Science of the Total Environment 794 (2021) 148689

Contents lists available at ScienceDirect

Science of the Total Environment

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

Optimizing irrigation in urban agriculture for tomato crops in rooftop greenhouses

Felipe Parada [a], Xavier Gabarrell [a,b], Martí Rufí-Salís [a], Verónica Arcas-Pilz [a], Pere Muñoz [a], Gara Villalba [a,b,*]

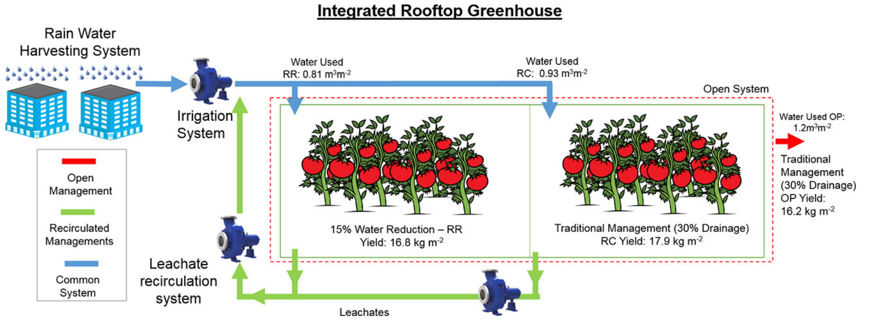
[a] Sostenipra Research Group (SGR 1683), Institute of Environmental Sciences and Technology (ICTA-UAB), MdM Unit of Excellence, Universitat (CEX2019-000940-M) Autònoma de Barcelona (UAB), Campus UAB, 08193 Bellaterra, Barcelona, Spain

[b] Department of Chemical, Biological and Environmental Engineering, School of Engineering, Building Q, Universitat Autònoma de Barcelona (UAB), 08193 Bellaterra, Spain

HIGHLIGHTS

- Recirculation systems reduce the marine and freshwater eutrophication.
- Leachate as irrigation water is an alternative for the reduction of irrigation water and maintains yields.
- It is necessary to find ways to fertilizer substitution and irrigation optimization.
- Water reduction management can increase in 7% the WUE of the tomato crop.
- The operation phase shows improvements in all of the impact categories evaluated.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 April 2021
Received in revised form 11 June 2021
Accepted 22 June 2021
Available online 29 June 2021

Editor: Damia Barcelo

Keywords:
Life cycle assessment (LCA)
Water-use efficiency (WUE)
Reduction water consumption
Eutrophication reduction
Leachate recirculation
Recirculation system

ABSTRACT

The rise of population in urban areas makes it ever more important to promote urban agriculture (UA) that is efficient in terms of water and nutrients. How to meet the irrigation demand of UA is of particular concern in urban areas where water sources are often limited. With the aim of determining how to reduce water use for irrigation while maintaining productivity and reducing environmental impacts in UA, this study explores the agronomic performance and environmental life cycle impacts and benefits of three different fertigation management practices used in a rooftop greenhouse for tomato crop in Barcelona: 1) open management (OP); 2) recirculation (RC), in which 30% of the drained, unused water is used to irrigate the crop; and 3) the same recirculated management of RC with a further reduction in fresh water input of 15%(RR). Despite the recirculation and reduction of water and nutrients, all three irrigation management practices resulted in similar yields: 16.2, 17.9, and 16.8 $\cdot$ kg $\cdot$ m^{-2} for OP, RC, and RR, respectively. In terms of water-use efficiency, RR management was the most efficient, requiring 48.7 $\cdot$ liters $\cdot$ kg^{-1} of tomato, followed by RC (52.4 $\cdot$ L $\cdot$ kg^{-1}) and OP (75.2 $\cdot$ L $\cdot$ kg^{-1}). RR presented an improvement of 7% in water-use efficiency. In terms of environmental performance, RC had the best performance in almost all impact categories during the operational phase, especially in regard to marine and freshwater eutrophication, with 44% and 93% fewer impacts than OP due to the recirculation of nutrients and reduced nutrient loss through leachates. In terms of infrastructure, even though recirculation management requires additional equipment, the materials present better performance in the range from 0.2 to 14% depending on the impact category. This study can support evaluation of agricultural projects in the city, through yields and water consumption presented, incentivizing good practices aligned with the sustainability of UA.

---

* Corresponding author at: Department of Chemical, Biological and Environmental Engineering, School of Engineering, Building Q, Universitat Autònoma de Barcelona (UAB), 08193 Bellaterra, Spain.

E-mail addresses: Felipe.Parada@uab.cat (F. Parada), Xavier.Gabarrell@uab.cat (X. Gabarrell), Marti.Rufi@uab.cat (M. Rufí-Salís), Veronica.Arcas@uab.cat (V. Arcas-Pilz), Pedro.Munoz@uab.cat (P. Muñoz), Gara.Villalba@uab.cat (G. Villalba).

https://doi.org/10.1016/j.scitotenv.2021.148689

1. Introduction

Current trends in population growth lead to an increase in demand for food, water, and energy. This demand becomes a challenge, particularly for urban areas where half of the world's population resides and is expected to rise to more than 70% by 2050 (UNDESA, 2018). Urban agriculture (UA) can meet part of that food demand, additionally providing further advantages, such as reduction of environmental impacts and food losses associated with transportation over long distances (Caldeira et al., 2019; Sanyé-Mengual et al., 2013). UA provides opportunities to improve urban metabolism through the optimization of urban cycles with agro-urban systems through the recovery of nutrients from urban organic waste and wastewater (De Corato, 2020; Ulm et al., 2019) and the integration of buildings with greenhouses on roofs for energy reduction (Nadal et al., 2017), thereby promoting the circularity of resources. In other words, increasing food sovereignty in cities cannot come at the price of increasing environmental impacts because more resources need to be imported.

Traditionally, agriculture has been characterized by the inefficient use of resources, both in terms of water and nutrients. Currently, agricultural practices consume more than 85% of available freshwater and 80% of the annual phosphate rock extracted globally (Shu et al., 2006; van Schilfgaarde, 1994). Additionally, the water supply is scarce and unstable due to extended dry periods, heatwaves, and low pluviometry (Schmidhuber and Tubiello, 2007). Today, there is scientific consensus on the depleting nature of phosphorus (Rittmann et al., 2011), where phosphate rocks are the main source of phosphorus, and 80% of the available stock is used in the production of fertilizers (Shu et al., 2006). The use of chemical fertilizers has increased up to 36% since 2002, indicating our dependence on a nonrenewable resource (FAOSTAT, 2017a). Steen (1998) mentioned that mineral P resources have been depleted in the last century. The intensified use of fertilizers results in eutrophication and other diffuse pollution problems (Chen et al., 2017, 2021; Nagendran, 2011; Novotny, 1999). For these reasons, optimizing water and fertilizer management in agriculture should be a priority, mostly in cities, where these resources are limited or come from faraway places.

For the development of UA, efficient use of water is essential (Tixier and de Bon, 2006), and some different technologies and management practices allow maximization of the use of water, such as drip irrigation systems, which enable reaching efficiencies in irrigation up to 95%; added to other measures, as climatic predictions can improve the amount of applied irrigation water. Mason et al. (2019) simulated different climates in the United States, showing the benefits of applying intelligent irrigation systems, which consider climatic information to determine the amount of water to apply to crops. They found a 46% average savings (ranging from 2 to 96%). Other studies have shown how the implementation of efficient irrigation systems reduces the amount of water and nutrients applied (Contreras et al., 2017; Hooshmand et al., 2019; Liu et al., 2019).

Although there seem to be ample benefits from UA, it is crucial to analyze crop production from a systemic life cycle approach to avoid counterproductive impacts and to improve system optimization. Additionally, a widely used method to evaluate the environmental performance of processes is life cycle assessment (LCA). This is used to assess the potential environmental impacts, both direct and indirect, associated with a product throughout its entire lifetime in a systemic approach and is useful in identifying opportunities to improve the process and reduce impacts (ISO 14040, 2006). To summarize, diverse that environmental impacts related to the operation stage are mainly associated with fertilizers, diesel and emissions from land use change. (Martínez-Blanco et al., 2011; Parajuli et al., 2019) Payen et al. (2015) conducted a study on tomato production in two countries with contrasting climates (Morocco and France), showing that impacts depend highly on water extraction and treatment for irrigation. Their study showed that although the tomato crop water consumption in both countries was similar, Morocco had over three times the freshwater depletion. On the other hand, as a result of having more sophisticated technologies and a cooler climate, French tomato production requires more energy consumption, resulting in higher global warming and eutrophication potentials. He et al. (2016) were able to show a better life cycle environmental performance by reducing chemical fertilizer and pesticide consumption in organically grown tomatoes, albeit more land was required to compensate for the lower yields. Rufí-Salís et al. (2020b) presented a study on an integrated rooftop greenhouse (i-RTG) with different crops grown using water recirculation management, identifying the best combination of crops in the greenhouse to define the generated environmental impacts; nevertheless, their study did not consider irrigation as a variable to be optimized.

To summarize, diverse authors have used LCA to evaluate crop production in UA systems; however, few have explored and quantified (Parajuli et al., 2019) how various water and nutrient optimization strategies can reduce the impacts while maintaining profitable yields. This study aims to contribute to this research gap in UA systems by analyzing alternatives for efficient water management strategies, such as the recirculation of water and nutrient flows and reduction of applied water while maintaining yield. Furthermore, since an irrigation system is used to fertilize crops, the reduction of water in recirculated irrigation management results in a reduced amount of fertilizers, which were also quantified by performing nutrient balances. In addition to yield, water efficiency, and nutrient balance, an environmental analysis of all three irrigation strategies was performed (functional unit of 1 kg of tomato) and determines the effect of water recirculation management on the yield and environmental burdens. The tomato crop was selected for three reasons: first, tomatoes are the most consumed horticultural crop in Europe (European Commission, 2011), with 24.6 million tons per year, and are mainly produced in Spain and Italy (Cook et al., 2018; FAOSTAT, 2017b). Second, tomatoes are traditionally grown in places with low precipitation and warm climates. An example of this is Almería (Spain), where the precipitation is near 218 mm per year (SIAR, 2019). Third, given its high water requirements, tomatoes are an excellent crop to study the benefits of producing them in urban areas with water and nutrient optimization strategies.

We hypothesize that the efficient use of water and nutrients through recirculation management reduces the environmental impacts of tomato production in UA through the contrast of three management practices and the generation of real data. The three strategies include open management and two types of recirculation management (with and without restrictive water irrigation) during two cultivation periods of tomato production in an i-RTG.

2. Materials and methods

2.1. Case study: the integrated rooftop greenhouse (i-RTG)

This study was performed in the i-RTG located inside the Institute of Environmental Science and Technology (ICTA-UAB) building on the Universitat Autònoma de Barcelona (Catalonia, Spain) campus located in the outskirts of Barcelona. The site is characterized by a Mediterranean climate with warm summers and rainy winters.

The experiment was conducted in the southeast-facing corner of the i-RTG for the production of the tomato species *Solanum lycopersicum* L. cultivar Arawak, with a total available area of 84.5 m^2 and a functional harvesting area of 63.5 m^2. The frame of the plantation was 0.33 × 1.1 m (Fig. 1) with a total of 171 tomato plants distributed in 57 perlite substrate bags (40 L), making a plant density of 2.7 $plant{\cdot}m^{-2}$. The study took place during two consecutive years, 2018 and 2019, where the tomato season lasted approximately 6 months each year.

A drip irrigation system was used with a 2 $L{\cdot}h^{-1}$ water flow in which fertilizer was applied according to need throughout the cropping season (Table 1).

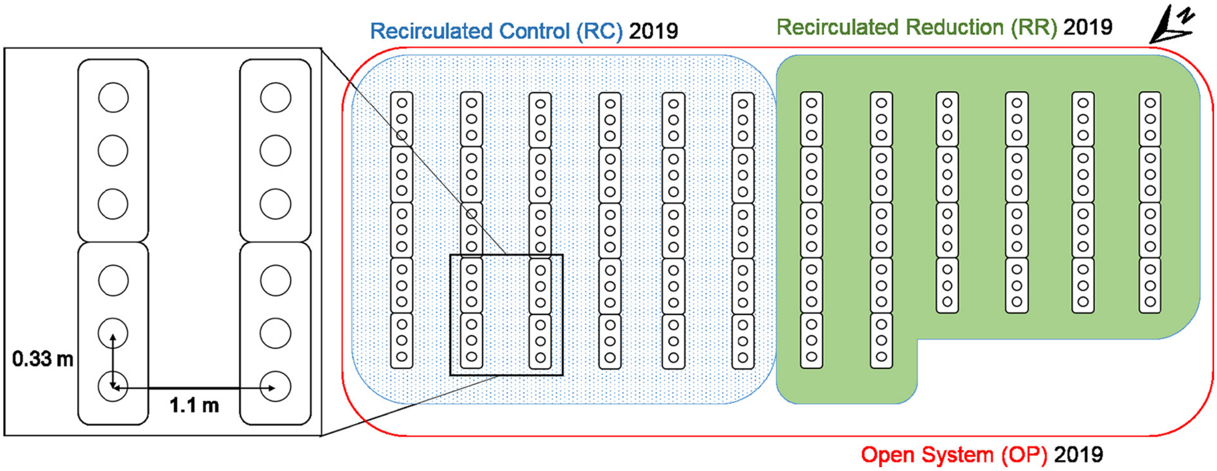


Fig. 1. Distribution of plants at the ICTA-UAB Laboratory of Urban Agriculture.

This building has a rainwater harvesting system (RWHS) which consists of a 100 m^3 tank buried under the building that is used to irrigate the crops inside the greenhouse. The rainwater used for irrigation was pumped from the RWHS to two containers of 300 L each inside the greenhouse on the top floor of the building.

The leachate was collected in slightly-tilted aluminum trays where the crop bags were placed. These allowed collecting the excess irrigation water (leachates) by gravity, towards a secondary container, for storage and distribution.

The leachate collection system was carried out through aluminum trays where the crop bags were placed. These allowed collecting the excess irrigation water (leachates) by gravity, towards a secondary container, to be later stored in a general container where it was stored to be redistributed.

The agronomic results were focused on the water and yield relationship. For the environmental part, the results were centered on the optimization of fertilizers, energy, and analysis of infrastructure. The three irrigation managements were performed as follows and summarized in Table 2: (1) open management (OP): traditional drip irrigation where 30% of the water supply was drained and discharged to the wastewater sewer, implemented in 2018; (2) recirculation control (RC): traditional drip irrigation with an identical 30% of drainage, but the drained water was collected and recirculated, implemented in 2019; and 3) leachate recirculation (RR): irrigation water volume was reduced by 15%, which was also recirculated and recycled, and implemented in 2019. The objective was to reduce water intake without compromising production. In this sense, different authors have discussed that a reduction of approximately 20% in potentiation evapotranspiration would not affect productivity. Considering that the hydroponic system requires a minimum leaching fraction, a 15% reduction in applied irrigation water was made (Favati et al., 2009; Wang et al., 2019). Irrigation was given in ten evenly distributed, daily doses.

Table 1
Concentration of fertilizers used.

Fertilizers	2018 OP $[g{\cdot}m^{-3}]^a$	2019 RC $[g{\cdot}m^{-3}]^a$	2019 RR $[g{\cdot}m^{-3}]^a$
KPO_4H_2	214	283	283
KNO_3	104	138	138
$K2SO_4$	277	367	367
$Ca(NO_3)_2$	403	533	533
$CaCl_2$	100	133	133
$Mg(NO_3)_2$	134	178	178
Hortrilon	8	11	11
Sequestrene	8	11	11

[a] Calculated on a basis of irrigation water applied. To prevent a low concentration of nutrients in the recirculated leachates and abrupt osmotic changes, the NPK concentration was increased.

2.2. Water-use efficiency (WUE)

To relate the amount of biomass produced to the amount of water used, the water-use efficiency was used as indicator (WUE) previously established in the literature (Green et al., 2010; Muñoz et al., 2008). The WUE is defined as the rate of biomass accumulation per unit of water consumed and allows a simple comparison of various crop production systems, such as greenhouse versus field production. For the present work, the WUE was calculated as the relation between water supplied (in liters) and yield (kg of tomatoes produced) for the entire crop cycle, as shown by Eq. (1).

$$WUE = \frac{Liters\ of\ added\ water\ to\ the\ system, [L]}{Kilograms\ of\ Tomatoes\ produced\ by\ the\ system [Kg]} \tag{1}$$

2.3. Nutrient balance

The nutrient balance was estimated by determining the nutrient input through the irrigation system and the nutrient output embodied in the crop, residual biomass, and leachates. The difference was attributed to the accumulation of nutrients in the perlite substrates and compared with previous studies as a cross check.

Eq. (2) was used to estimate the total amount of nutrients (nitrite, nitrate, phosphorus, and potassium) in both water flows: input (irrigation) and output (leachates or drainage).

$$Total\ amount\ of\ nutrients\ from\ irrigation\ or\ leachates\ [kg] = \frac{\sum X_i * [Nc]_i}{10^6} \tag{2}$$

where i is a specific period of time, X_i represents the partial volume [L] for period i, and Nc_i is the nutrient concentration $[mg{\cdot}L^{-1}]$. In this way, the total amount of nutrients is the sum of the multiplication of the partial concertation by the volume. To obtain nitrite and nitrate concentrations, the irrigation and leachate samples collected directly from the dripper three times per week with ion chromatography were analyzed (ICS-1000 and AS-DV by Dionex), whereas nitrate, total phosphorus, and potassium concentrations were obtained via atomic spectroscopy (optima 4300DV by PerkinElmer).

To estimate the nutrients embodied in the crop and residual biomass, Eq. (3) was used, where DM_i represents the partial dry matter of the sample of tomatoes $[g_{\ dry\ matter}]$, and $Nc_{DM\ i}$ is the nutrient

Table 2
Crops and treatment under assessment.

Management	Initial plants	Daily drainage	Year	Start	Ends
Open (OP)	171	~30%	2018	10th January	30th July
Recirculated control (RC)	90	~30%	2019	14th January	2nd August
Recirculated reduction (RR) (~15% irrigation reduction of RC)	81				

concentration [mg·g $^{-1}_{\text{dry matter}}$] obtained by gas chromatography for N (6890 by Agilent Technologies and 5973 by HP) and atomic spectroscopy (Optima 4300 DV by PerkinElmer) for P and K. Five tomato samples for each irrigation management were used.

$$\textit{Total amount of nutrients from biomass and tomatoes}\ [kg] = \sum DM_i * [Nc_{DM}]_i \tag{3}$$

To estimate nitrogen emissions to the atmosphere, the value proposed by Llorach-Massana et al. (2017), which considers an emission factor of 0.00785 kg·N_2O^{-1} per kg·N^{-1}, was used.

Finally, the nutrient balance was calculated with Eq. (4) (values expressed in Kg), where X_T represents the total mass of nutrient supplied by the irrigation. X_L is the amount of nutrients in the leachates. X_Y and X_B represent nutrient uptake by tomatoes and the rest of the biomass (leaves and stem). X_{EA} represents the emissions to the atmosphere, which in our case is only applicable to N in the form of N_2O.

$$X_T = X_L + X_B + X_Y + X_{EA} \tag{4}$$

2.4. Life cycle assessment (LCA)

The LCA (ISO 14040, 2006) methodology was used in this study because it provides a broad vision of the environmental impacts, allowing us to determine the particular contributions of each item considered in our system. This provides a big picture on the performance of the different water management and its implications at the productive level, considering all life cycle stages for tomato production.

The main function of the greenhouse is food production, 1 kg of tomatoes was determined as a descriptor. In the same way, previous research has used this functional unit as a reference in tomato (Piezer et al., 2019; Pineda et al., 2020) and other crops (Arcas-Pilz et al., 2021; Rufí-Salís et al., 2020a).

System Boundaries.

To better discuss the results, the assessment is separated into two systems, as shown in Fig. 2: 1) the infrastructure, which considers all life cycle stages of the greenhouse structure, RWHS, auxiliary equipment, and recirculation system, as well as any materials that had more than a 5-year lifespan; and 2) the operational system, which includes all life cycle stages of the fertilizers, growth media, pesticides, nursery plants, and energy (treatment, pumping, and transport). The auxiliary equipment considered in this work is crop trays, manometers, pumps, water polyethylene tanks (2 × 300 L), and leachates polyethylene tank (300 L). (For more details see the supplementary information Appendix C). Waste management for the operation system considered the transport and landfilling of perlite after three years of use. Biomass obtained throughout the experiment due to pruning and at the end of the production season was composted, although this process was not considered within the environmental analysis. The impacts from transport to the distribution of the tomatoes to the consumers are not considered since the building personnel consumed the tomatoes. (See Fig. 3.)

2.4.1. Inventory

Previous inventories developed for this i-RTG were used for the RWHS and nursery plants (Sanjuan-Delmás et al., 2020; Sanyé-Mengual et al., 2015) and auxiliary equipment Rufí-Salís et al. (2020a).

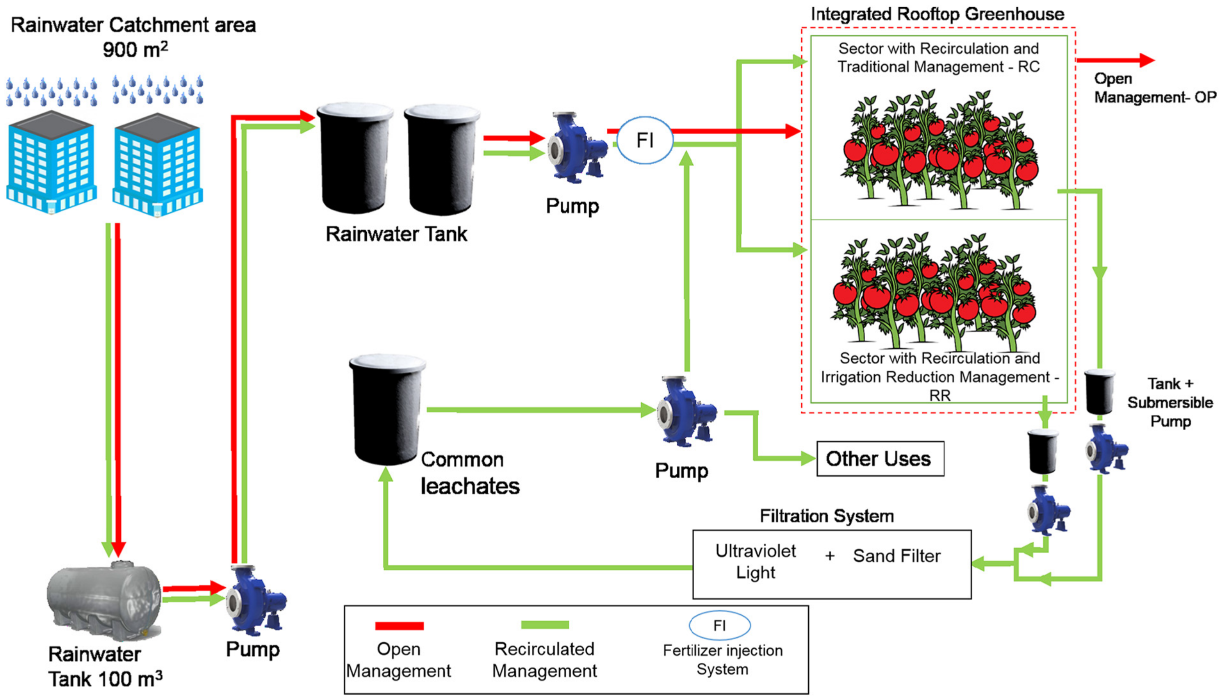


Fig. 2. The three irrigation schemes, including auxiliary equipment. OP management (red line), recirculated management (green line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

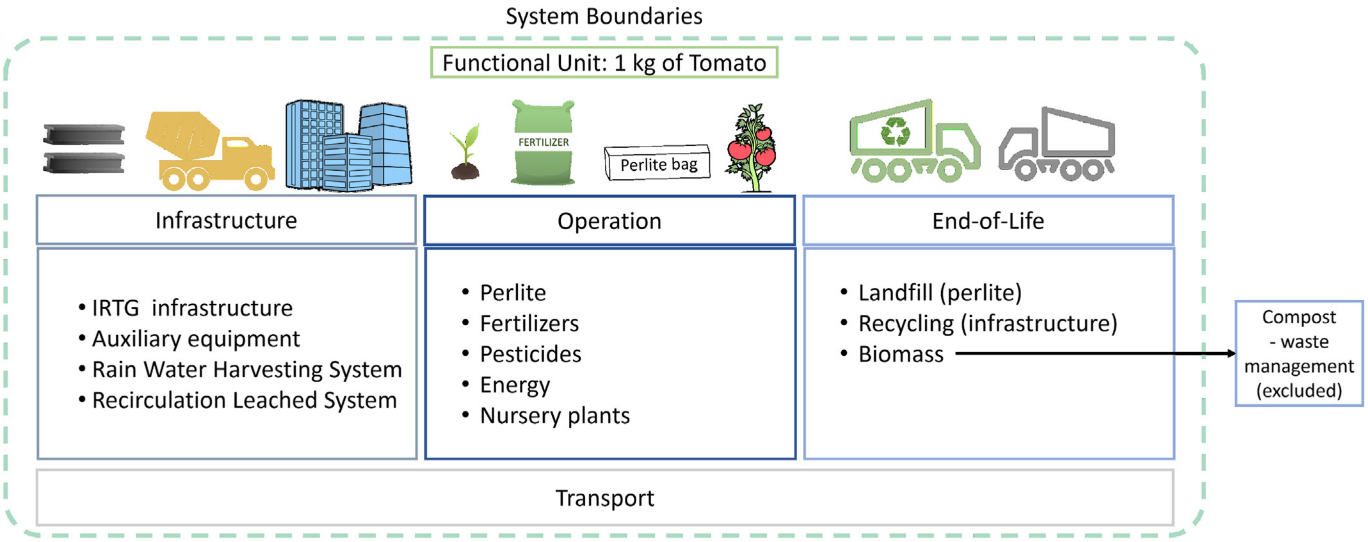


Fig. 3. Diagram of system boundaries, depicted by the dotted green line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The emissions in the leachate were considered to be directly emitted to the aquatic environment and were determined to be $^{-}NO_2$ and $^{-}NO_3$. Air emissions from nitrogen fertilization were calculated using emission factors by Montero et al. (2011) and the IPCC (De Klein et al., 2006). The life cycle inventory is available in the supplementary information (Appendix C.1 and C.2) for the infrastructure and operational subsystems, respectively. An impact allocation procedure based on rainwater volume consumed was applied to estimate the impacts of the RWHS attributed to the crops because this system is also used for irrigation of ornamental plants throughout the building, as had been done previously for other i-RTG studies (Rufí-Salís et al., 2020b). An allocation procedure was applied for the fertilizers, which were calculated in a linear proportion concerning the irrigation water applied. In the same way for pesticides, the proportion was calculated in a linear proportion to the number of plants present at that moment in the field.

Finally, impact assessment was performed with Simapro 9 software, and environmental information was acquired from Ecoinvent Database v3.5 (Wernet et al., 2016). The life cycle impact assessment (LCIA) entailed the use of the Recipe 2016 method (Hierarchical) at the midpoint level (Huijbregts et al., 2017). The impact categories considered in this study were global warming, (kg CO_2 equivalent), terrestrial acidification (kg SO_2 equivalent), freshwater eutrophication (kg P equivalent), marine eutrophication (kg N equivalent), fossil resource scarcity (kg oil equivalent), cumulative energy demand (MJ), and ecotoxicity (kg 1,4-DB equivalent), which is the sum of marine, terrestrial, and freshwater ecotoxicities. A cutoff criterion was used to estimate the environmental impacts, and it was assumed that the secondary product receives the impacts and benefits of the recycling process.

3. Results

This section presents the experimental, analytical, and environmental results of the three irrigation management schemes. First, the water-use efficiency (WUE) is presented, where OP was the least efficient and RR was the most efficient. Next, the temperature and relative humidity were similar for both 2018 and 2019, thereby affecting the yield equally for all experiments. Second, nutrient balance was performed to determine the nutrient flows for an accurate accounting of the emissions to the environment. Finally, the results of the life cycle analysis identify the environmental benefits and costs for the infrastructure and the operation of these schemes.

Despite the recirculation and reduction of water and nutrients, all three irrigation schemes obtained similar yields ranging from 16.2 $kg\cdot m^{-2}$ for open management (OP) to 17.9 $kg\cdot m^{-2}$ for recirculation control (RC), as shown in Table 3. These values are consistent with those achieved in other studies of tomato production in conventional greenhouses under similar ventilation conditions, such as Boulard et al. (2011), who reported 15 $kg\cdot m^{-2}$ in France, and Muñoz et al. (2008), who reported a similar value of 16.5 $kg\cdot m^{-2}$ in Spain.

WUE was calculated to determine the biomass accumulation (edible yield) per liter of irrigated water to be able to compare productivity among the various irrigation systems explored. Here, leachate recirculation management (RR) showed the best performance, with 48.7 $L\cdot kg^{-1}$, follow by recirculation control (RC -52.4 L·kg-1) and open system (75.2 L·kg-1) as shown in Table 3. Although RR obtained less production, in terms of WUE was approximately 35% more efficient than OP management.

3.1. Yield and climatic variables

Yield depends not only on water and nutrients but also on other factors, such as the amount of radiation received. Consequently, it is important to determine to what degree radiation contributed to the yields obtained, rather than or in addition to the irrigation scheme chosen. The total radiation (more details in supplementary information - Appendix E) during the crop season in 2018 and 2019 was very similar, averaging 3610 MJ and 3988 MJ, respectively (~7% difference), thereby allowing us to discard any hypothesis that similar yields were obtained in the RR and RC systems as in the OP system due to more radiation compensating for the lack of water or nutrients. This situation contrasts with the one presented by Rufí-Salís et al. (2020b), where important differences in terms of radiation above 60% were given in crop seasons of 60 and 90 days long (green bean crop). Longer campaigns, such as the tomato cycle, are more stable in terms of accumulated radiation since a longer period of time allows climatic variability to be absorbed.

Table 3
Summary of agronomic variables (yield, water used, and WUE).

Parameter	Unit	2018 OP	2019 RC	2019 RR	RC/OP	RR/OP	RR/RC
Yield[a]	$kg\cdot m^{-2}$	16.2	17.9	16.8	110.2%	103.2%	93.7%
Water used[b]	$L\cdot m^{-2}$	1220.7	936.8	815.7	76.3%	66.4%	87.1%
WUE[c]	$L\cdot kg^{-1}$	75.2	52.4	48.7	69.3%	64.4%	92.9%

[a] Yield considering all tomatoes harvested, divided by effective harvest area.
[b] Calculated on a basis of irrigation water added to the system.
[c] Water-use efficiency considering liters per kilogram of tomatoes.

The temperature and relative humidity during the experimental periods of the two years. In terms of temperature, 2018 was initially slightly colder, but March onwards, the temperature inside the urban agriculture laboratory was similar for both years. Regarding outdoor temperatures, 2019 was slightly colder until April, after which there were no significant differences in temperature. The internal relative humidity was higher in 2018. The external relative humidity was very similar in both years. A summary of the temperature, relative humidity, vapor pressure deficit, and radiation for both years can be found in supplementary information - Appendix D.

3.2. Nutrient balance

Nutrient balance calculations were performed for N, P, and K, and the results are shown in Table 4. The calculations based on measured concentrations were able to total account for 77 to 84% of N, 59 to 69% of P, and 86 to 92% of K. The remaining amounts of nutrients are assumed to be accumulated in the perlite bags, since the conditions were similar to Sanjuan-Delmás et al. (2020) for the same substrate (with values of 5% of N, 6% of P, and K values were marginal), and the rest of the values are possibly attributable to dissipative losses. Despite a reduction in nutrients supplied in the RC and RR systems, all three systems showed similar assimilation rates of N in the tomatoes, ranging between 22 and 24%, indicating that the recirculation schemes did not cause an insufficient nutrient supply. K accounted for more in the RC and RR systems (20 and 22%, respectively) than in the OP management (18%). The results were opposite for P assimilation: RC and RR assimilated less P (10 and 11%, respectively) than OP (15%). In terms of nitrogen in the tomatoes, all management practices showed similar values, ranging from 22% to 24% (Table 4). In terms of phosphorus accounting in the biomass, there was a difference of 12% between OP and RC (36 and 24%). Potassium accounted in biomass present a maximum difference between RR and OP (40% and 30%, respectively).

3.3. Life cycle assessment

Life cycle assessment was performed on all three irrigation management practices, and the results were disaggregated into the operational phase (use of fertilizers, substrate, pesticides, and nursery plants) and infrastructure (auxiliary equipment, greenhouse structure, and RWHS), as shown in Fig. 4. In terms of the operational stage, freshwater and marine eutrophication impacts were reduced by 59% and 98%, respectively, in the RC management due to the avoided leaching of nitrogen and phosphorus. In general, energy and fertilizer use were the highest contributors in all impact categories, ranging from 35% in fossil resource scarcity to 99% in marine eutrophication for the OP management. The energy used within the RWHS system was to pump water from the 100 m^3 tank buried underground to the 2 containers (300 L each one) inside the greenhouse on the top floor of the building, where it was distributed to the plants through the irrigation system. The reduced energy requirement due to less volume of water being used in the RR and RC management was enough to offset the energy required for the additional pumping during recirculation, resulting in overall reduction in the global warming category of 28% and 19% for RR and RC, respectively, compared with OP. Since all three schemes used water from the same rainwater harvesting system, there were no energy savings associated with fewer water treatment requirements for RR and RC. Pesticides, substrates and nursery plants represented less than 5% of the impact in this analysis. The main factor was the substrate, and its impacts were associated with transport from its production site. The impact from pesticides can be explained by the implementation of integrated pest control. This type of control reduces to a minimum the application of chemical products for pest and disease control. As mentioned above, the greenhouse is connected to the building, the application of chemicals is very restricted. Organic products are in low concentrations and are used to control pests and diseases. In this sense, the risks of generating an impact are minimum, both for health and for the environment.

The infrastructure category includes the greenhouse structure, RWHS, and auxiliary equipment, which are all applicable to all three systems, and consequently, all three have similar impacts in all categories. Differences were only due to the small variability in the yield.

In particular, it is important to mention that for the RWHS, the items that presented the highest impacts in all categories were the production of the glass fiber tank and injection molding. Auxiliary equipment exerted high relative impacts on terrestrial acidification, freshwater eutrophication, and ecotoxicity. These impacts are associated with the use of aluminum and injection molding.

4. Discussion

This section discusses the results in light of previous literature, focusing first on the effect of water management on the obtained yields, in addition to the influence of other variables such as greenhouse materials. Second, the effect of water and nutrient management was examined on environmental performance through life cycle analysis and how the various schemes affected the nutrient-uptake capacity of the crop. Last, through a sensitivity analysis, the following question was answered: what is the minimum yield that still provides environmental benefits? Finally, we analyze the potential optimization of the different elements within the operational subsystem and provide recommendations for greenhouse infrastructure.

4.1. Effect of water management on crop yield

Water reduction and recirculation did not limit productivity of the tomato plants. The yields obtained in the configurations with

Table 4
Mass balance of nutrients by management.

	Nutrients	Input [kg]	Output [kg]				Input/output [%]				Total	Nutrient-uptake efficiency	Nutrient-Use Efficiency
		Irrigation water	Leachates	Air emission	Biomass	Tomato	Leachates/Other uses	Air emission	Biomass	Tomato	[%]		
2018 OP	N	6.38	1.39	0.05	2.34	1.55	22	0.8	37	24	84	0.61	162
	P	2.34	0.42		0.85	0.36	18	–	36	15	69	0.52	441
	K	16.72	6.57		4.96	2.93	39	–	30	18	87	0.47	62
2019 RC	N	2.5	0.41	0.02	0.95	0.55	16	0.8	38	22	77	0.60	221
	P	1.27	0.32		0.31	0.13	25	–	24	10	59	0.35	435
	K	5.73	1.72		2.07	1.14	30	–	36	20	86	0.56	96
2019 RR	N	2.08	0.35	0.02	0.87	0.5	17	0.8	42	24	84	0.66	239
	P	1.06	0.27		0.28	0.11	25	–	27	11	63	0.32	470
	K	4.75	1.45		1.89	1.05	30	–	40	22	92	0.67	105

*Absorbed macronutrient (N-P-K) was determined from the biomass and tomatoes. We extend the equation of Albornoz et al. (2020) for nitrogen for all macronutrients to determine uptake efficiency and use efficiency. The last two columns are as follows: nutrient-uptake efficiency determined as nutrients absorbed by the plant [kg]/nutrients supplied through irrigation [kg]; and nutrient-use efficiency calculated as the mass of tomatoes harvested [kg]/nutrients supplied from planting until harvest [kg].

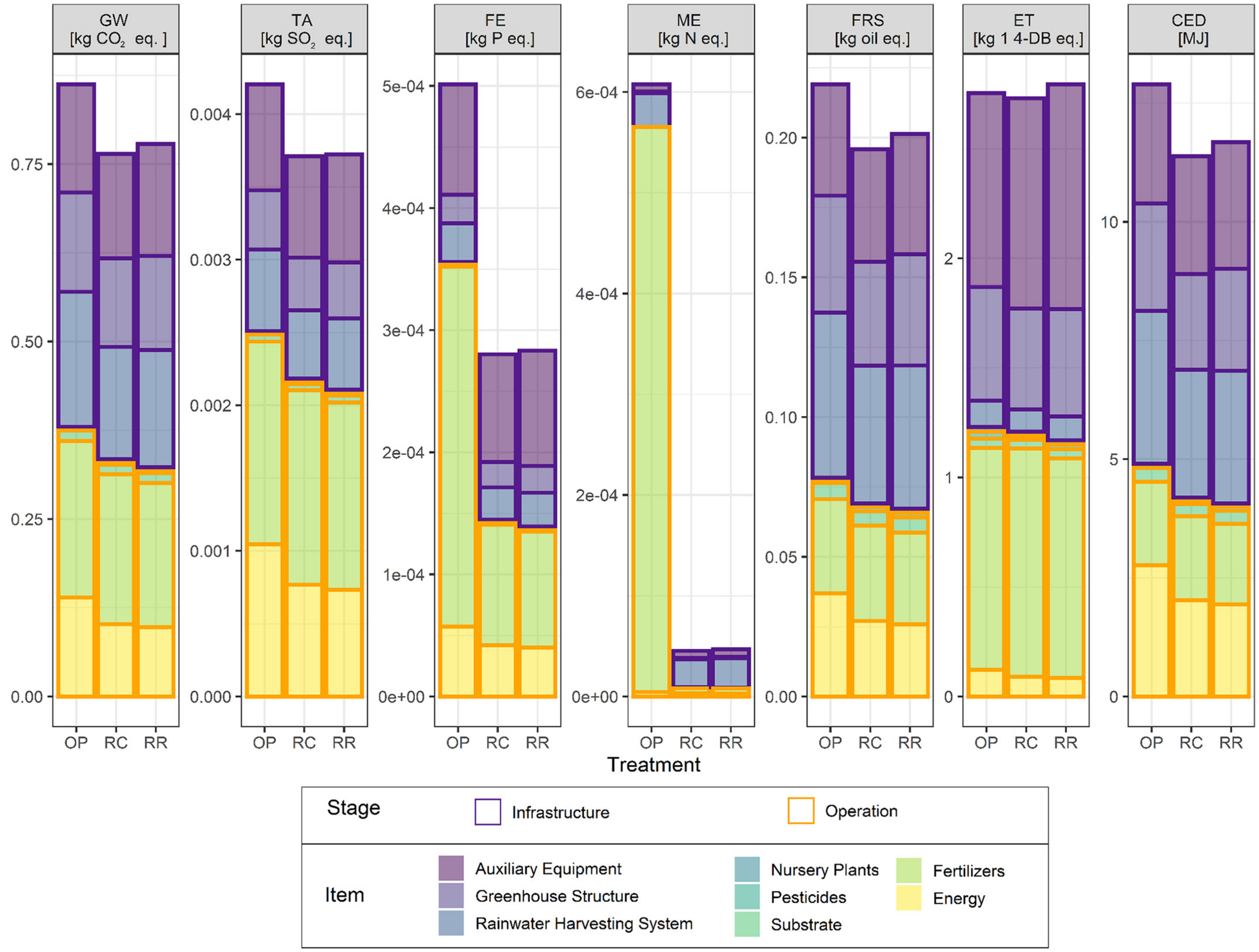


Fig. 4. Environmental performance per kg of tomato crop. Open management (OP), recirculated management control and reduction (RC and RR). Global warming (GW), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), fossil resource scarcity (FRS) and ecotoxicity (ET). The numerical data are presented in supplementary information - Appendix A and B.

recirculation (RC) and reduction (RR) were similar and even slightly higher than the yields obtained in open management (OP), which was irrigated conventionally for the tomato variety under study. To analyze water consumption further, the WUE was calculated as indicator, which indicates water consumed per biomass accumulation and was calculated. The RR strategy had the lowest WUE because it used 13% less water, while its yield was slightly lower than that of RC (6.3% lower). The WUE values were similar to those found in previous studies, such as Chen et al. (2018), who presented an experiment of irrigation/aeration levels in a solar greenhouse with tomato production (in soil) in a semiarid region, obtaining a WUE from 35.7 L·kg^{-1} to 65.3 L·kg^{1}. Furthermore, our results confirm previous studies that found that limiting the water supply actually improved the nutrient metabolism of the plant. For example, previous studies (Favati et al., 2009; Wang et al., 2019) found that reducing irrigation applied to tomato crops resulted in better water-use efficiency and that appropriate deficit irrigation can improve fruit quality in terms of nutritional characteristics. Zhang et al. (2017) also found that reducing irrigation to 80% of evapotranspiration did not reduce yield.

The question that arises is to what degree can water be reduced while maintaining yield in this hydroponic urban agricultural setup? A drastic reduction in irrigation can have detrimental effects concerning the crop's final yield. Therefore, it is necessary to reach a balance that reduces water inputs while maintaining satisfactory production. Previous research conducted on tomato crops in the same climate (Muñoz et al., 2008) has shown lower WUEs than those in this study, ranging between 30.2 and 36.2 L·kg^{-1}, approximately 20 L·kg^{-1} less in comparison with our results, indicating that there is still margin in terms of water reduction. To ascertain to what degree irrigation can be reduced without affecting the yield, some considerations must be taken into account. It is important to understand that the intensified salinization of the substrate due to a decrease in applied water can reduce the accumulation of biomass due to the increase in osmotic potential in the substrate solution. This can be alleviated through irrigation management that favors the removal of excess salts at the same time that water is reincorporated into the substrate. It is also important to maintain the matrix potential of the substrate, defined as the force with which water is held by particles and pore space (Yadvinder-Singh et al., 2014). In our situation, tomatoes have been estimated to be −10 and − 40 kPa (Baudoin et al., 2017; Buttaro et al., 2015); if water is reduced to the point where the matrix potential is below this value, the assimilation of CO_2 by the plant is reduced by closing the stomata as a defense mechanism.

Another strategy to optimize water is to vary the distribution of irrigation throughout the day. In our experiments, ten irrigations were applied per day, increasing the quantity towards solar zenith, and reducing it in the afternoon (in accordance with water demand). Other strategies are worth exploring, such as more frequent irrigation times with less volume or increasing irrigation to favor more leaching and water reuse. The aim of the latter strategy is to promote transpiration at times of increased water demand, to avoid physiological limitations, and favor adaptive behavior of the crop, to minimal hydric and nutritional requirements (Li et al., 2017; Madrid et al., 2009; Ullah et al., 2017). Water demand models, such as the Penman-Monteith fixed equation (Gong et al., 2019; Qiu et al., 2013), can also aid in more precisely determining the amount of water to apply. However, these models need to be adapted to urban agricultural technologies to be applied to these systems.

In addition to water, yield is also influenced by temperature and radiation. Both years of our experiments had very similar radiation, relative humidity, wind speed, and temperature. Consequently, evapotranspiration rates were comparable; therefore, the impact of climatic variables on the yield in the various schemes was reviewed. However, it is necessary to emphasize the importance of selecting greenhouse materials that allow a high transmittance rate to obtain optimal productive conditions. The i-RTG is composed of polycarbonate (with a lifespan of 10 years) that allows 88% theoretical transmissivity (Model Marlon CS - Brett Martin), is resistant to impacts and has an intermediate level of insulation. While other materials with higher transmittance may be employed, it is important to consider lifespan and resistance because that will directly affect the life cycle impacts of the infrastructure (Parajuli et al., 2021). Muñoz-Liesa et al. (2021) suggested that both glass and glass films have a similar transmittance of 90% and are environmentally better than polycarbonate. Glass has a long lifespan (15 years) in contrast to film (3–5 years) (Antón et al., 2012). However, the glass is rigid and has a heavy weight (1400 $g \cdot m^{-2}$), requiring a greater structure to support it, in contrast to plastic film with greater flexibility and lower weight (230 $g \cdot m^{-2}$) (Castilla Prados, 2004). The i-RTG setup had a satisfactory balance between transmittance, flexibility, weight, and environmental impacts.

In addition to the transmissivity of the material, it is also important to consider the effective radiation (interior radiation/external radiation) that reaches the plants. In our case, the structure and configuration of our greenhouse generates shadows and opaque walls, which reduce the amount of radiation inside the greenhouse. To compensate for the shadows inside the greenhouse and to maximize light throughout the day, the rows of tomato plants have a north-south orientation. Even so, the maximum effective radiation in the i-RTG has been estimated to be 45% for an entire year. It is relevant to emphasize the importance of designing rooftop greenhouses to maximize radiation further.

4.2. Effect of water and nutrient management on environmental and agronomical performance

There are two main environmental improvements derived from the application of recirculation strategies. First, the release of nutrients to the aquatic environment is minimized, thus considerably reducing the contribution to freshwater and marine eutrophication. Second, the nutrients that are recovered through the recirculation system are used again instantly, maximizing the efficiency of the use of resources and avoiding the additional impact generated by new fertilizers and their transport. Considering that some macronutrients, such as P, are nonrenewable and have negligible recycling rates (Villalba et al., 2008), improving use efficiency is critical in current nutrient-intensive agriculture. The reduction of nutrients has resulted in the most significant life cycle benefits. These benefits are appreciated in the reduction of marine and freshwater eutrophication, as well as the reduction of energy required for fertigation, as shown in Fig. 5. OP presents a greater impact in terms of energy for all impact categories. The remaining items (substrates, fertilizers, pesticides and nursery plants) in the three management systems have similar impacts.

Other research has shown similar results concerning the impact of fertilizers during the operational stage. Muñoz et al. (2017) confirmed our findings that recirculation systems can reduce impacts. Similarly, Rufí-Salís et al. (2020a) showed how open systems have a high impact in the freshwater and marine eutrophication categories, with 90% for both impact categories, due to the leachate emission of phosphorus and nitrogen to the environment.

In addition to reducing nutrients through recirculation and reduction, impacts can be further minimized by substituting chemical fertilizers, such as calcium nitrate and potassium sulfate. Determining appropriate substitutes requires understanding the various combinations of NPK. For example, the use potassium nitrate (with an N:P:K ratio of 13-0-45) instead of potassium sulfate (0-0-50) to deliver potassium to the plants, the first fertilizer also provides nitrogen in the form of nitrate, which could highly affect the nutrient dynamics at the crop, plant and substrate

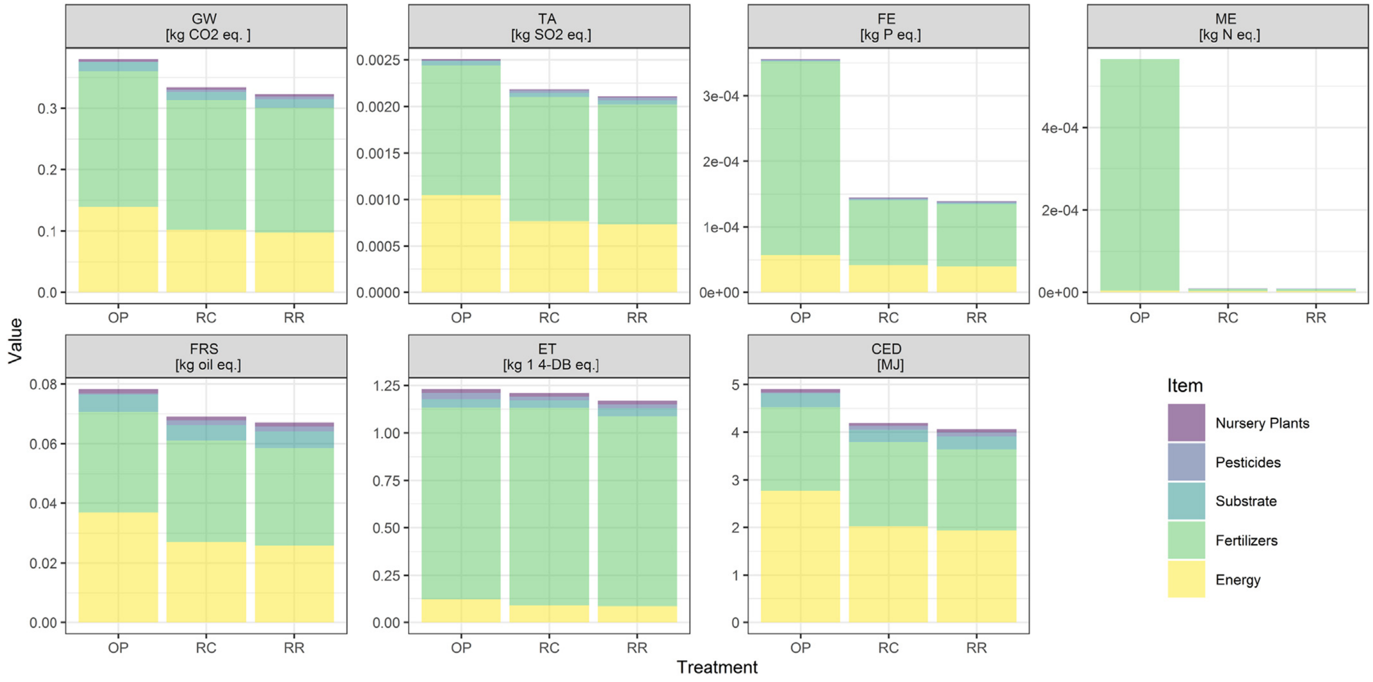


Fig. 5. Life cycle impacts of the Recirculation and Recovery (RR), Recirculation (RC), and Open (OP) systems during the operational stage.

levels. In this way, fertigation schemes that constantly evaluate the nutrient dynamics of the crop and that also consider environmental aspects can be highly effective in reducing the impact of agriculture.

To evaluate the agronomical performance of the various schemes, the nutrient uptake and use efficiency was analyzed, which are shown in Table 4. The nitrogen-uptake efficiency, defined as the nitrogen absorbed to the nitrogen supplied to the irrigation system, was similar in the three treatments, ranging between 0.60 and 0.66. This is an important finding of the experiments: the recirculation and reduction schemes of nutrients and water did not affect the nutrient-uptake capacity of the crop. Additionally, the nitrogen-use efficiency calculated as the mass of total tomatoes harvested (in kg) divided by the mass of nitrogen supplied to all tomato plants for the entire experimental cycle (kg) was lowest for the OP system, further indicating that the recirculation and reduction schemes resulted in higher nitrogen-use efficiency. Other studies have also shown that reductions in supplied nitrogen have increased the efficiency of the use of this resource (Min et al., 2011), and the RC and RR management practices present 37% - 48% more efficiency than OP. In this sense, this value can be explained by the effect of the recirculation system, which reduces the amount of nitrogen applied, causing the biomass-nutrient ratio to increase, in contrast to the nutrient-uptake efficiency.

In contrast, phosphorus-uptake efficiency showed a reduction in the recirculated managements compared with the OP system, from 0.52 (OP) to 0.35 (RR) kg of P absorbed per kg supplied. One potential explanation is that due to recirculation, sulfate ions accumulate over time, creating high concentrations of sulfate anions that compete with phosphates for root uptake, as has been seen in other studies (Marcelis and Heuvelink, 2019; Pardossi et al., 2002). Aulakh and Pasricha (1977) presented a test of nutrient assimilation rates and different concentrations of phosphorus and sulfur in *Phaseolus aureus* L. They mentioned that an antagonistic effect between these ions could be explained by competition at the root absorption sites or for the same uptake pathways. This could explain the lower rate of phosphorus assimilation in the recirculation treatments. However, in terms of nutritional value, phosphorus-use efficiency was comparable among all three treatments, with a range from 441 to 470 kg of tomatoes produced per kilogram of phosphorus applied. Regarding potassium, both uptake and use efficiency showed the same increasing trend from OP to RC to RR. The highest value observed in RR could be explained by an increase in potassium retention in the tissues of a plant associated with a water deficit (De Luca et al., 2021).

Analytical validation is required to utilize the full potential of fertilization management strategies by improving nutrient retention through dilution or increasing the concentration if required. The application of sensors would allow fertilization management to be better adjusted to the needs of the crop while maximizing the efficiency of irrigation strategies. Through the measurement of moisture in the substrate to have more efficient control of humidity and irrigation (Zotarelli et al., 2009), and through nutrient availability sensors, the management of both irrigation water and recirculation water quality can be better adjusted.

4.3. Effect of radiation on yield and life cycle impacts

Since the environmental impacts determined through LCA are dependent directly and linearly on the yield, a logical next step is to determine the minimum yield that still provides environmental benefits. First, to need consider the variability of yield related to the radiation received by the crop. To do so, the model proposed by Montero et al. (2017) was adapted to obtain a theoretical yield based on the potential radiation range during a standard growth period (195 days) and the radiation-use efficiency of the tomato plant of 8.77 $g \cdot MJ^{-1}$ (Montero et al., 2017). Radiation data were obtained from a nearby weather station 8 km northeast (Ruralcat, 2019) from the laboratory for eleven consecutive years (2009 to 2019). During the standard growth period, the maximum and minimum radiation values obtained were 3541 and 3904 MJ (accumulated per season), respectively; therefore, obtaining the minimum and maximum theoretical yield ranges.

Next, based on the LCA results of the RC treatment, the life cycle inventory was adjusted to determine the LCA for both the minimum and maximum yield that could occur due to radiation variability. The amount of water used for each theoretical yield was adjusted by means of the WUE (water potentially consumed = yield [kg]/WUE [$L \cdot kg^{-1}$]). Based on the water used, the new impacts of energy and RWHS were estimated. The fertilizers varied proportionally to the variation in yield (for a more detailed review, see supplementary information - Appendix E and F).

Fig. 6 shows that impacts increased by approximately 8% when the minimum yield was considered. The highest increase was observed in cumulative energy demand (9.7%), and the lowest was observed in ecotoxicity (5.1%). In contrast, when analyzing the maximum yield, impacts were only reduced on average by a value close to 1%, even with positive values (terrestrial acidification). The greatest reduction was seen in ecotoxicity (4.6%). Since water-use efficiency presents an average value higher than the one obtained within the present study, although there is a rational use, productivity (yield increase) tends to be above efficiency; this situation generates an overestimation in water consumption, which translates into a more significant impact. The theoretical maximum performance obtained with the model is 11% higher than the yield obtained in RC. Despite the yield increase, environmental performance does not show improvements due to the increase in the operational values.

5. Final remarks and conclusions

Our main conclusion is that the implementation of water and nutrient recirculation and reduction in the i-RTG for tomato plants did

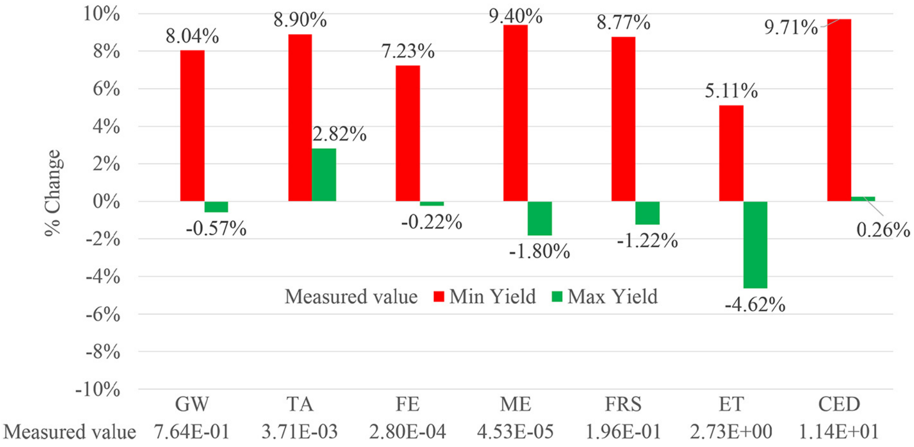


Fig. 6. Sensitivity analysis with the minimum and maximum theoretical yields.

not affect the yield, while it minimized eutrophication impacts related to nutrient discharge and increased water-use efficiency. The methodology applied has proven to be consistent for the environmental analysis of an i-RTG as in other research (Rufí-Salís et al., 2020b; Sanjuan-Delmás et al., 2018). It may be replicable for different types of production.

This work provides information on the environmental impacts associated to food production and how they can be solved through the implementation of the recirculation system in an i-RTG. This kind of system allows the reuse leachates and nutrient recovery, in contrast open systems, is usually extensive, irrigation control is more complex and less efficient. Additionally, the characteristics of the substrate in soilless systems are homogeneous in all crop bags used in the greenhouse, unlike what occurs in open systems where the soil can present high spatial variability in the physical and chemical characteristics. In this sense, fertilization plans adjusted by mass balance, which consider the availability of soil nutrients, together with the removal of the crop, are an important tool for managing the impacts of open systems.

In terms of water-use efficiency, RR management was the most efficient, requiring 48.7 L per kg of harvested tomato, followed by RC (52.4 L·kg1) and OP (75.2·L·kg-1). Among recirculation management practices, irrigation reduction (RR) presented an improvement of 7% in water-use efficiency. In terms of environmental performance, RC shows the best performance in almost all impact categories during the operational phase, especially in marine and freshwater eutrophication, with 44% and 93% fewer impacts. For the infrastructure phase, the replacement of materials such as aluminum with lower impact recycled plastics.

This study can support the decision-making process of the design of agricultural projects in the city, through yields and water consumption obtained per square meter, in order to have a basis to contrast for urban agriculture projects. Similarly, to have more information about the environmental impacts generated within a recirculating crop, in order to compare other UA typologies. As well as can help the activity of incentivizing good practices aligned with the sustainability of urban agriculture. At the domestic or private level, the idea of promoting the use of closed production systems, in order to reduce nutrient emissions to the environment, and their derived detrimental effects, can be highlighted.

For further research it is necessary to consider: 1) developing ways to optimize irrigation distribution which ultimately reduces overall water and fertilizer consumption because uptake efficiency is improved; 2) choosing highly transmissive materials while safeguarding low life cycle impacts and long lifetimes; and 3) finding ways to ensure high effective radiation for greenhouses, especially those that are accommodated to already existing buildings that were not originally designed to maximize radiation on the entire surface of the rooftop.

CRediT authorship contribution statement

Felipe Parada: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Xavier Gabarrell:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Martí Rufí-Salís:** Methodology, Data curation, Visualization, Writing – review & editing. **Verónica Arcas-Pilz:** Methodology, Investigation, Writing – review & editing. **Pere Muñoz:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Gara Villalba:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

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.

Acknowledgments

We would like to acknowledge the following funding sources for this work: the European Commission's ERC Consolidator grant 818002-URBAG led by G. Villalba and the National Commission for Scientific and Technological Research (Chile) for the grant awarded to F. Parada [grant number PFCHA-CONICYT 2017 – Folio 72180248].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.148689.

References

Albornoz, F., Nario, A., Saavedra, M., Videla, X., 2020. Rootstock x environment interactions on nitrogen-use efficiency in grafted tomato plants at different phenological stages. Agronomy 10, 350. https://doi.org/10.3390/agronomy10030350.

Antón, A., Torrellas, M., Montero, J.I., Ruijs, M., Vermeulen, P., Stanghellini, C., 2012. Environmental impact assessment of Dutch tomato crop production in a Venlo glasshouse. Acta Hortic., 781–791 https://doi.org/10.17660/ActaHortic.2012.927.97.

Arcas-Pilz, V., Rufí-Salís, M., Parada, F., Gabarrell, X., Villalba, G., 2021. Assessing the environmental behavior of alternative fertigation methods in soilless systems: the case of Phaseolus vulgaris with struvite and rhizobia inoculation. Sci. Total Environ. 770, 144744. https://doi.org/10.1016/j.scitotenv.2020.144744.

Aulakh, M.S., Pasricha, N.S., 1977. Interaction effect of sulphur and phosphorus on growth and nutrient content of moong (Phaseolus aureus L.). Plant Soil 47, 341–350. https://doi.org/10.1007/BF00011493.

Baudoin, W., Nersisyan, A., Shamilov, A., Hodder, A., Gutierrez, D., De Pascale, S., Nicola, S., Gruda, N., Urban, L., Tanny, J., 2017. Good Agricultural Practices for Greenhouse Vegetable Production in the South East European Countries - Principles for Sustainable Intensification of Smallholder Farms.

Boulard, T., Raeppel, C., Brun, R., Lecompte, F., Hayer, F., Carmassi, G., Gaillard, G., 2011. Environmental impact of greenhouse tomato production in France. Agron. Sustain. Dev. 31, 757. https://doi.org/10.1007/s13593-011-0031-3.

Buttaro, D., Santamaria, P., Signore, A., Cantore, V., Boari, F., Montesano, F.F., Parente, A., 2015. Irrigation management of greenhouse tomato and cucumber using tensiometer: effects on yield, quality and water use. Agric. Agric. Sci. Procedia 4, 440–444. https://doi.org/10.1016/j.aaspro.2015.03.050 Efficient irrigation management and its effects in urban and rural landscapes.

Caldeira, C., De Laurentiis, V., Corrado, S., van Holsteijn, F., Sala, S., 2019. Quantification of food waste per product group along the food supply chain in the European Union: a mass flow analysis. Resour. Conserv. Recycl. 149, 479–488. https://doi.org/10.1016/j.resconrec.2019.06.011.

Castilla Prados, N., 2004. Cápitulo 4: El invernadero de plástico, in: Invernaderos de Plástico. Ediciones Mundi-Prensa.

Chen, Y., Wen, X., Wang, B., Nie, P., 2017. Agricultural pollution and regulation: how to subsidize agriculture? J. Clean. Prod. 164, 258–264. https://doi.org/10.1016/j.jclepro.2017.06.216.

Chen, H., Hou, H., Hu, H., Shang, Z., Zhu, Y., Cai, H., Qaisar, S., 2018. Aeration of different irrigation levels affects net global warming potential and carbon footprint for greenhouse tomato systems. Sci. Hortic. 242, 10–19. https://doi.org/10.1016/j.scienta.2018.07.021.

Chen, Y., Hu, S., Guo, Z., Cui, T., Zhang, L., Lu, C., Yu, Y., Luo, Z., Fu, H., Jin, Y., 2021. Effect of balanced nutrient fertilizer: a case study in Pinggu District, Beijing, China. Sci. Total Environ. 754, 142069. https://doi.org/10.1016/j.scitotenv.2020.142069.

Contreras, J.I., Alonso, F., Cánovas, G., Baeza, R., 2017. Irrigation management of greenhouse zucchini with different soil matric potential level. Agronomic and environmental effects. Agric. Water Manag. 183, 26–34. https://doi.org/10.1016/j.agwat.2016.09.025 Special Issue: Advances on ICTs for Water Management in Agriculture.

Cook, E., European Commission, Statistical Office of the European Union, 2018. Agriculture, Forestry and Fishery Statistics: 2018 Edition.

De Corato, U., 2020. Agricultural waste recycling in horticultural intensive farming systems by on-farm composting and compost-based tea application improves soil quality and plant health: a review under the perspective of a circular economy. Sci. Total Environ. 738, 139840. https://doi.org/10.1016/j.scitotenv.2020.139840.

De Klein, C., Novoa, R.S.A., Ogle, S., Smith, K., Rochette, P., Wirth, T.C., Mcconkey, B.G., Mosier, A., Rypdal, K., 2006. N2O emissions from managed soils, and CO2 emissions from lime and urea application. 2006 IPCC Guidel. Natl. Greenh. Gas Invent, p. 4.

De Luca, A., Corell, M., Chivet, M., Parrado, M.A., Pardo, J.M., Leidi, E.O., 2021. Reassessing the role of potassium in tomato grown with water shortages. Horticulturae 7, 20. https://doi.org/10.3390/horticulturae7020020.

European Commission, 2011. Food: From Farm to Fork Statistics, 2011 Ed. Ed, Eurostat Pocketbooks. Publications Office of the European Union, Luxemburg.

FAOSTAT, 2017a. Food and Agriculture Organization of the United Nations FAO, Statistical Database. Fertilizers by Nutrient. [WWW Document]. URL. http://www.fao.org/faostat/en/#data/RFN (accessed 5.12.20).

FAOSTAT, 2017b. Food and Agriculture Organization of the United Nations FAO, Statistical Database. Crops. Tomatoe. [WWW Document]. URL. http://www.fao.org/faostat/en/#data/RFN (accessed 5.12.20).

Favati, F., Lovelli, S., Galgano, F., Miccolis, V., Di Tommaso, T., Candido, V., 2009. Processing tomato quality as affected by irrigation scheduling. Sci. Hortic. 122, 562–571. https://doi.org/10.1016/j.scienta.2009.06.026.

Gong, X., Liu, H., Sun, J., Gao, Y., Zhang, H., 2019. Comparison of Shuttleworth-Wallace model and dual crop coefficient method for estimating evapotranspiration of tomato cultivated in a solar greenhouse. Agric. Water Manag. 217, 141–153. https://doi.org/10.1016/j.agwat.2019.02.012.

Green, T.R., Yu, Q., Ma, L., Wang, T.-D., 2010. Crop water use efficiency at multiple scales. Agric. Water Manag. 97, 1099–1101. https://doi.org/10.1016/j.agwat.2010.03.018 Crop water use efficiency at multiple scales.

He, X., Qiao, Y., Liu, Y., Dendler, L., Yin, C., Martin, F., 2016. Environmental impact assessment of organic and conventional tomato production in urban greenhouses of Beijing city. China. J. Clean. Prod. 134, 251–258. https://doi.org/10.1016/j.jclepro.2015.12.004 Special Volume: Transitions to Sustainable Consumption and Production in Cities.

Hooshmand, M., Albaji, M., Boroomand Nasab, S., Alam Zadeh Ansari, N., 2019. The effect of deficit irrigation on yield and yield components of greenhouse tomato (Solanum lycopersicum) in hydroponic culture in Ahvaz region, Iran. Sci. Hortic. 254, 84–90. https://doi.org/10.1016/j.scienta.2019.04.084.

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. https://doi.org/10.1007/s11367-016-1246-y.

ISO 14040, 2006. ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework. International Standard Organization.

Li, Y., Sun, Y., Liao, S., Zou, G., Zhao, T., Chen, Y., Yang, J., Zhang, L., 2017. Effects of two slow-release nitrogen fertilizers and irrigation on yield, quality, and water-fertilizer productivity of greenhouse tomato. Agric. Water Manag. 186, 139–146. https://doi.org/10.1016/j.agwat.2017.02.006.

Liu, H., Li, H., Ning, H., Zhang, X., Li, S., Pang, J., Wang, G., Sun, J., 2019. Optimizing irrigation frequency and amount to balance yield, fruit quality and water use efficiency of greenhouse tomato. Agric. Water Manag. 226, 105787. https://doi.org/10.1016/j.agwat.2019.105787.

Llorach-Massana, P., Muñoz, P., Riera, M.R., Gabarrell, X., Rieradevall, J., Montero, J.I., Villalba, G., 2017. N2O emissions from protected soilless crops for more precise food and urban agriculture life cycle assessments. J. Clean. Prod. 149, 1118–1126. https://doi.org/10.1016/j.jclepro.2017.02.191.

Madrid, R., Barba, E.M., Sánchez, A., García, A.L., 2009. Effects of organic fertilisers and irrigation level on physical and chemical quality of industrial tomato fruit (cv. Nautilus). J. Sci. Food Agric. 89, 2608–2615. https://doi.org/10.1002/jsfa.3763.

Marcelis, L., Heuvelink, E., 2019. Achieving Sustainable Greenhouse Cultivation. Burleigh Dodds Science Publishing Limited https://doi.org/10.1201/9780429266744.

Martínez-Blanco, J., Muñoz, P., Antón, A., Rieradevall, J., 2011. Assessment of tomato Mediterranean production in open-field and standard multi-tunnel greenhouse, with compost or mineral fertilizers, from an agricultural and environmental standpoint. J. Clean. Prod. 19, 985–997. https://doi.org/10.1016/j.jclepro.2010.11.018.

Mason, B., Rufí-Salís, M., Parada, F., Gabarrell, X., Gruden, C., 2019. Intelligent urban irrigation systems: saving water and maintaining crop yields. Agric. Water Manag. 226, 105812. https://doi.org/10.1016/j.agwat.2019.105812.

Min, J., Zhao, X., Shi, W.-M., Xing, G.-X., Zhu, Z.-L., 2011. Nitrogen balance and loss in a greenhouse vegetable system in southeastern China. Pedosphere 21, 464–472. https://doi.org/10.1016/S1002-0160(11)60148-3.

Montero, J.I., Antón, A., Torrellas, M., Ruijs, M.N.A., Vermeulen, P.C.M., 2011. Environmental and Economic Profile of Present Greenhouse Production Systems in Europe - EUPHOROS Deliverable N 5 Final Report (No. Deliverable 5 Final Report). European Commission, Cabrils/Wageningen.

Montero, J.I., Baeza, E., Heuvelink, E., Rieradevall, J., Muñoz, P., Ercilla, M., Stanghellini, C., 2017. Productivity of a building-integrated roof top greenhouse in a Mediterranean climate. Agric. Syst. 158, 14–22. https://doi.org/10.1016/j.agsy.2017.08.002.

Muñoz, P., Antón, A., Paranjpe, A., Ariño, J., Montero, J.I., 2008. High decrease in nitrate leaching by lower N input without reducing greenhouse tomato yield. Agron. Sustain. Dev. 28, 489–495. https://doi.org/10.1051/agro:2008024.

Muñoz, P., Flores, J.S., Antón, A., Montero, J.I., 2017. Combination of greenhouse and open-field crop fertigation can increase sustainability of horticultural crops in the Mediterranean region. Acta Hortic., 627–634 https://doi.org/10.17660/ActaHortic.2017.1170.78.

Muñoz-Liesa, J., Toboso-Chavero, S., Mendoza Beltran, A., Cuerva, E., Gallo, E., Gassó-Domingo, S., Josa, A., 2021. Building-integrated agriculture: Are we shifting environmental impacts? An environmental assessment and structural improvement of urban greenhouses. Resour. Conserv. Recycl. 169, 105526. https://doi.org/10.1016/j.resconrec.2021.105526.

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. https://doi.org/10.1016/j.apenergy.2016.11.051.

Nagendran, R., 2011. Chapter 24 - agricultural waste and pollution, in: Letcher, T.M., Vallero, D.A. (Eds.), Waste. Academic Press, Boston, pp. 341–355. doi:https://doi.org/10.1016/B978-0-12-381475-3.10024-5.

Novotny, V., 1999. Diffuse pollution from agriculture — a worldwide outlook. Water Sci. Technol. 39, 1–13. https://doi.org/10.1016/S0273-1223(99)00027-X Integrated Management of Water Quality: The Role of Agricultural Diffuse Pollution Sources.

Parajuli, R., Thoma, G., Matlock, M.D., 2019. Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: a review. Sci. Total Environ. 650, 2863–2879. https://doi.org/10.1016/j.scitotenv.2018.10.019.

Parajuli, R., Matlock, M.D., Thoma, G., 2021. Cradle to grave environmental impact evaluation of the consumption of potato and tomato products. Sci. Total Environ. 758, 143662. https://doi.org/10.1016/j.scitotenv.2020.143662.

Pardossi, A., Malorgio, F., Incrocci, L., Campiotti, C.A., Tognoni, F., 2002. A comparison between two methods to control nutrient delivery to greenhouse melons grown in recirculating nutrient solution culture. Sci. Hortic. 92, 89–95. https://doi.org/10.1016/S0304-4238(01)00292-8.

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. https://doi.org/10.1016/j.jclepro.2014.10.007.

Piezer, K., Petit-Boix, A., Sanjuan-Delmás, D., Briese, E., Celik, I., Rieradevall, J., Gabarrell, X., Josa, A., Apul, D., 2019. Ecological network analysis of growing tomatoes in an urban rooftop greenhouse. Sci. Total Environ. 651, 1495–1504. https://doi.org/10.1016/j.scitotenv.2018.09.293.

Pineda, I.T., Lee, Y.D., Kim, Y.S., Lee, S.M., Park, K.S., 2020. Review of inventory data in life cycle assessment applied in production of fresh tomato in greenhouse. J. Clean. Prod. 124395. https://doi.org/10.1016/j.jclepro.2020.124395.

Qiu, R., Song, J., Du, T., Kang, S., Tong, L., Chen, R., Wu, L., 2013. Response of evapotranspiration and yield to planting density of solar greenhouse grown tomato in northwest China. Agric. Water Manag. 130, 44–51. https://doi.org/10.1016/j.agwat.2013.08.013.

Rittmann, B.E., Mayer, B., Westerhoff, P., Edwards, M., 2011. Capturing the lost phosphorus. Chemosphere. The Phosphorus Cycle 84, 846–853. https://doi.org/10.1016/j.chemosphere.2011.02.001.

Rufí-Salís, M., Parada, F., Arcas-Pilz, V., Petit-Boix, A., Villalba, G., Gabarrell, X., 2020a. Closed-loop crop cascade to optimize nutrient flows and grow low-impact vegetables in cities. Front. Plant Sci. 11. https://doi.org/10.3389/fpls.2020.596550.

Rufí-Salís, M., Petit-Boix, A., Villalba, G., Ercilla-Montserrat, M., Sanjuan-Delmás, D., Parada, F., Arcas, V., Muñoz-Liesa, J., Gabarrell, X., 2020b. Identifying eco-efficient year-round crop combinations for rooftop greenhouse agriculture. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-019-01724-5.

Ruralcat, 2019. Weather data - Ruralcat [WWW document]. URL. https://ruralcat.gencat.cat/web/guest/agrometeo.estacions?p_auth=OKK5BXY6&p_p_id=AgrometeoEstacions_WAR_AgrometeoEstacions100SNAPSHOT&p_p_lifecycle=1&p_p_state=normal&p_p_mode=view&p_p_col_id=column-2&p_p_col_pos=1&p_p_col_count=2&_AgrometeoEstacions_WAR_AgrometeoEstacions100SNAPSHOT_action=goEstacion.

Sanjuan-Delmás, D., Llorach-Massana, P., Nadal, A., Ercilla-Montserrat, M., Muñoz, P., Montero, J.I., Josa, A., Gabarrell, X., Rieradevall, J., 2018. Environmental assessment of an integrated rooftop greenhouse for food production in cities. J. Clean. Prod. 177, 326–337. https://doi.org/10.1016/j.jclepro.2017.12.147.

Sanjuan-Delmás, D., Josa, A., Muñoz, P., Gassó, S., Rieradevall, J., Gabarrell, X., 2020. Applying nutrient dynamics to adjust the nutrient-water balance in hydroponic crops. A case study with open hydroponic tomato crops from Barcelona. Sci. Hortic. 261, 108908. https://doi.org/10.1016/j.scienta.2019.108908.

Sanyé-Mengual, E., Cerón-Palma, I., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2013. Environmental analysis of the logistics of agricultural products from roof top greenhouses in Mediterranean urban areas. J. Sci. Food Agric. 93, 100–109. https://doi.org/10.1002/jsfa.5736.

Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2015. An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain. Assessing new forms of urban agriculture from the greenhouse structure to the final product level. Int. J. Life Cycle Assess. 20, 350–366. https://doi.org/10.1007/s11367-014-0836-9.

Schmidhuber, J., Tubiello, F.N., 2007. Global food security under climate change. Proc. Natl. Acad. Sci. 104, 19703–19708. https://doi.org/10.1073/pnas.0701976104.

Shu, L., Schneider, P., Jegatheesan, V., Johnson, J., 2006. An economic evaluation of phosphorus recovery as struvite from digester supernatant. Bioresour. Technol. 97, 2211–2216. https://doi.org/10.1016/j.biortech.2005.11.005.

SIAR, 2019. Sistema de información Agroclimática para el Regadío. [WWW Document]. URL. http://eportal.mapama.gob.es (accessed 11.21.19).

Steen, P., 1998. The most appropriate health care in the right place, and the right time. The importance of clinical decision support criteria in home health care. Home Care Provid. 3, 25–27 quiz 28–29. https://doi.org/10.1016/s1084-628x(98)90152-6.

Tixier, P., de Bon, H., 2006. Urban horticulture. In: Veenhuizen, R. van (Ed.), Cities Farming for the Future : Urban Agriculture for Green and Productive Cities. IDRC, Ottawa, ON, CA.

Ullah, I., Hanping, M., Chuan, Z., Javed, Q., Azeem, A., 2017. Optimization of irrigation and nutrient concentration based on economic returns, substrate salt accumulation and water use efficiency for tomato in greenhouse. Arch. Agron. Soil Sci. 63, 1748–1762. https://doi.org/10.1080/03650340.2017.1306641.

Ulm, F., Avelar, D., Hobson, P., Penha-Lopes, G., Dias, T., Máguas, C., Cruz, C., 2019. Sustainable urban agriculture using compost and an open-pollinated maize variety. J. Clean. Prod. 212, 622–629. https://doi.org/10.1016/j.jclepro.2018.12.069.

UNDESA, 2018. Press Release World Urbanization Prospects 2018 - Population Division. United Nation -Dep. Econ. Soc. Aff.

van Schilfgaarde, J., 1994. Irrigation — a blessing or a curse. Agric. Water Manag. 25, 203–219. https://doi.org/10.1016/0378-3774(94)90061-2.

Villalba, G., Liu, Y., Schroder, H., Ayres, R.U., 2008. Global phosphorus flows in the industrial economy from a production perspective. J. Ind. Ecol. 12, 557–569. https://doi.org/10.1111/j.1530-9290.2008.00050.x.

Wang, X., Yun, J., Shi, P., Li, Z., Li, P., Xing, Y., 2019. Root growth, fruit yield and water use efficiency of greenhouse grown tomato under different irrigation regimes and nitrogen levels. J. Plant Growth Regul. 38, 400–415. https://doi.org/10.1007/s00344-018-9850-7.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Yadvinder-Singh, Kukal, S.S., Jat, M.L., Sidhu, H.S., 2014. Chapter four - improving water productivity of wheat-based cropping systems in South Asia for sustained productivity. In: Sparks, D. (Ed.), Advances in Agronomy. Academic Press, pp. 157–258 https://doi.org/10.1016/B978-0-12-800131-8.00004-2.

Zhang, H., Xiong, Y., Huang, G., Xu, X., Huang, Q., 2017. Effects of water stress on processing tomatoes yield, quality and water use efficiency with plastic mulched drip irrigation in sandy soil of the Hetao Irrigation District. Agric. Water Manag. 179, 205–214. https://doi.org/10.1016/j.agwat.2016.07.022 Special Issue on Improving Agricultural Water Productivity to Ensure Food Security under Changing Environments Overseen by: Brent Clothier.

Zotarelli, L., Dukes, M.D., Scholberg, J.M.S., Muñoz-Carpena, R., Icerman, J., 2009. Tomato nitrogen accumulation and fertilizer use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agric. Water Manag. 96, 1247–1258. https://doi.org/10.1016/j.agwat.2009.03.019.