 2019. Decoupled aquaponic systems. In: Goddek, S., Joyce, A., Kotzen, B., Burnell, G.

(Eds.), Aquaponics Food Production Systems. Springer Nature, SpringerOpen, pp. 201–229.
Goddek, S., Keesman, K.J., 2018. The necessity of desalination technology for designing and sizing multi-loop aquaponics systems. Desalination 428, 76–85.
Goddek, S., Körner, O., 2019. A fully integrated simulation model of multi-loop aquaponics: a case study for system sizing in different environments. Agric. Syst. 171, 143–154.
Goddek, S., Vermeulen, T., 2018. Comparison of Lactuca sativa growth performance in conventional and RAS-based hydroponic systems. Aquacult. Int. 26, 1377–1386.
Gruda, N., Bisbis, M., Tanny, J., 2019. Impacts of protected vegetable cultivation on climate change and adaptation strategies for cleaner production – a review. J. Clean. Prod. 225, 324–339.
Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., Van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147.
Keesman, K.J., Körner, O., Wagner, K., Urban, J., Karimanzira, D., Rauschenbach, T., Goddek, S., 2019. Aquaponics system modelling. In: Goddek, S., Joyce, A., Kotzen, B., Burnell, G. (Eds.), Aquaponics Food Production Systems. Springer Nature, SpringerOpen, pp. 267–299.
Kloas, W., Groß, R., Baganz, D., Graupner, J., Monsees, H., Schmidt, U., Staaks, G., Suhl, J., Tschirner, M., Wittstock, B., Wuertz, S., Zikova, A., Rennert, B., 2015. A new concept for aquaponic systems to improve sustainability, increase productivity, and reduce environmental impacts. Aquacult. Environ. Interact. 7, 179–192.
Körner, O., 2004. Evaluation of crop photosynthesis models for dynamic climate control. Acta Hortic. 654, 295–302.
Körner, O., Andreassen, A.U., Aaslyng, J.M., 2006. Simulating dynamic control of supplementary lighting. Acta Hortic. 711, 151–156.
Körner, O., Gutzmann, E., Kledal, P.R., 2017. A dynamic model simulating the symbiotic effects in aquaponic systems. Acta Hortic. 1170, 309–316.
Körner, O., Hansen, J.B., 2012. An on-line tool for optimising greenhouse crop production. Acta Hortic. 957, 147–154.
Körner, O., Pedersen, J.S., Jaegerholm, J., 2018. Simulating lettuce production in multi layer moving gutter systems. Acta Hortic. 1227, 283–290. https://doi.org/10.17660/ActaHortic.2018.1227.34.
Körner, O., Warner, D., Tzilivakis, J., Eveleens-Clark, B., Heuvelink, E., 2008. Decision support for optimising energy consumption in European greenhouses. Acta Hortic. 801, 803–810.
Monsees, H., Suhl, J., Paul, M., Kloas, W., Dannehl, D., Würtz, S., 2019. Lettuce (Lactuca sativa, variety Salanova) production in decoupled aquaponic systems: same yield and similar quality as in conventional hydroponic systems but drastically reduced greenhouse gas emissions by saving inorganic fertilizer. PloS One 16 (6), e0218368.
Nadal, A., Llorach-Massana, P., Cuerva, E., López-Capel, E., Montero, J.I., Josa, A., Rieradevall, J., Royapoor, M., 2017. Building-integrated rooftop greenhouses: an energy and environmental assessment in the mediterranean context. Appl. Energy 187, 338–351.
Ntinas, G.K., Dannehl, D., Schuch, I., Rocksch, T., Schmidt, U., 2020. Sustainable greenhouse production with minimised carbon footprint by energy export. Biosyst. Eng. 189, 164–178.
Opdam, J.J.G., Schoonderbeek, G.G., Heller, E.M.B., De Gelder, A., 2005. Closed greenhouse: a starting point for sustainable entrepreneurship in horticulture. Acta Hortic. 691, 517–524.
Payen, S., Basset-Mens, C., Perret, S., 2015. LCA of local and imported tomato: an energy and water trade-off. J. Clean. Prod. 87, 139–148.
Pluimers, J.C., 2001. An Environmental System Analysis of Greenhouse Horticulture in the Netherlands. Wageningen University, Wageningen, The Netherlands, p. 181.
Ramírez, T., Kläring, H.P., Körner, O., 2019. Does interruption of supplementary lighting affect the long-term carbon dioxide exchange of greenhouse tomato crops? Biosyst. Eng. 187, 69–80.
Savvas, D., Chatzieustratiou, E., Pervolaraki, G., Gizas, G., Sigrimis, N., 2008. Modelling Na and Cl concentrations in the recycling nutrient solution of a closed-cycle pepper cultivation. Biosyst. Eng. 99 (2).
Schmautz, Z., Loeu, F., Liebisch, F., Graber, A., Mathis, A., Bulc, T.G., Junge, R., 2016. Tomato productivity and quality in aquaponics: comparison of three hydroponic methods. Water 8 (533), 1–21.
Schmidt, A., Ulf, A., Jensen, A.A., Kamstrup, O., 2003. In: Documents, L. (Ed.), Comparative life lycle assessment of three insulation materials -stone wool, flax and paper wool. Ecomed publishers.
Stoessel, F., Juraske, R., Pfister, S., Hellweg, S., 2011. Life cycle inventory and carbon and water FoodPrint of fruits and vegetables: application to a Swiss retailer. Environ. Sci. Technol. 6 (46), 3253–3262.
Torrellas, M., Antón, A., López, J.C., Baeza, E.J., Parra, J.P., Muñoz, P., Montero, J.I., 2012. LCA of a tomato crop in a multi-tunnel greenhouse in Almeria. Int. J. Life Cycle Assess. 17 (7), 863–875.
Torres Pineda, I., Cho, J.H., Lee, D., Lee, S.M., Yu, S., Lee, Y.D., 2020. Environmental impact of fresh tomato production in an urban rooftop greenhouse in a humid continental climate in South Korea. Sustainability 12 (21), 9029.
Vadiee, A., Martin, V., 2012. Energy management in horticultural applications through the closed greenhouse concept, state of the art. Renew. Sustain. Energy Rev. 16, 5087–5100.
Weidema, B., 2003. Market Information in Life Cycle Assessment, Environmental Project No. 863 2003. Danish Ministry of the Environment, Copenhagen, Denmark, p. 147.
Weidema, B.P., Schmidt, J., 2010. Avoiding allocation in life cycle assessment revisited. J. Ind. Ecol. 14 (2), 192–195.
Workman, D., 2020a. Tomatoes Imports by Country. worldstopexports.com.
Workman, D., 2020b. Top Lettuce Exports by Country. worldstopexports.com.
Wu, F., Ghamkhar, R., Ashton, W., Hicks, A.L., 2019. Sustainable seafood and vegetable production: aquaponics as a potential opportunity in urban areas. Integrated Environ. Assess. Manag. 15 (6), 832–843.
Yu, W., Körner, O., Schmidt, U., 2020. Crop photosynthetic performance monitoring based on a combined system of measured and modelled chloroplast electron transport rate in greenhouse tomato. Front. Plant Sci. 11 (1038), 1–15.