Universitat Autònoma de Barcelona

Reducing the Environmental Impact of Food Production in Urban Agriculture by Optimizing Irrigation

Felipe Agustín Parada Molina

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Doctoral thesis

Supervisors: Dr. Xavier Gabarrell Durany (UAB)
Dra. Gara Villalba Méndez (UAB)
Dr. Pere Muñoz Odina (UAB)

Academic tutor: Dr. Xavier Gabarrell Durany (UAB)

A thesis submitted in fulfilment of the requirements for the Doctoral degree in Environmental Sciences and Technology

Sostenipra research group
Institut de Ciència i Tecnologia Ambientals (ICTA-UAB)
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“Que el tiempo revele lo que la historia calló…”

Gonzalo Agustín Martín P-M.

The present thesis entitled Reducing the environmental impact of food production in urban agriculture by reducing water consumption by Felipe Agustín Parada Molina, has been carried out at the Institute of Environmental Science and Technology (ICTA) at the Universitat Autònoma de Barcelona (UAB).

Felipe Agustín Parada Molina

Under the supervision of Dr. Xavier Gabarrell, Dra. Gara Villalba, and Dr. Pere Muñoz, from the ICTA and the Department of Chemical Biological and Environmental Engineering at the UAB.
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Xavier Gabarrell Gara Villalba Pere Muñoz

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3. List of acronyms, abbreviations and notation

1.4 DB $_{eq.}$	1.4 dichlorobenzene equivalent emissions
AB	Abtew equation
AH	Ahooghalandari equation
ALL	Allen equation
BA	Baier equation
CE	Circular Economy
CEC	Cation Exchange Capacity
CED	Cumulative energy demand
c_p	Specific heat of the air
da	Mean air density at constant pressure
e_a	Actual vapor pressure
e_s	Saturation vapor pressure
ET	Ecotoxicity - kg 14-DB equivalent
ET_0	Evapotranspiration reference
ET_c	Crop Evapotranspiration
FE	Fresh water eutrophication - kg P equivalent
FRS	Fossil Resource Scarcity - kg oil equivalent
GWP	Global warming potential - kg CO_2 equivalent
HG	Hargreaves equation
ICTA	Institute of Environmental Science and Technology (UAB)
IPCC	Intergovernmental Panel on Climate Change
IR	Irmak equation
i-RTG	Integrated Roof Top Greenhouse
ISO	International Organization for Standardization
JE	Jensen equation
K_2SO_4	Potassium sulphate
Kc	Crop Coefficient (FAO 56)
KNO_3	Potassium nitrate

kPa	kilo Pascals
KPO_4H_2	Monopotassium phosphate
LAU- 1	Laboratory of Urban Agriculture 1 (South-East) ICTA-UAB
LAU- 2	Laboratory of Urban Agriculture 2 (South-West) ICTA-UAB
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MA	Makkink equation
MAE	Mean Absolute Error
MC	McCloud equation
ME	Marine Eutrophication - kg N equivalent
MSW	Municipal solid waste
OFMSW	Organic fraction of the municipal solid waste
OM	Organic matter
OP	Open irrigation system
PM	Penman-Monteith equation
PO_4^{3-} eq.	Phosphate equivalent emissions
r	Pearson correlation coefficient
Ra	Extra-terrestrial radiation
r_a	Surface aerodynamic resistances
RC	Recirculation System - control irrigation
RH	Relative Humidity
RMSE	Root Mean Squared Error
Rn	Net Radiation
RO	Romanenko equation
RR	Recirculation System - reduction irrigation
Rs	Incident radiation
r_s	Bulk surface resistances
SO_2 eq.	Sulphur dioxide equivalent emissions
Sostenipra	Sustainability and Environmental Prevention Group

TA	Terrestrial acidification - kg SO_2 equivalent
TAL	Talaee equation
T_{AVG}	Average Temperature (max and min)
T_{max}	Maximum daily temperature
T_{mean}	Mean Temperature Day
T_{min}	Minimum daily temperature
TR	Trajkovic equation
UA	Urban agriculture
UAB	Universitat Autònoma de Barcelona
WHC	Water Holding Capacity
WUE	Water Use Efficiency
γ	Psychrometric constant
λET	Latent heat flux
Δ	Slope of the saturation vapor pressure

4. Acknowledgments

A mis directores Xavier Gabarrell, Gara Villalba, y Pere Muñoz, por todos los consejos y tiempo dedicados este trabajo, a Joan Rieradevall por el apoyo. A mi madre Elizabeth por ser y estar siempre en cada momento, a mi abuela Julia por esperarme, a mi hermano Fabian por sus palabras, a mi familia entera, por siempre apoyar cada paso, Erika, Marcela, Rodrigo, en especial a Pia por todo el apoyo, trabajo, ayuda y cariño compartido durante tanto tiempo. A administración de ICTA, en especial a Cristina, Isabel y Maica por sus palabras y consejos. A la mesa directiva de CuatroSuelos, Fabio, Luis y Rodrigo por toda su ayuda. A mis amigos de Chile, Diego, Roberto, Ariel, Pola, Paula, Pablo por todo el ánimo. A todas las personas que forjaron la base de mi para llegar aquí, profesores de la Universidad de Chile por la formación que me dieron, Cristian, Ian, Osvaldo, Manuel. A Rossana, María, Bea, por las herramientas que me entregaron al partir. Finalmente, y no menos importante, mis amigos con los que he vivido este viaje, Vero, Martí, Mireia, Ramiro, Joan, Perla, Ana M., Ana, Gaia, María, Susana, Laura, Isabel y Núria, por todo el cariño y paciencia, que han tenido todo este tiempo, por todo el apoyo, por todos los abrazos, las caídas y victorias que hemos vivimos juntos, tardes de café conversando y arreglando este triste mundo que merece ser vivido.

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5. Summary

It is expected that 75% of the global population will live in cities by 2050. This situation has generated great concern worldwide due to the increased environmental impacts associated with the consumption of resources such as water and energy, particularly for food production. Urban agriculture (UA) has emerged as a strategy to make cities more self-sufficient. Under the context of climate change and water scarcity, the implementation of different UA solutions needs to be aligned with circular strategies that optimise the use of resources. Rooftop greenhouses allow for sustained production over time, together with the optimisation of the use of resources, such as water, light and fertilisers. The present work addresses the general objective of reducing the environmental impact of UA by optimising crop water management in rooftop greenhouses. To achieve this, a water demand model is developed based on experimental data generated in three tomato growing seasons of 7 months each. Second, the replacement of conventional substrates with organic, renewable substrates is explored via various experiments with lettuce. Finally, the life cycle environmental impacts of water consumption under various irrigation regimes for tomato crops are determined. Together, these three parts of this dissertation aim to respond to the following research questions:

- **Question 1:** Is it possible to construct a simple water demand model to determine the water requirements of a hydroponic crop in a rooftop greenhouse based on its climatic characteristics?
- **Question 2:** Is it possible to maintain yields using organic substrates from the city under water deficit management?
- **Question 3:** To what extent can environmental impacts from a life cycle approach be reduced through optimised water management of tomato crops?

Chapter 2 presents materials and methods, including an agronomic analysis, which provides a detailed description of the greenhouses as well as their irrigation systems and a description of all the management implemented within the greenhouse (fertilisation, pests, pruning and harvesting, among others). To

determine the environmental impacts associated with agronomic management, a life cycle analysis (LCA) was implemented through the construction of an inventory where all the materials used in both the infrastructure and production stages were quantified. The LCA is also supported by the results of water and nutrient flows to provide a holistic view of the analysis of the production system. Lastly, bearing in mind the need to optimise water resources, a statistic modelling of water demand was carried out, where climatic data was collected from the greenhouse and related to water consumption, adjusted for the phenological stage of the crop under study.

Chapter 3 outlines the proposed water demand model, including a comparison with other previously published models. It also details the interaction and predictability of the climatic variables the average greenhouse temperature being the most representative, followed by the mean external temperature and radiation. It also delves into the applicability of the proposed model, presenting its scope and requirements.

Next, in Chapter 4, a comparison of organic substrates under different levels of water stress is presented. The substrates were characterized after being evaluated during three cycles of lettuce cultivation, and compost and its derivatives show a good response to water deficiency, maintaining productivity, and even improving it under specific stress conditions.

Chapter 5 details the agronomic and environmental effects evaluated in different irrigation strategies, seeking an optimisation of water resources in UA. In this sense, the lineal irrigation systems present a high environmental impact in terms of eutrophication due to the nitrogen and phosphorus released into the environment. It is also possible to show that the implementation of recirculation systems can reduce water consumption while at the same time reducing some categories of environmental impact. The fact that applying a strategy with recirculation and water reduction allows a reduction in water consumption together with an increase in the efficiency of water use due to the ratio of the biomass produced vs. water transpired is favourable stands out.

A description of the most significant contributions of this thesis can be found in Chapter 6. Considering the optimisation of resources and water as a central axis, the water demand model is highlighted, despite not exhibiting precision similar to that of physical models, and can be used on different scales, by urban farmers, managers, and scientists which is a consideration for any model under development. In this sense, determining how much water to apply is a very useful tool to be able to better control the water inputs to food production systems. To minimise the effect of water scarcity, the incorporation of compost from municipal waste is discussed, and how this process maintains the lettuce crop when a water cut is generated is discussed. The benefit is not only in maintaining yields but also in contributing to nutrient cycling and waste recycling. Finally, emphasis is placed on the need to maintain environmental studies of food production to ensure its efficiency. In this way, it is recommended to avoid linear irrigation strategies due to the large amount of nitrogen and phosphorus released into the environment. The implementation of recirculation systems which reduce the emission of nutrients and have been shown to improve water use efficiency by 13% is recommended. In the future, it will be necessary to deepen these circularity strategies, which are complementary to those presented in this dissertation. For example, the use of more complex models that allow for improved prediction, including variables that can be easily obtained, measured or estimated. It should be emphasized that an environmental perspective is essential to maintain a critical view of food production. The present dissertation contributes to the development of cleaner food production.

6. Resumen

Se prevé que el 75% de la población mundial vivirá en ciudades en el año 2050. Esta situación ha generado una gran preocupación en todo el mundo debido al aumento de los impactos ambientales asociados al consumo de recursos como el agua y la energía, especialmente para la producción de alimentos. La agricultura urbana (AU) ha surgido como una estrategia para que las ciudades sean más autosuficientes. En el contexto del cambio climático y la escasez de agua, la aplicación de las diferentes soluciones de la AU debe estar alineada con las estrategias circulares que optimizan el uso de los recursos. Los invernaderos sobre cubierta permiten una producción sostenida en el tiempo, junto con la optimización del uso de recursos, como el agua, la luz y los fertilizantes. El presente trabajo aborda el objetivo general de reducir el impacto ambiental de la AU mediante la optimización de la gestión del agua de los cultivos en los invernaderos de cubierta. Para ello, se desarrolla un modelo de demanda hídrica, basado en datos experimentales generados en tres temporadas de cultivo de tomate de 7 meses cada una. En segundo lugar, se explora la sustitución de sustratos convencionales por sustratos orgánicos y renovables mediante varios experimentos con lechugas. Por último, se determinan los impactos ambientales del ciclo de vida del consumo de agua bajo varios regímenes de riego para el cultivo de tomate. En conjunto, estas tres partes de la tesis pretenden responder a las siguientes preguntas de investigación:

- **Pregunta 1:** ¿Es posible construir un modelo sencillo de demanda de agua para determinar las necesidades hídricas de un cultivo hidropónico en un invernadero en cubierta en función de sus características climáticas?
- **Pregunta 2:** ¿Es posible mantener los rendimientos utilizando sustratos orgánicos de la ciudad bajo una gestión del déficit hídrico?
- **Pregunta 3:** ¿En qué medida se puede reducir el impacto ambiental desde un enfoque de ciclo de vida mediante la gestión optimizada del agua en los cultivos de tomate?

En el capítulo 2 se presentan los materiales y métodos, incluyendo un análisis agronómico, que proporciona una descripción detallada de los invernaderos así como de sus sistemas de riego y una descripción de todos los manejos

implementados dentro del invernadero (fertilización, plagas, poda y cosecha, entre otros). Para determinar los impactos ambientales asociados al manejo agronómico, se implementó un análisis de ciclo de vida (ACV) a través de la construcción de un inventario donde se cuantificaron todos los materiales utilizados tanto en la infraestructura como en las etapas de producción. El ACV se apoya también en los resultados de los flujos de agua y nutrientes para ofrecer una visión holística del análisis del sistema de producción. Finalmente, teniendo en cuenta la necesidad de optimizar los recursos hídricos, se realizó una modelización estadística de la demanda de agua, en la que se recogieron datos climáticos del invernadero y se relacionaron con el consumo de agua, ajustado al estado fenológico del cultivo en estudio.

En el capítulo 3 se presenta el modelo de demanda de agua propuesto, incluyendo una comparación con otros modelos publicados anteriormente. También se detalla la interacción y predictibilidad de las variables climáticas, siendo la temperatura media del invernadero la más representativa, seguida de la temperatura media exterior y la radiación. También se profundiza en la aplicabilidad del modelo propuesto, presentando su alcance y requisitos.

A continuación, en el capítulo 4, se presenta una comparación de sustratos orgánicos bajo diferentes niveles de estrés hídrico. Los sustratos fueron caracterizados después de ser evaluados durante tres ciclos de cultivo de lechuga, el compost y sus mezclas con sustrato convencional, muestran una buena respuesta a la deficiencia de agua, manteniendo la productividad, e incluso mejorándola bajo condiciones específicas de estrés.

En el capítulo 5 se detallan los efectos agronómicos y ambientales evaluados en diferentes estrategias de riego, buscando una optimización de los recursos hídricos en la AU. En este sentido, el sistema de riego lineal presenta un alto impacto ambiental en términos de eutrofización debido al nitrógeno y al fósforo liberados al medio ambiente. También es posible demostrar que la aplicación de sistemas de recirculación puede reducir el consumo de agua y, al mismo tiempo, algunas categorías de impacto ambiental. Destaca el hecho de que la aplicación de una estrategia con recirculación y reducción de agua permite una reducción del consumo de agua junto con un aumento de la eficiencia del uso del agua debido a que la relación entre la biomasa producida y el agua transpirada es favorable.

En el capítulo 6 se describen las aportaciones más significativas de esta tesis. Considerando la optimización de los recursos y del agua como eje central, se destaca el modelo de demanda de agua, que a pesar de no presentar una precisión similar a la de los modelos físicos, puede ser utilizado a diferentes escalas, por agricultores urbanos, gestores y científicos lo cual es una consideración para cualquier modelo en desarrollo. En este sentido, la determinación de la cantidad de agua a aplicar es una herramienta muy útil para poder controlar mejor los aportes de agua a los sistemas de producción de alimentos. Para minimizar el efecto de la escasez de agua, se discute la incorporación de compost a partir de residuos municipales, y cómo este proceso mantiene el cultivo de lechuga cuando se genera un corte de agua. El beneficio no sólo consiste en mantener el rendimiento, sino también en contribuir al ciclo de los nutrientes y al reciclaje de los residuos. Por último, se destaca en la necesidad de mantener los estudios ambientales de la producción de alimentos para garantizar su eficiencia. Así, se recomienda evitar las estrategias de riego lineal debido a la gran cantidad de nitrógeno y fósforo que se libera al medio ambiente. Se recomienda la implantación de sistemas de recirculación que reducen la emisión de nutrientes y que han demostrado mejorar la eficiencia del uso del agua en un 13%. En el futuro, será necesario profundizar en estas estrategias de circularidad, que son complementarias a las presentadas en esta disertación. Por ejemplo, el uso de modelos más complejos que permitan mejorar la predicción, incluyendo variables de fácil obtención, medición o estimación. Cabe destacar que la perspectiva medioambiental es esencial para mantener una visión crítica de la producción de alimentos. La presente tesis contribuye al desarrollo de una producción alimentaria más limpia.

7. Resum

S'espera que el 75% de la població mundial viurà en ciutats en l'any 2050. Aquesta situació ha generat una gran preocupació a tot el món degut a de l'augment dels impactes ambientals associats al consum de recursos com l'aigua i l'energia, especialment per a la producció d'aliments. L'agricultura urbana (AU) ha sorgit com una estratègia perquè les ciutats siguin més autosuficients. En el context del canvi climàtic i l'escassetat d'aigua, l'aplicació de les diferents solucions de l'AU ha d'estar alineada amb les estratègies circulars que optimitzen l'ús dels recursos. Els hivernacles sobre coberta permeten una producció sostinguda en el temps, juntament amb l'optimització de l'ús dels recursos, com l'aigua, la llum i els fertilitzants. El present treball aborda l'objectiu general de reduir l'impacte ambiental dels AU mitjançant l'optimització de la gestió de l'aigua dels cultius en els hivernacles de coberta. Per a això en primer lloc, es desenvolupa un model de demanda hídrica, basat en dades experimentals generades en tres temporades de cultiu de tomàquet de 7 mesos cadascuna. En segon lloc, s'explora la substitució de substrats convencionals per substrats orgànics i renovables mitjançant diversos experiments amb enciams. Finalment, es determinen els impactes ambientals del cicle de vida del consum d'aigua sota diversos règims de reg per al cultiu de tomàquet. En conjunt, aquestes tres parts de la tesi pretenen respondre a les següents preguntes de recerca:

- **Pregunta 1:** És possible construir un model senzill de demanda d'aigua per a determinar les necessitats hídriques d'un cultiu hidropònic en un hivernacle en coberta en funció de les seves característiques climàtiques?
- **Pregunta 2:** És possible mantenir els rendiments utilitzant substrats orgànics de la ciutat sota una gestió del dèficit hídric?
- **Pregunta 3:** En quina mesura es pot reduir l'impacte ambiental des d'un enfocament de cicle de vida mitjançant la gestió optimitzada de l'aigua en els cultius de tomàquet?

En el capítol 2 es presenten els materials i mètodes, incloent una anàlisi agronòmica, que proporciona una descripció detallada dels hivernacles així com dels seus sistemes de reg i una descripció de tots els manejos implementats dins

de l'hivernacle (fertilització, plagues, poda i collita, entre altres). Per a determinar els impactes ambientals associats al maneig agronòmic, es va implementar una anàlisi de cicle de vida (ACV) a través de la construcció d'un inventari on es van quantificar tots els materials utilitzats tant en la infraestructura com en les etapes de producció. El ACV es recolza també en els resultats dels fluxos d'aigua i nutrients per a oferir una visió holística de l'anàlisi del sistema de producció. Per últim, tenint en compte la necessitat d'optimitzar els recursos hídrics, es va realitzar una modelització estadística de la demanda d'aigua, en la qual es van recollir dades climàtiques de l'hivernacle i es van relacionar amb el consum d'aigua, ajustat a l'estat fenològic del cultiu en estudi.

En el capítol 3 es presenta el model de demanda d'aigua proposat, incloent una comparació amb altres models publicats anteriorment. També es detalla la interacció i predictibilitat de les variables climàtiques, sent la temperatura mitjana de l'hivernacle la més representativa, seguida de la temperatura mitjana exterior i la radiació. També s'aprofundeix en l'aplicabilitat del model proposat, presentant el seu abast i requisits.

A continuació, en el capítol 4, es presenta una comparació de substrats orgànics sota diferents nivells d'estrès hídric. Els substrats van ser caracteritzats després de ser avaluats durant tres cicles de cultiu d'enciam, i el compost i les seves mescles amb substrat convencional, mostren una bona resposta mostren una bona resposta a la deficiència d'aigua, mantenint la productivitat, i fins i tot millorant-la sota condicions específiques d'estrès.

En el capítol 5 es detallen els efectes agronòmics i ambientals avaluats en diferents estratègies de reg, buscant una optimització dels recursos hídrics en l’AU. En aquest sentit, el sistema de reg lineal presenta un alt impacte ambiental en termes d'eutrofització a causa del nitrogen i el fòsfor alliberats al medi ambient. També és possible demostrar que l'aplicació de sistemes de recirculació pot reduir el consum d'aigua i, al mateix temps, algunes categories d'impacte ambiental. Destaca el fet que l'aplicació d'una estratègia amb recirculació i reducció d'aigua permet una reducció del consum d'aigua juntament amb un augment de l'eficiència de l'ús de l'aigua degut a que la relació entre la biomassa produïda i l'aigua transpirada és favorable.

En el capítol 6 es descriuen les aportacions més significatives d'aquesta tesi. Considerant l'optimització dels recursos i de l'aigua com a eix central, es destaca el model de demanda d'aigua, que malgrat no presentar una precisió similar a la dels models físics, pot ser utilitzat a diferents escales per agricultors urbans, gestors i científics, la qual cosa és una consideració per a qualsevol model en desenvolupament. En aquest sentit, la determinació de la quantitat d'aigua a aplicar és una eina molt útil per a poder controlar millor les aportacions d'aigua als sistemes de producció d'aliments. Per a minimitzar l'efecte de l'escassetat d'aigua, es discuteix la incorporació de compost a partir de residus municipals, i com aquest procés manté el cultiu d'enciam quan es genera un tall d'aigua. El benefici no només consisteix a mantenir el rendiment, sinó també a contribuir al cicle dels nutrients i al reciclatge dels residus. Finalment, remarca en la necessitat de mantenir els estudis ambientals de la producció d'aliments per a garantir la seva eficiència. Així, es recomana evitar les estratègies de reg lineal a causa de la gran quantitat de nitrogen i fòsfor que s'allibera el medi ambient. Es recomana la implantació de sistemes de recirculació que redueixen l'emissió de nutrients i que han demostrat millorar l'eficiència de l'ús de l'aigua en un 13%. En el futur, serà necessari aprofundir en aquestes estratègies de circularitat, que són complementàries a les presentades en aquesta dissertació. Per exemple, l'ús de models més complexos que permetin millorar la predicció, incloent variables de fàcil obtenció, mesurament o estimació. Cal destacar que la perspectiva mediambiental és essencial per a mantenir una visió crítica de la producció d'aliments. La present tesi contribueix al desenvolupament d'una producció alimentària més neta.

8. Preface and Structure of the dissertation

This thesis was carried out from January 2018 to March 2022, in agreement with the PhD programme in Environmental Science and Technology of the Universitat Autònoma de Barcelona. The study period was performed in the group of Sustainability and Environmental Prevention (SosteniPrA), in the facilities of the Institute of Environmental Science and Technology (ICTA-UAB). The author has been grateful to the National Commission for Scientific and Technological Research (Chile) [grant number PFCHA-CONICYT 2017 – Folio 72180248]. The research developed in the present work was conducted in a María de Maeztu program for Units of Excellence in R&D [MDM-2015-0552 \ CEX2019-000940-M]. Thanks to the Spanish Ministry of Economy, Industry, and Competitiveness (Spain).

This thesis is developed in the area of UA, particularly in rooftop greenhouses. Due to climate change, and the decrease in water resources in Mediterranean areas, an optimization of the water consumption of crops is carried out considering a circular economy perspective. Using modelling as a tool to reduce water input to food production systems, in parallel, environmental analysis as an indicator to compare food production in the city with conventional systems.

This thesis was elaborated in the framework of the project Fertilice city II, project 'Integrated rooftop greenhouses: energy, waste and CO_2 symbiosis with the building. Towards foods security in a circular economy' (CTM2016-75772-C3-1-R) and the project "Municipis resilients a les pandèmies mitjançant el nexe de l'agricultura de proximitat, energia, aigua i residus" (AGAUR 2020PANDE00021).

Figure I. present the general structure of the present dissertation.

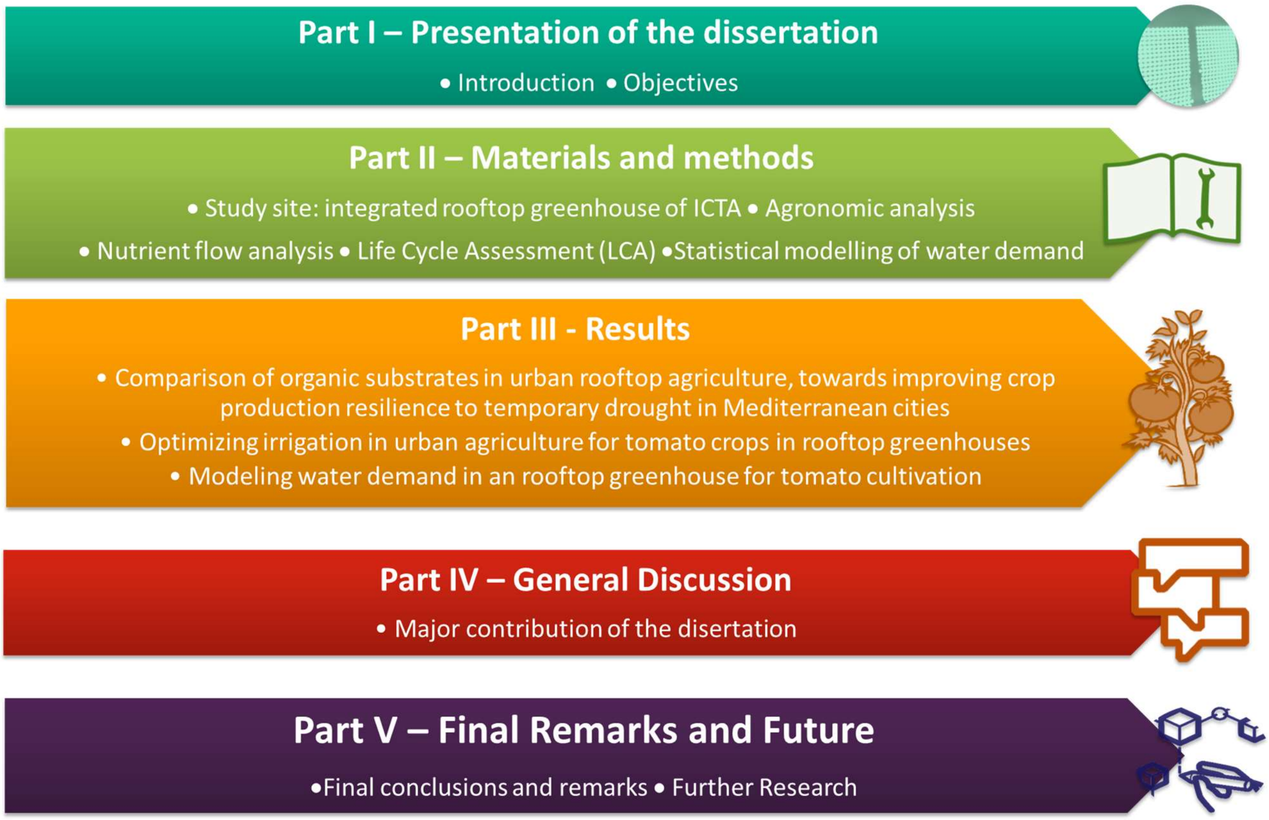


Figure I . Dissertation Structure.

Part I – Presentation of the dissertation

Part I presents the introduction to the dissertation (**Chapter 1**), firstly describing the objectives of the work carried out. Secondly, it establishes the theoretical bases on which the research is based.

Part II – Material and methods

Part II describes the materials and methods (**Chapter 2**) used in the research, describing the integrated rooftop greenhouse (i-RTG) as the study site. Subsequently, the agronomic analysis considers measurements such as fresh/dry weight of biomass, radiation, temperature, among others. On the other hand, it describes the methodology for obtaining the flow of nutrients into and out of the production system (Greenhouse). It then describes the limits of the system, and how a LCA was applied to tomato production. Finally, the statistical modelling techniques for the development of a water demand model are detailed.

Part III – Results

Part III develops the results obtained in this work. Firstly, the results obtained in **Chapter 3** are presented, [*Modelling water demand in a rooftop greenhouse for tomato cultivation*] detailing how the water balances within the rooftop greenhouse were related to adjusting a simple water demand model. Subsequently, in **Chapter 4**, [*Comparison of organic substrates in urban rooftop agriculture, towards improving crop production resilience to temporary drought in Mediterranean cities*] it is described how the use of organic substrates, from municipal waste, can be used in conditions of low water availability, presenting similar results to those of traditional substrates. Finally, **Chapter 5** [*Optimizing irrigation in urban agriculture for tomato crops in rooftop greenhouses*]details how the restrictive management with a recirculating irrigation system presents different environmental trade-offs between inputs (energy, fertiliser, water) and the yield of a tomato crop.

Part IV – General Discussion

Part IV presents **Chapter 6**, [*Mayor Contributions of the Dissertation*] described and an analysis is made of how, by means of different strategies, it is possible to reduce the consumption of water as well as different inputs in the production of inputs (e.g. fertilizer and energy) in greenhouses.

Part V – Final Remarks and Future

This is the final part of the dissertation, **Chapter 7** [*Final conclusions and remarks Further Research*], are detailed the main conclusions and answering the research questions posed at the beginning of the research. Subsequently, a further research section is detailing the steps to be followed in the research associated with the optimization of food production through water.

9. Dissemination and training

The present doctoral thesis is based in a set of two scientific articles and one chapter of results:

- **Parada, F.**, Ercilla Montserrat, M., Arcas-Pilz, V., Lopez-Capel E., Montero, J.I., Gabarrell, X., Villalba, G., Rieradevall J., Muñoz, P. Comparison of organic substrates in urban rooftop agriculture, towards improving crop production resilience to temporary drought in Mediterranean cities (2021). *Journal of the Science of Food and Agriculture*. (DOI: https://doi.org/10.1002/jsfa.11241)
- **Parada, F.**, Gabarrell, X., Rufí-Salís, M., Arcas-Pilz, V., Muñoz, P., Villalba, G. Optimizing irrigation management for urban agriculture: life cycle assessment of tomato production in rooftop greenhouses. (2021). *Science of The Total Environment* (DOI: https://doi.org/10.1016/j.scitotenv.2021.148689)
- Chapter: Modelling of the water demand within an integrated rooftop greenhouse (i-RTG), for tomato cultivation.

Preliminary information was presented in different international instances as congress or symposiums:

- **Parada, F.**, Ercilla Montserrat, M., Arcas-Pilz, V., Rufí-Salís, M., Villalba, G., Gabarrell, X., Muñoz, P., 2019a. Substrate selection in urban agriculture, water holding capacity and resilience to water stress, in: GreenSys2019 - International Symposium on Advanced Technologies and Management for Innovative Greenhouses.
- **Parada, F.**, Gabarrell, X., Rufí-Salís, M., Arcas-Pilz, V., Muñoz, P., Villalba, G., 2020. Water management strategies for a food production in circular cities, in: International Society for Industrial Ecology Conference, ISIE Americas.
- **Parada, F.**, Rufí-Salís, M., Arcas-Pilz, V., Muñoz-Liesa, J., Petit-Boix, A., Villalba, G., Gabarrell, X., 2019b. Life Cycle Assessment: Reduction in water consumption through irrigation optimization strategies, in: International Conference on Life Cycle Assessment in Latin America (CILCA).
- **Parada, F.**, Rufí-Salís, M., Arcas-Pilz, V., Villalba, G., Gabarrell, X., 2019c. Urban Agriculture: Estimation of the environmental impacts associated with different water sources, at the building and neighbourhood scale, in: 2nd ICTA-UAB Spring Symposium.

Due to the professional and academic background of the author of this dissertation, he contributed to other research related to UA from an environmental and social point of view. Participations in scientific articles:

- Arcas-Pilz, V., **Parada, F.**, Rufí-Salís, M., Stringari, G., González, R., Villalba, G., Gabarrell, X., 2022. Extended use and optimization of struvite in hydroponic cultivation systems. Resources, Conservation and Recycling 179, 106130. https://doi.org/10.1016/j.resconrec.2021.106130

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

- Arcas-Pilz, V., **Parada, F.**, Villalba, G., Rufí-Salís, M., Rosell-Melé, A., Gabarrell Durany, X., 2021a. Improving the Fertigation of Soilless Urban Vertical Agriculture Through the Combination of Struvite and Rhizobia Inoculation in Phaseolus vulgaris. Front. Plant Sci. 12. https://doi.org/10.3389/fpls.2021.649304

- Rufí-Salís, M., **Parada, F.**, Arcas-Pilz, V., Petit-Boix, A., Villalba, G., Gabarrell, X., 2020. 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-Pilz, V., Muñoz-Liesa, J., Gabarrell, X., 2020. 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

- Rufí-Salís, M., Petit-Boix, A., Villalba, G., Sanjuan-Delmás, D., **Parada, F.**, Ercilla-Montserrat, M., Arcas-Pilz, V., Muñoz-Liesa, J., Rieradevall, J., Gabarrell, X., 2020. Recirculating water and nutrients in urban agriculture: An opportunity towards environmental sustainability and water use efficiency? Journal of Cleaner Production 261, 121213. https://doi.org/10.1016/j.jclepro.2020.121213

Participation in scientific articles based on co-supervised master student or internship students.

- Bonilla-Gámez, N.B., Toboso-Chavero, S., **Parada, F.**, Civit, B., Arena, A., Rieradevall, J., Gabarrell X., 2021. Environmental impact assessment of agro-services symbiosis in semiarid urban frontier territories. Case study of Mendoza (Argentina). Science of Total Environment 145682. https://doi.org/10.1016/j.scitotenv.2021.145682

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

- Zambrano-Prado, P., Pons-Gumí, D., Toboso-Chavero, S., **Parada, F.**, Josa, A., Gabarrell, X., Rieradevall, J., 2021. Perceptions on barriers and opportunities for integrating urban agri-green roofs: A European Mediterranean compact city case. Cities 114, 103196. https://doi.org/10.1016/j.cities.2021.103196

Participation and contribution in other research presented in congress:

- Arcas-Pilz, V., Rufí-Salís, M., **Parada, F.**, Petit-Boix, A., Villalba, G., Gabarrell, X., 2019. Different treatments for the availability of Phosphorus with Struvite for Soilless systems (Poster)., in: GreenSys2019 - International Symposium on Advanced Technologies and Management for Innovative Greenhouses.

- Muñoz-Liesa, J., **Parada, F.**, Rufí-Salís, M., Arcas-Pilz, V., Zambrano, P., Cuerva, E., Jarauta, E., Hervada, C., Gibergans, J., Josa, A., 2019a. Energy performance through forced and natural ventilation systems in building integrated rooftop greenhouses. (Oral Presentation), in: GreenSys2019 - International Symposium on Advanced Technologies and Management for Innovative Greenhouses.

- Muñoz-Liesa, J., Rufí-Salís, M., **Parada, F.**, Royapoor, M., López-Capel, E., Cuerva, E., Gassó-Domingo, S., Josa, A., Gabarrell, X., 2019b. Improving the metabolism of energy buildings: integrated rooftop greenhouses (Poster), in: 2nd ICTA-UAB Spring Symposium.

- Rufí-Salís, M., Arcas-Pilz, V., **Parada, F.**, Muñoz-Liesa, J., Villalba, G., Gabarrell, X., Petit-Boix, A., 2019a. Assessing phosphorus fertilizer potential of wastewater's struvite. Towards circular economy in urban agriculture (Poster)., in: Conferencia Internacional Sobre Análisis de Ciclo de Vida En Latinoamérica. CILCA.

- Rufí-Salís, M., Arcas-Pilz, V., **Parada, F.**, Petit-Boix, A., Muñoz, P., 2019b. Improving urban agriculture sustainability with Life Cycle Assessment - LCA (Poster), in: GreenSys2019 - International Symposium on Advanced Technologies and Management for Innovative Greenhouses.

- Rufí-Salís, M., Ercilla Montserrat, M., Sanjuan-Demás, D., Petit-Boix, A., Arcas-Pilz, V., **Parada, F.**, Toboso-Chavero, S., Muñoz-Liesa, J., Rieradevall, J., Gabarrell, X., 2019c. Intercropping, urban agriculture and circular economy. A first approach using Life Cycle Assessment to determine best annual crop combination (Oral Presentation). in: Conferencia Internacional Sobre Análisis de Ciclo de Vida En Latinoamérica. CILCA.

- Muñoz-Liesa, J., Cuerva, E., **Parada, F.**, Gassó-Domingo, S., Josa, A., Nemecek, T. Multifunctionality in rooftop greenhouses: Increasing energy and crop yields through improved covering materials. (Poster), in: 13th International Conference on Life Cycle Assessment of Food. LCAFOODS2022

Other participations on the PhD. Formation:

- Fertilecity II project: (CTM2016-75772-C3-1-R, AI/UE-Feder). Agrourban sustainability through greenhouse. Integrated rooftop greenhouse: symbiosis energy water and CO2 with the building - Towards urban food security in a circular economy. MINECO (Spain).
- Organizing Committee - ICTA-UAB International Conference 2020 on Low-Carbon Lifestyle Changes (Online conference) (DOI: https://doi.org/10.1016/j.jclepro.2021.126287)
- Collaborative research in project IRES – International Research Experience for Undergraduates. Life cycle management and ecosystem services applied to urban agriculture. National science foundations founds.
- Guided visits to the ICTA-UAB building, for different users, researchers, students, general public.
- Pandèmies project: "Municipis resilients a les pandèmies mitjançant el nexe de l'agricultura de proximitat, energia, aigua i residus. Del pilot al municipi." (AGAUR), 020PANDE00021, 2021.
- SIRAH project: Promoting access to open urban agriculture from the Fertilecity lab to the city. State Research Agency, PDC2021-121054-C22, 2021.

Workshops carried out:

- "Research on Building Integrated Urban Agriculture Systems performed at the ICTA of the Universitat Autònoma de Barcelona", to the students of the course on "Urban Agriculture" within the Master degree on "Global Change Ecology and Sustainable Development Goals", University of Bologna.
- "Statistics for agricultural research" to the students of the course on "Experimental Design", within Agricultural school to Agronomy degree, Americas University (UDLA).

Courses:

- Advanced statistical computing using R (2018). 4 Applied Statistics Service of the UAB. Duration 12 hours.
- Introductory Course of R and R Studio. Statistical Programming with R. (2018). ICTA- UAB. Duration 18 hours.
- Database for the Environmental Analysis of the Circular Economy at the Urban Level, U-CENET.
- Food-E Winter School: Sustainability Assessment of City-Region Food Systems. (Funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement – 862663)

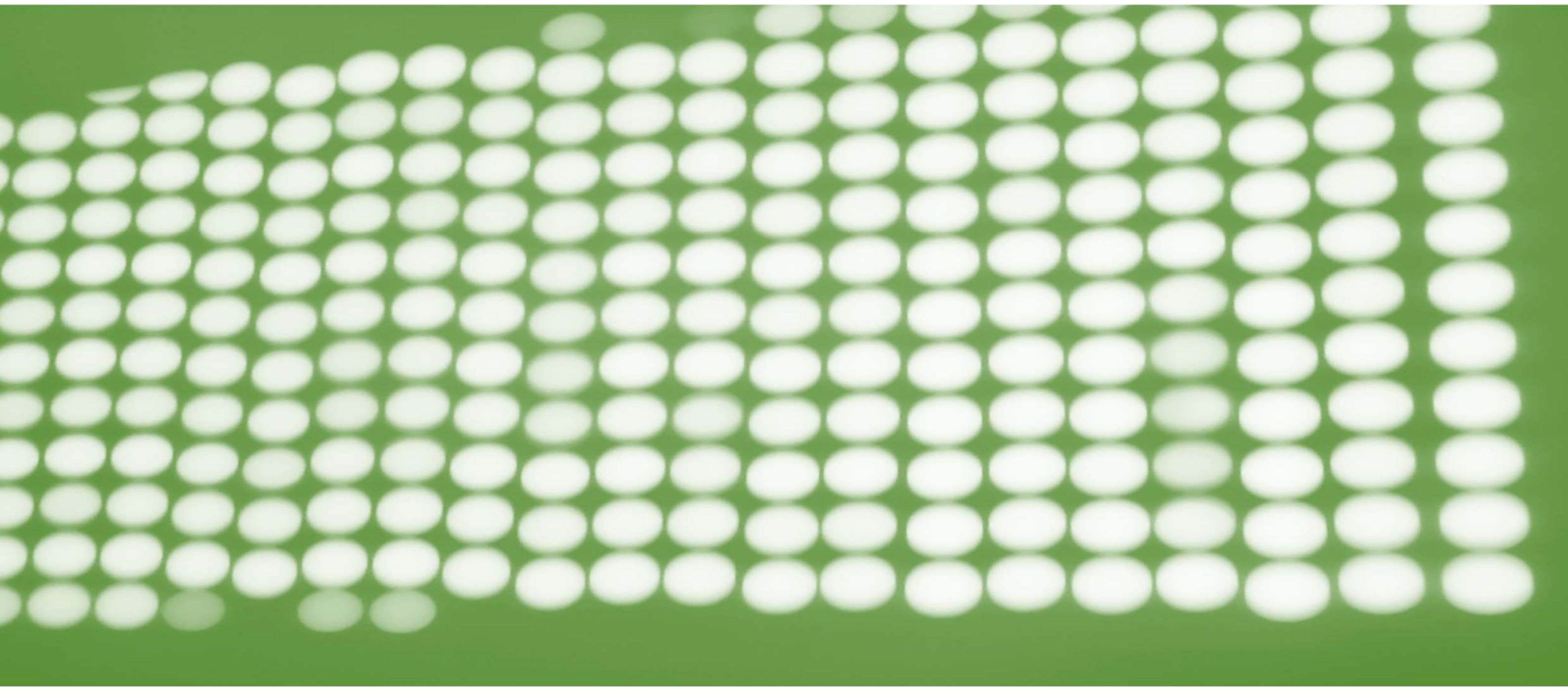
Participation in supervision on master thesis:

- Environmental impact assessment of agro-services symbiosis in semiarid urban frontier territories. Case study of Mendoza (Argentina). Student: Natalia Bonilla. Supervisors: Susana Toboso-Chavero, **Felipe Parada**, Bárbara Civit, Joan Rieradevall, Xavier Gabarrell.
- A literature review of technologies and methods to optimize photosynthesis in urban greenhouses. Student: Gabriel Malaquin. Supervisors: Veronica Arcas-Pilz, **Felipe Parada**, Xavier Gabarrell.
- Assessment of improvements of polyculture against monoculture in an urban farming hydroponic system. Student: Leonardo Parra. Supervisors: Arcas-Pilz, **Felipe Parada**, Xavier Gabarrell.
- Barriers and opportunities for Urban Agri-Green Roofs in Mediterranean cities. Case study of Barcelona. Student: David Pons. Supervisors: Perla Zambrano-Prado, Susana Toboso-Chavero, **Felipe Parada**, Alejandro Josa, Xavier Gabarrell, Joan Rieradevall.
- Comparative environmental assessment of polyculture rooftop home urban gardens in the Mediterranean region. Student: Jai Verma. Supervisors: Marti Rufí-Salís, **Felipe Parada**, Joan Rieradevall Pons, Xavier Gabarrell.

Participation on books:

- Barreres i oportunitats de les cobertes mosaico. Ajuntament de Barcelona. Calvo, L., Bermejo, J., Arranz, L., Jimeno, A., Rieradevall Pons, J., Gabarrell Durany, X., Toboso, S., **Parada, F.**, Pons, D., 2019. Barcelona.

Part I



Chapter 1.

Introduction, research question, objectives.

Chapter 1 describes the current state of water in the world and the impact of climate change, reducing the availability of this resource in Mediterranean. It also explains how this reduction affects agriculture, as well as the current alternatives available to mitigate this situation. Additionally, it shows how the methods are assessed using water as a limiting constraint. Subsequently, urban agriculture (UA) is presented as a complementary resource to food production in cities, and from a circular economy perspective, it is possible to improve the sustainability cities This is assessed through an environmental analysis of how this tool has been applied to conventional and urban agriculture. Finally, the research questions are presented, followed by the objectives (general and specific).

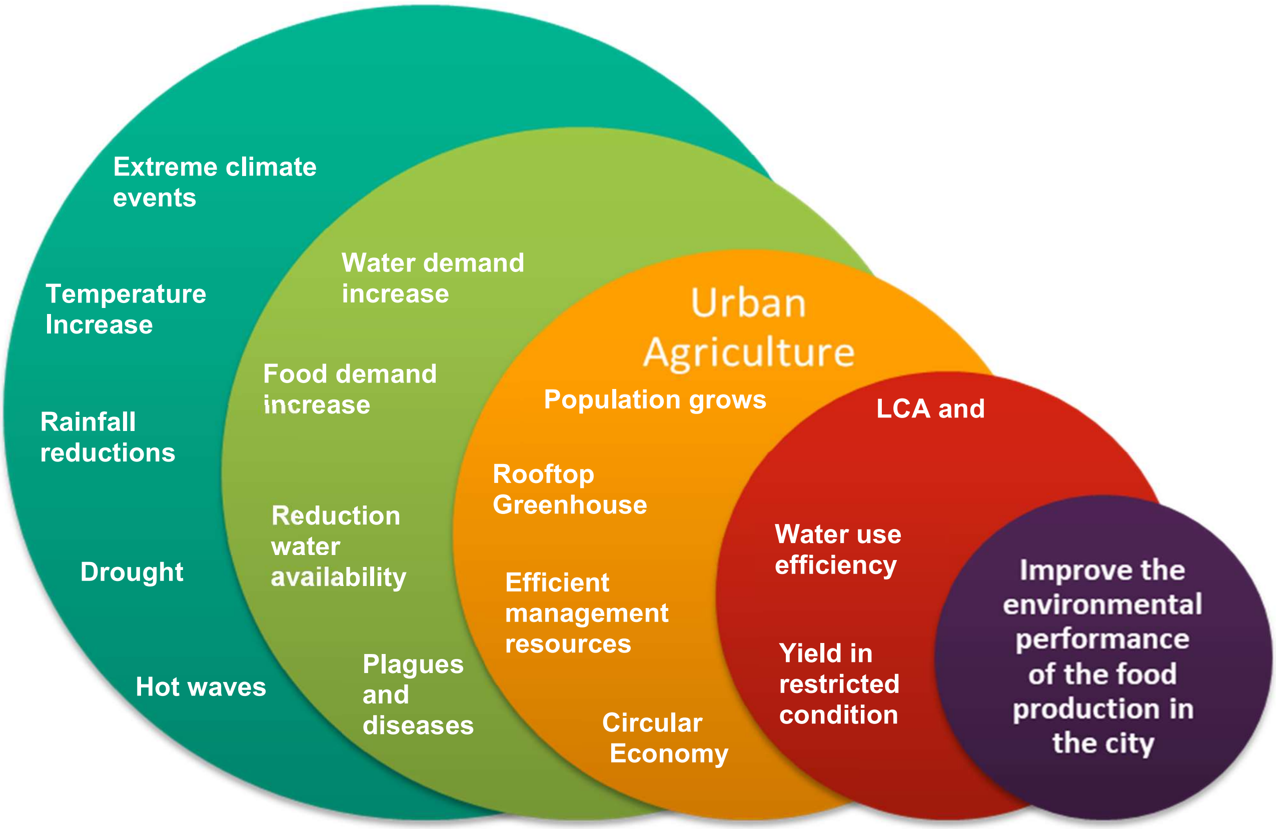
This chapter is structured as follows:

- Research question and objectives
- The state of the water
- Global water resources
- Ways to optimize the water use
- Evaluating yields in agriculture through water
- Urban Agriculture (UA) alternative to food production at the city level
- Typologies of UA
- UA in circular economy perspective
- Environmental analysis and Life cycle assessment (LCA)
- Interaction Water Food into the city

1. Chapter 1: Introduction

The current water situation is described, considering its reduced availability in Mediterranean areas, and its effect on food production. From a water perspective, the way food production is evaluated, agronomically and environmentally and improvements in intensive agriculture production in cities through rooftop greenhouses are introduced. Additionally, in the framework of the circular economy, it is possible to reduce the environmental impact and contribute to the development of more sustainable cities. Finally, the interaction of water and food production in the city is explored (Figure 1.1).

Figure 1.1 General outline of the dissertation.



The motivation for this work is the development of sustainable UA in the context of water scarcity. At the city level, water is a scarce resource, and there is evidence that the implementation of UA can improve the input/output ratio (I/O) of this resource. Through the use of different technologies and management, it is possible to minimise water consumption in food production. One example is restrictive water management, which improves the I/O ratio and maintains yields, or reduces them minimally. Another alternative is the use of organic matter (in the grow media), which improves the physicochemical properties of the substrates under water deficit conditions, providing a longer water supply to the crops. Both alternatives should be accompanied by the implementation of irrigation systems (technology) that are in line with efficient water management, such as drip irrigation. Finally, the monitoring of climate variables is widely implemented, which has allowed for a better understanding of energy flows within the city. This, in turn, has allowed the implementation of technology using water demand models and is a method for determining the amount of irrigation to be applied. The present work seeks to optimise the use of this resource through the use of aforementioned technology and strategies at the greenhouse level.

1.1.Research question and objectives

In the context of water scarcity, population growth within cities is alarming. It is essential to look for new alternatives that meet the demands of the city. UA must provide integral solutions that increase food production and improve productive efficiency (reduction of inputs and food losses).

This dissertation attempts to analyse how different strategies for optimising water use affect the yield and environmental performance of food produced in UA. The following research questions were formulated.

- **Question 1:** Is it possible to construct a simple water demand model to determine the water requirements of a hydroponic crop in a rooftop greenhouse based on its climatic characteristics?
- **Question 2:** Is it possible to maintain yields using organic substrates from the city under water deficit management?
- **Question 3:** To what extent can environmental impacts from a life cycle approach be reduced through optimised water management of tomato crops?

To answer the research questions, one general objective and three specific objectives were established.

General:

- The main objective of this dissertation is to reduce the environmental impact of urban agriculture, with a focus on efficient crop water management.

Specific:

- Develop a water demand model based on experimental work and 3 campaigns of tomato with i-RTG climate data.
- Determine hydric resilience of lettuce cultivation using organic substrates used in urban agriculture in a framework of the circular economy.
- Determine the contribution of environmental impacts of a life cycle approach to water consumption on tomato cultivation, contrasting different water management strategies.
- Contribute to the development of different ways to improve the environment of urban agriculture.

1.2.The state of the water

1.2.1. Global water resources

Water is a fundamental resource for life on the planet; Abbott et al., (2019) states that only 1.9% of water is terrestrial freshwater (Figure 1.2). The same authors show that in terms of flow rates, agriculture is the main user of freshwater. Much of the freshwater is in the form of ice, leaving even less than 5% of freshwater available for human use and food production.

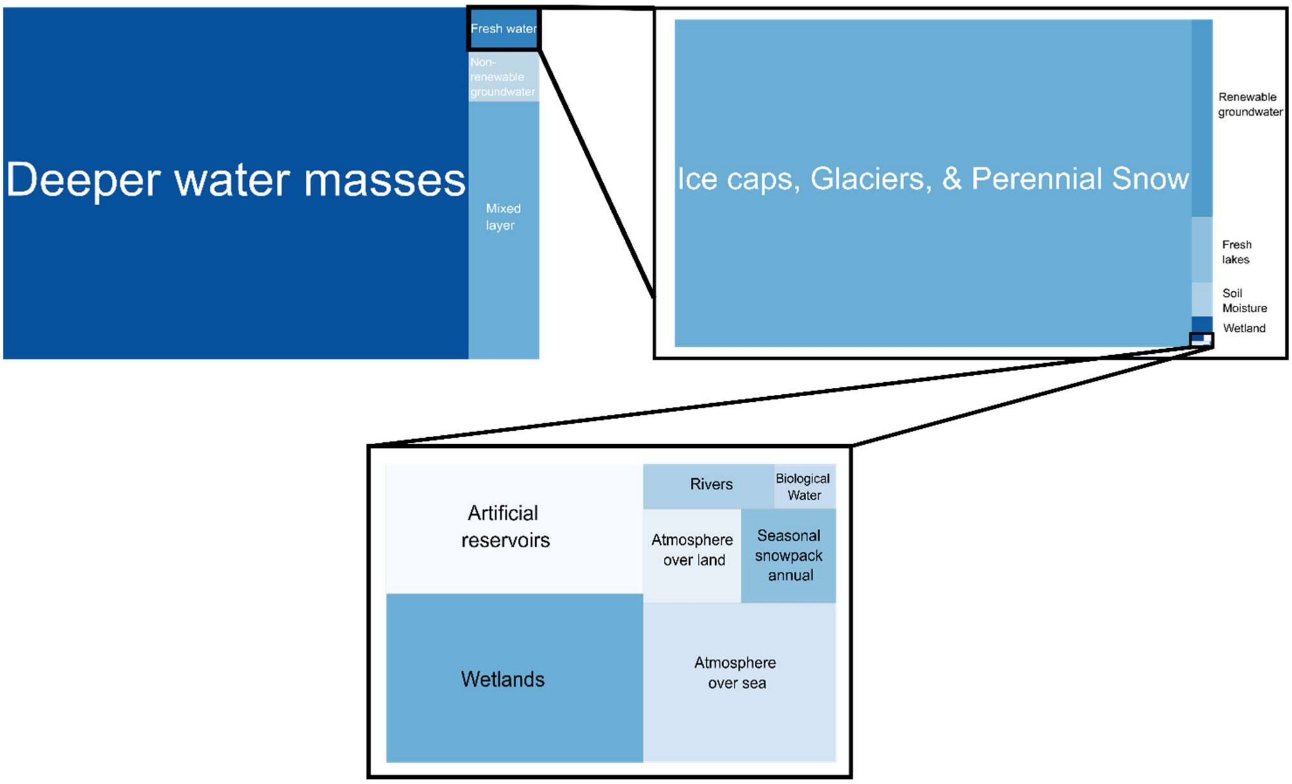


Figure 1.2. Distribution of global water.
Modified from Abbott et al., 2019.

The latest version of the Intergovernmental Panel on Climate Change (IPCC) report in 2021 shows that global hot temperature extremes will increase with the intensification of droughts across the Mediterranean basin.

An increase in drought in the short to medium term can cause extreme heat stress and have a detrimental effect on crop yields. Prolonged droughts cause long-term damage to ecosystems, such as contamination of aquifers with marine intrusion and reduction of water flow in superficial water. These changes can lead to socioeconomic problems from limited access to water to economic losses (FAO, 2021).

In the predicted scenarios of continuously decreasing freshwater availability in Mediterranean ecosystems, an imbalance between the supply and demand of water resources is evident. According to the National Weather Service of the United States (NWS) there are different types of droughts: meteorological, agricultural, socioeconomic and hydrological. They are defined as follows:

> *"Meteorological Drought is based on the degree of dryness or rainfall deficit and the length of the dry period.*
>
> *Hydrological Drought is based on the impact of rainfall deficits on the water supply such as streamflow, reservoir and lake levels, and groundwater table decline.*
>
> *Agricultural Drought refers to the impacts on agriculture by factors such as rainfall deficits, soil water deficits, reduced groundwater, or reservoir levels needed for irrigation.*
>
> *Socioeconomic Drought considers the impact of drought conditions (meteorological, agricultural, or hydrological drought) on the supply and demand of some economic goods such as fruits, vegetables, grains, and meat. Socioeconomic drought occurs when the demand for an economic good exceeds supply as a result of a weather-related deficit in the water supply."*

In the Mediterranean basin, droughts have occurred repeatedly in the past three decades. More specifically, Spain has experienced frequent droughts, such as the severe drought of 1991. In Spain, 68% of the total water demand is used for agricultural production (Llamas, 2000) and the country relies heavily on irrigation. It was reported that during the 1991 drought, 500,000 hectares of irrigated agricultural land were affected, resulting in economic losses of between 3 and 4.2 billion euros (Garrido and Gomez-Ramos, 2011). This had a negative effect in socioeconomic terms, leading to awareness and the development of a drought policy. A drought prediction system was established to aid decision-making regarding a management system, which was developed to generate emergency plans for urban water supply (FAO, 2019). In Barcelona, the use of drinking water for irrigation was forbidden during the 2008 drought (Decreto 84/2007, 2007). This situation gave rise to alternative methods for reducing the impact of low water supply on food production systems.

Sanchez-Lorenzo et al., (2014) show from 1980 to 2011, evapotranspiration has increased, reaching an estimated +0.1 mm d^{-1} $decade^{-1}$, which could translate into an increase in evapotranspiration of about 3% every 10 years. Particularly in Catalonia, projections for the period 2012-2021 (compared to 1971-2000 averages) project that by 2050, precipitation will fall by between 5.3 and 8.3%, depending on the area (Coastal zone, Pyrenees, or Inland). In addition an average temperature increase of 1.4º Celsius is projected for all of this zone of the Mediterranean basin (Calbó et al., 2016). The sum of this different phenomena has promoted other alternatives to reduce the impact of low water supply on food production systems.

1.2.2. Water as a scarce resource for food production

Agriculture is particularly vulnerable to water scarcity and has adapted to climatic conditions to maintain food production (European Environment Agency., 2019). Water scarcity directly affects food production. Its effect on photosynthesis is due to significant reductions in the amount of transpiration/CO_2 assimilation, which directly affects crop yields. Depending on the magnitude of the water restriction, the crop may even be damaged to the point where it cannot recover (Briggs and Shantz, 1911).

Water is a highly demanded resource vital for life, the development of society and different industries. Today, we find ourselves in a situation characterized by the conflict between low water availability and high requirements. To address this, strategies for improving plant physiology, technology, and productive systems would be beneficial.

Plant based strategies

The first strategy to improve water use focuses on the development of drought-resistant/tolerant crops, which can produce food under conditions of low water availability (FAO, 2016). Similarly, another alternative is the development of salinity tolerant crops, which thrive where other crops typically could not grow due to osmotic stress (Atzori et al., 2016; Nozzi et al., 2016).Technological strategies

The second strategy is to use water sources that are not traditionally considered suitable for irrigation (Atzori et al., 2019). This reduces the pressure exerted on fresh water by agriculture and allows its use for other purposes. In Europe, the reuse of wastewater is a strategy for supplying irrigation to green areas in cities (Rodríguez-Villanueva and Sauri, 2021). An industrial example of the reuse of treated water in Catalonia is the petrochemical complex of Tarragona, the largest chemical hub in southern Europe. An environmental use of this treated water is for the irrigation needs for landscaping in Port Aventura Park (Sanz et al., 2014).This is an example of leveraging technology to increase the amount of usable water that it is possible to apply at the city level. In addition, other technologies as rainwater harvesting systems have been shown to be a viable alternative for reducing the harmful effects of climate change, such as floods or extreme droughts (de Sá Silva et al., 2022; Petit-Boix et al., 2018) promoting water saving, through several uses, such as irrigation water, washing clothes, toilet uses (Morales-Pinzón et al., 2014).

System strategies

Finally, the integration of various technologies within a system is another approach to optimisation. Examples include the implementation of irrigation systems, the use of greenhouses and sensorisation in forced production systems, among others (FAO, 2016). The objective of this approach is to provide the best growing conditions for the crop, considering its requirements (temperature, water, nutrients, reducing pests and diseases). These improvements are more accessible for use; they can be quickly applied by users who want to improve their productivity.

Intensification in food production is a constant process that seeks to increase crop productivity by improving environmental conditions. Particularly, in the present dissertation, we examine abiotic improvements through protected cultivation. Castilla, (2004) mentioned the advantages of protected cultivation, such as the following:

- Reduces the water requirement of the crop
- Protects against low temperatures
- Reduces wind speed damage

- Generates of microclimates in arid and semiarid areas
- Reduces pest and disease damage
- Extends production areas and production cycles
- Improves the efficiency of resource use
- Provides climate control
- Leads to stable production over time

There are several examples of crop protection, including the use of wind screens, plastic protection against weeds, insect screens, and different films for crop protection. Specifically, this dissertation address the use of polycarbonate greenhouses in the interior of cities.

Research has shown that greenhouse production improves resource efficiency because it leads to a reduction in water consumption due to the technical improvements that are implemented. Greenhouses or forced production systems require a higher input of energy due to the high level of technology and expertise needed, as well as a higher economic cost (Ntinas et al., 2017).

Forced food production can improve the input/output ratio of the production system. Control of climatic variables enhances production, minimising inputs (water, which in turn optimises the use of fertilisers and energy). In addition, environmental conditions are optimised, and agricultural management is improved.

1.3.Ways to optimise water use

Currently, there are several methods for applying irrigation, all of which aim to maintain the most productive conditions in terms of crop water consumption. In the context of water scarcity, minimising the input of water while maintaining yield is crucial for sustainable agriculture. In general, optimisation of water involves:

(1) use of irrigation schedules, (2) leachate rates, (3) use of sensors to monitor the water content of the substrate[1], and (4) modelling of water demand through climatic parameters.

First, irrigation schedules are used, where irrigation times are established (which may vary according to the season), and irrigation is applied at preset frequencies (e.g., irrigation every 4 days). Although the simplest method does not require a high degree of expertise to implement, it exhibits a series of disadvantages in terms of management. Although this approach considers the general climatic conditions, in specific circumstances, it does not adjust to the immediate demands of the crops, resulting in excess irrigation application (Zotarelli et al., 2009).

The second strategy, the use of the leachate percentage, is a process in which the ratio of irrigation water applied to leachate produced is evaluated on a daily basis. The goal is to maintain a ratio (leachate/irrigation water) of 30%, thus ensuring good physico-chemical conditions of the rhizosphere, avoiding the concentration of salts, and maintaining an adequate level of nutrients in the substrate solution. This represents adequate management, but additional systems need to be implemented to allow the reuse of the leachate. The release of leachate into the environment results in increased environmental impacts associated with eutrophication (marine and freshwater) due to the excessive release of phosphorus and nitrogen (Rufí-Salís et al., 2020b). For these reasons, these alternatives for irrigation management, although effective, are challenging to apply on a small scale.

Third, the use of sensors, probes, or other devices to measure the moisture content of the substrate (electrical conductivity and temperature) allows for very tight water management, maintaining levels within a range that does not limit plant transpiration and for concomitance of the yield. A limitation of this method is the fact that several sampling sites are necessary to generate a representative value for the crop, as well as the calibrations associated with the substrate. A previously

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[1] A substrate is a solid matrix free of plant pathogens and has properties that ensure an adequate supply of aeration, water, and nutrients for a growing plant (Gruda, 2019).

obtained value is not directly transferable to other crops, so it would need to be adjusted at a minimum. Finally, the use of water demand prediction models is a viable alternative, and adjusting the level of information required depends on the expected results. For very precise results, a large amount of data will be required for the implementation of physical models, which are highly accurate but very demanding in terms of the number of variables they require to be measured. On the other hand, for private management, either for commercial or private purposes, it is possible to use simpler models, such as empirical or statistical models, which are less demanding in terms of their information requirements but maintain minimum representability.

The development of specific models that can predict the crop water demand in diverse conditions is needed to provide information about the amount of water that crops require, reducing the frequency of overirrigated conditions. In this way, different alternatives can be used to determine the water flux within the substrate-plant–atmosphere system. Currently, two lines of research are considered. Physical models are based on the relationship between physical variables (temperature, radiation, relative humidity) and the amount of water evapotranspired. Physical models are built on energy balances, energy input and output, and the general model is presented in Equation 1.1.

$$\boldsymbol{R_n - G - \lambda ET - H = 0} \qquad \text{(Eq. 1.1)}$$

where net radiation (R_n) is the input of energy (unique positive parameter). On the other hand, the outputs of the system (negative parameters) are the sensible heat (H), the latent heat flux (λET), and finally the soil heat flux (G). This generalisation allows us to understand the energy flows within the food production system and only consider only the vertical flux (ignoring the horizontal energy flux) (Allen et al., 2006).

One of the most validated models in the scientific field is the Penman–Monteith model (Equation 1.2), which determines the reference evapotranspiration (ET_0). This type of balance-based model requires a high level of information, which allows it to be applied in different conditions, but it limits its use due to the large number of variables required to be measured for its implementation.

$$\lambda ET_0 = \frac{\Delta \cdot (R_n - G) + \rho_a \cdot c_p \cdot \left(\frac{VPD}{r_a}\right)}{\Delta + \gamma \cdot \left(1 + \frac{r_s}{r_a}\right)} \qquad \text{(Eq. 1.2)}$$

where VPD is the vapour pressure deficit of the air (saturation vapour pressure less actual vapour pressure), ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, γ is the psychrometric constant, r_s and r_a are the (bulk) surface and aerodynamic resistances, respectively, λ is the vapourization latent heat, and Δ represents the slope vapour pressure curve.

In contrast, empirical modes require fewer variables to determine ET_0; however, these models are used under specific conditions, where constant factors are normally used that integrate the specific variability of the site where it has been developed. The low information requirement favours this type of model due to low requirements in terms of data. One of the most widely used models is that of Hargreaves and A. Samani, (1985), which is based on the temperature: 3 temperature variables and one radiation variable (Equation 1.3):

$$ET_0 = 0.0023 \cdot \frac{R_a}{\lambda} \cdot (T_{AVG} + 17.8) \cdot (T_{max} - T_{min})^{0.5} \qquad \text{(Eq. 1.3)}$$

where Ra represents extraterrestrial radiation (constant factor varying according to the day of the year), and T_{AVG}, T_{max} and T_{min} are the daily average, maximum and minimum temperature values, respectively. It is important to note the difference between Equations 1.2 and 1.3, where λET is expressed as a heat flux [MJ $m^{-2}day^{-1}$], and the second, it is expressed as a water flux in [mm $m^{-2}day^{-1}$]. Both values represent a flow of either water or energy, which is harnessed to determine transpiration.

The European Climate Assessment & Dataset project (ECA&D, 2021; Klein Tank et al., 2002) presents a compilation of historical climate data. In addition, Catalonia has a network of meteorological stations throughout the territory (Ruralcat, 2019). The Catalan dataset is very complete and considers different climatic variables, such as dew point temperature, maximum and minimum temperature, wind speed, relative humidity, and solar radiation.

In parallel, the installation of sensors to monitor water needs is becoming increasingly common for all types of users, including researchers, companies, and the public. In UA microclimates show stable behaviour. Food production on rooftops presents a new productive condition, where the wind speed (Muñoz-Liesa et al., 2020) and different types of exposure and shading (product of the alleged constructions) play important roles (Allen et al., 2006; Gong et al., 2020). This point is key to efficient water management, as windy conditions are associated with higher water demand (Montero et al., 2017). The monitoring of climatic variables is a key issue due to the new conditions imposed by the city environment where the crop grows.

The development of tools that facilitate water management at all levels (urban farmers, researchers and businesses) is highly desirable, and the use of simple models to predict water demand is required (Katsoulas and Stanghellini, 2019) to improve fertigation management and optimisation.

1.4.Evaluating yields in agriculture in terms of water use

Traditionally, yield in production systems has been evaluated based on the most limited resource, which typically has been surface area. An example is product quintals per hectare or kilograms per square metre (Cherubini et al., 2009). In places where water is scarce, other types of indicators are used, such as the product per unit of water used or water use efficiency (Fernández et al., 2020). Within UA, both land and water are scarce, competing with residential and industrial uses for both resources.

Fairweather et al., (2003) mentions water use efficiency (WUE) as a concept widely used for defining a ratio of water use and crop production, where the inputs (water) and outputs (yield) are evaluated. Depending on the scale of the analysis, the input values of WUE can also be expressed as irrigation water supply or irrigation water used (excluding losses).

Barrett and Associates, (1999), explain WUE can be used as a generic concept and applied to any area/sector. At the same time, their study develops specific terms derived from WUE, expanding the range of available performance indicators.

Table 1.1 shows indices associated with water consumption and crop yield. Each index responds to a specific relationship, such as the intrinsic water use efficiency, which shows the photosynthetic capacity of the crop, relating CO_2 assimilation with transpiration and allowing comparison at the photosynthetic system level. Another example is the crop water use index, which relates crop production to evapotranspiration considering losses, such as stress.

Table 1.1 Different water use efficiency indices.

Index	Units
Instant Water Use (or Intrinsic WUE)	$\frac{CO_{2Assimilated}[molm^{-2}s^{-1}]}{H_2O_{Transpirated}[molm^{-2}s^{-1}]}$
Crop Water Use	$\frac{Total\ product[kg]}{Evapotranspiration[mm]}$
Irrigation Water Use	$\frac{Total\ product[kg]}{Total\ water\ applied[m^3]}$
Farm Water Use	$\frac{Total\ product[kg]}{Total\ water\ abstracted[m^3]}$
Gross Production Economic Water Use	$\frac{Gross\ Production[\$]}{Total\ water\ applied[m^3]}$

Source: Barrett and Associates, (1999), (Hatfield and Dold, 2019) Modified.

Considering the different indices and nomenclature presented within this dissertation, the concept of water use efficiency was evaluated as the ratio between the amount of water used and the amount of yield obtained, as shown in Equation 1.4.

$$\boldsymbol{WUE} = \frac{\boldsymbol{Liters\ of\ water\ evapotranspirated}}{\boldsymbol{Kg\ of\ edible\ tomatoe}} \qquad \text{(Eq. 1.4)}$$

This indicator was selected because it allows a quick comparison of the amount of water used by different crops. As mentioned above, water scarcity is a relevant topic to assess in Mediterranean ecosystems. The WUE facilitates a contrast of productive yield of different crops by using transpired water as input. By applying transpiration in the WUE equation, it seeks to isolate the performance of the crop, avoiding interference from the irrigation system. The use of edible crops as output (in this case, tomato), is a common unit value. Other research has used the same indicator as means for contrasting and comparing crops, and even production systems (Liu and Song, 2020; Wang et al., 2021).

1.5.Urban Agriculture (UA) potential as urban food supply

There is currently growing concern about the sustainability and food sovereignty of cities due to population growth. The United Nations, (2019) FAO estimates that by 2050, approximately 70% of the world's population will live in urban areas. This has raised concerns due to increased consumption of different resources, such as energy, food, and water. This increase leads to environmental pressure by cities due to the higher resource use. In the context of drought associated with climate change, food production is at risk. One way to address this issue is through UA, which takes advantage of spaces and resources from the city. Through the implementation of different production systems, it is possible to reduce the pressure on food production.

There are several types of production spaces within city boundaries (Sanyé-Mengual, 2015a). Figure 1.3 shows different UA typologies, showing the wide range of alternatives available today for development in the city (Sanyé-Mengual, 2015a). Soil is the most frequent typology due to its ease of implementation. In contrast, other systems (rooftop farming) require technology. There is an increasing need to implement complementary systems (substrates, greenhouses, or irrigation systems). It is important to highlight the fact that each one requires a particular analysis for its implementation (e.g., that rooftop cultivation requires a surface with minimum structural resistance). In addition to the typologies that the UA offers and to see how they are integrated into the urban ecosystem through different uses, such as research, economic and social uses. In this way, self-production is complementary and is gaining increasing strength at the city level (Appolloni et al., 2021). One example of the advantages of UA is the use of currently unused spaces, such as rooftops (Gasperi et al., 2016). These spaces can have good exposure to radiation, which creates a favourable condition for food production. In addition, within the city, food transport is reduced, as is the use of packaging. It enhances trade at the local level by using food production as a sociocultural space. In this way, UA is horizontally integrated into society, taking advantage of unused spaces. It is necessary to look for adaptations to traditional systems that meet urban conditions and requirements.

Within the present dissertation, the definition of urban agriculture is based on that of Lohrberg et al., (2016):

> *"Urban agriculture spans all actors, communities, activities, places and economies that focus on biological production (crops, animal products, biomass for energy), in a spatial context that, according to local opinions and standards, is categorised as "urban".*

Several instances have been implemented globally: (1) the Institute of Environmental Science and Technology (ICTA), which has an integrated rooftop greenhouse located in the Universitat Autònoma de Barcelona (UAB). ICTA-UAB has been used as an example for the development of different initiatives in UA through Interreg Europe in the project "Greenhouses to Reduce CO_2 on Roofs". The experience developed in ICTA-UAB has been used to develop various manuals to promote the implementation of UA in Europe. (2) Another example of

UA is the Gotham Greens (GG), located in the United States. GG is the first commercial rooftop in this country, currently with nine operating greenhouses.

This is an example of successful cases of UA in global businesses with nearly one hundred workers in the whole company (Gotham Greens, 2021). At a minor scale, UA allows unused space to be leveraged, together with the promotion of local economies, by developing a smaller logistical apparatus in terms of deliveries, selection and storage (Oliveira et al., 2021).

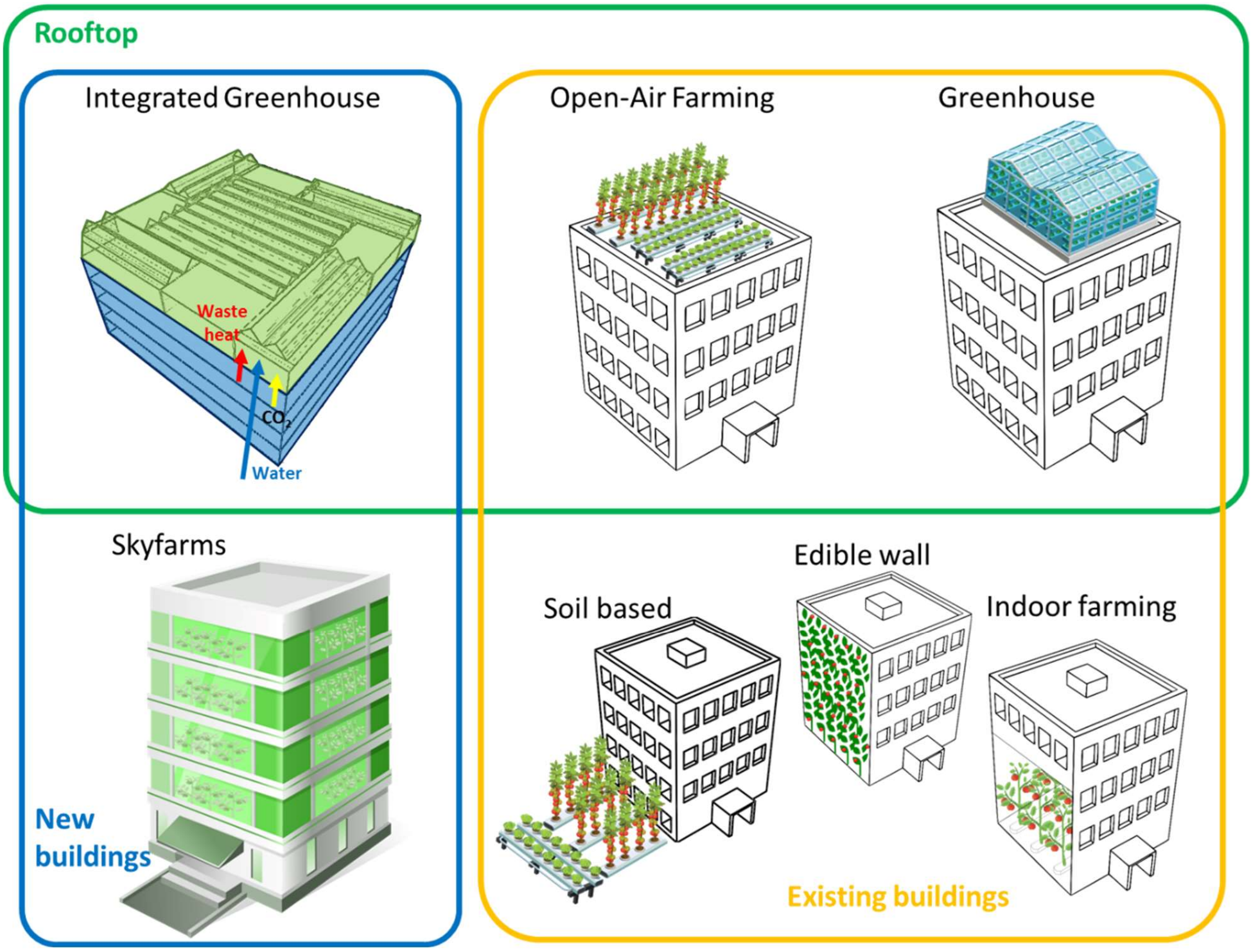


Figure 1.3 Typologies of UA.

For social purposes, the Barcelona city council pilot program designed for citizens of Barcelona with moderate to very marked disability has shown improvements in the quality of life of the participants through the introduction of UA on rooftops. The social benefits are seen in terms of physical and emotional well-being

(Triguero-Mas, 2020), as well as development of social integration for people with mental and intellectual disabilities. Food production in cities is under development, and several public and private institutions are interested in its implementation through the application of incentives for the development of UA projects (Ajuntament de Barcelona, 2021a, 2021b).

Based on the wide range of possibilities and alternatives that exist today around UA, a constant analysis of the production systems is needed. It allows to identify the points of lower efficiency to generate a constant optimisation. As a way to optimise food production at the city level, growing conditions such as irrigation management, radiation, and temperature should be improved (Appolloni et al., 2020).

Currently, the implementation of the perspective circular economy (CE) over UA systems is possible due to the integration of different subsystems that join the city. Thus, the recycling of waste, together with the reuse of raw materials (Manríquez-Altamirano et al., 2020), also supports new business models at the city level (Sanyé-Mengual, 2015b).

For the present work, the definition of the circular economy used is proposed by Nobre and Tavares, (2021), defined as:

> *"An economic system that targets zero waste and pollution throughout materials lifecycles, from environment extraction to industrial transformation, and to final consumers, applying to all involved ecosystems. Upon its lifetime end, materials return to either an industrial process or, in case of a treated organic residual, safely back to the environment as in a natural regenerating cycle. It operates creating value at the macro, meso and micro levels and exploits to the fullest the sustainability nested concept. Used energy sources are clean and renewable. Resources use and consumption are efficient. Government agencies and responsible consumers play an active role ensuring correct system long-term operation."*

Currently, there are several experiences at the city level, where UA is taking more space. Due to the decrease in rainfall, there is less water available in the whole Mediterranean basin. In this situation, it is necessary to look for new alternatives to maintain food production in the city and to be efficient in the use of resources. Within the framework of water use efficiency, various strategies have been proposed to overcome the problems associated with low water availability.

Considering the circular economy as the main axis of development, several alternatives can be implemented. i) The use of organic substrates coming from local organic waste (domestic or municipal). ii) The properties of compost have proven to be beneficial to agricultural production and have both physical (structural and water retention capacity) and chemical (improved cation exchange capacity) properties. (Gruda, 2019; Machado et al., 2021). By contributing stabilised organic matter, compost is used to improve physical properties, contributing to the formation of macro and mesopores by improving the substrate structure (Wallace et al., 2020) and promoting the aeration and flow of excess water in the substrate. The advantages of using compost as a substrate in cities include, the evident reduction of waste sent to landfills, together with the cycling of nutrients, which are used by hydroponic crops (De Corato, 2020). In this sense, being able to environmentally quantify the benefits offered by the different strategies is fundamental to be able to have a critical view of food production when deciding how to produce our food.

1.6. Environmental analysis

To assess the performance of different products and systems, environmental analyses have been widely used; through material flow analysis, it is possible to determine the different environmental impacts.

Several research studies have used life cycle analysis (LCA) as a tool to determine the environmental performance of specific processes or products in food production (Guo et al., 2021), as well as holistic views of the system (Parajuli et al., 2021). Specifically, it has been used as a tool to analyse and compare hydroponic systems with traditional systems (Martínez-Blanco et al., 2011).

Applying life cycle tools to inner-city food production would make it easier to determine (1) the amount of resources and inputs used, (2) calculate the environmental impacts at each stage/process, and (3) determine the most relevant stages/processes in terms of environmental impacts (Irabien and Darton, 2016).

In this regard, previous environmental analyses have been carried out at the agricultural level (Brentrup et al., 2004; Roy et al., 2009). Several environmental studies using LCA have shown that the greatest impacts are associated with fertilisers (Armengot et al., 2021) and transport (Roy et al., 2008) of food products. In greenhouse production, the impact contribution of fertilisers decreases due to the increase in infrastructure (Anton et al., 2005).

Research has been carried out on greenhouses, contrasting the level of technology involved in heating and ventilation(Payen et al., 2015). The first ones stand out because usually their highest environmental impacts are associated with the large amount of energy required to elevate the temperature; although their yields are usually higher, the increase is not enough to compensate for the amount of energy they consume. On the other hand, passively heated greenhouses tend to have a lower impact, despite having lower yields (Boulard et al., 2011).

In addition, LCA has been applied to UA production in various typologies, resulting in lower environmental impacts associated with the reduction of transport compared to conventional agriculture (Sanyé-Mengual, 2015b). It is worth mentioning that in terms of specific environmental indicators, UA has exhibited a greater impact in terms of ecotoxicity due to the use of materials for its construction, particularly steel and polycarbonate (Muñoz-Liesa et al., 2021).

1.7.Water urban cycle

The hydrological cycle drives diverse processes, such as the transport of pollutants, nutrient fluxes, and surface and groundwater water in the landscape. Urbanization changes several of the fluxes in this cycle due to a reduction in the opportunity for infiltration (impervious surface or a reduction in vegetation, among others) (Fisher et al., 2016), affecting recharge (water input) and evapotranspiration and reducing groundwater storage (Bell et al., 2016).

To address these hydrological changes, green infrastructure can be implemented, which is defined by The European Commission, (2019) as "two complementary planning approaches. One starting from a physical mapping of existing green infrastructure components identifying and delineating landscape elements such as protected areas, ecological networks, other protected areas, etc. To ensure that those elements lead to the delivery of multiple ecosystem services, the second functional approach also takes into consideration ecosystem service-based mapping targeting connectivity and delivery of multiple ecosystem services such as provisioning, regulating and cultural services."

Green infrastructure has demonstrated a benefit to the hydrologic urban water cycle due to improved management of stormwater runoff, delayed runoff, and water infiltration into the soil. (USDA, 2020). The green infrastructure aims to maintain ecosystem services, where the UA can complement these services at the city level in three ways: (1) local food production, (2) biodiversity and environmental services, and (3) social/cultural and economic services (Lin et al., 2017). UA is integrated into green infrastructures, contributing positively to the city's water cycle, reducing runoff and improving the use of this resource through food production (Deksissa et al., 2021). In addition, UA improves the self-sufficiency of the community, reduces its environmental impacts, and promotes local economies through food production. (Sanyé-Mengual, 2015a)

One way that UA is used to reduce runoff is by storing rainwater. An example of the implementation of this system is in the ICTA-UAB's rooftop greenhouse, which has a 100 m^3 storage tank. (Sanjuan-Delmás et al., 2018). Rainwater is used for food production, maintenance of ornamental plants, and toilets. UA contributes by using rainwater, which is aligned with Sustainable Development Goals (SDGs) 6, 8, 11 and 12 (Ensure availability and sustainable management of water and sanitation for all, decent work and economic growth, sustainable cities and communities, and responsible consumption and production, respectively). According to them, there is a need to promote economic growth by considering resilient cities from the perspective of sustainable consumption/production and efficient water use and management. (United Nations, 2019b)

Concerning SDG 6, improvements in UA can be seen not only in the improvements in water efficiency but also in other advantages associated with the reduction of food transport. The traditional agricultural production chain has high loss rates. Parfitt et al., (2010) concludes that 10-40% of food waste is lost and can reach up to 50%. All of these losses are associated with aesthetic issues (condition, size, quality). In the United States, 31% of total food is lost at retail and consumers, where 19% of the total loss is caused by vegetables. (Buzby et al., 2014)

An increase in UA could reduce food losses associated with the long supply chain by reducing food transport distances. In parallel, the amount of food production can be reduced, thus making city-level production systems more efficient (Langemeyer et al., 2021). Benis and Ferrão, (2017) present a study in which reducing the production chains for vegetables is mentioned, and it is possible to reduce the range of 0.85% to 3.83% of the environmental impact (in terms of GHG emissions).

In the framework of a circular economy, one of the pillars of sustainable development is the reduction of losses and recycling of waste. Canet-Martí et al., (2021) state that the implementation of UA improves the input/output ratio of the productive system due to different strategies applied, such as the recirculation of nutrients, the use of compost, or struvite.

The input optimisation recommended in the circular economy strategies could represent reductions in the environmental burdens generated by agricultural production. This is attributed to lower energy consumption due to water transport and application. In terms of fertiliser, a reduction in input radiation has translated into a reduction in the input/output ratio, which has been shown to reduce impacts associated with agricultural production. Open hydroponic production systems, which are more tightly managed, reduce the amount of nutrients released into the environment, with corresponding environmental improvements.

There is currently a focus on maximising yields in the food industry, where intensification of production is focused on obtaining more kg of product per square metre. This has resulted in an increase in the resources used in agricultural production. Consumer concerns about the origin and type of production have forced companies to look for more sustainable ways of producing agricultural products.

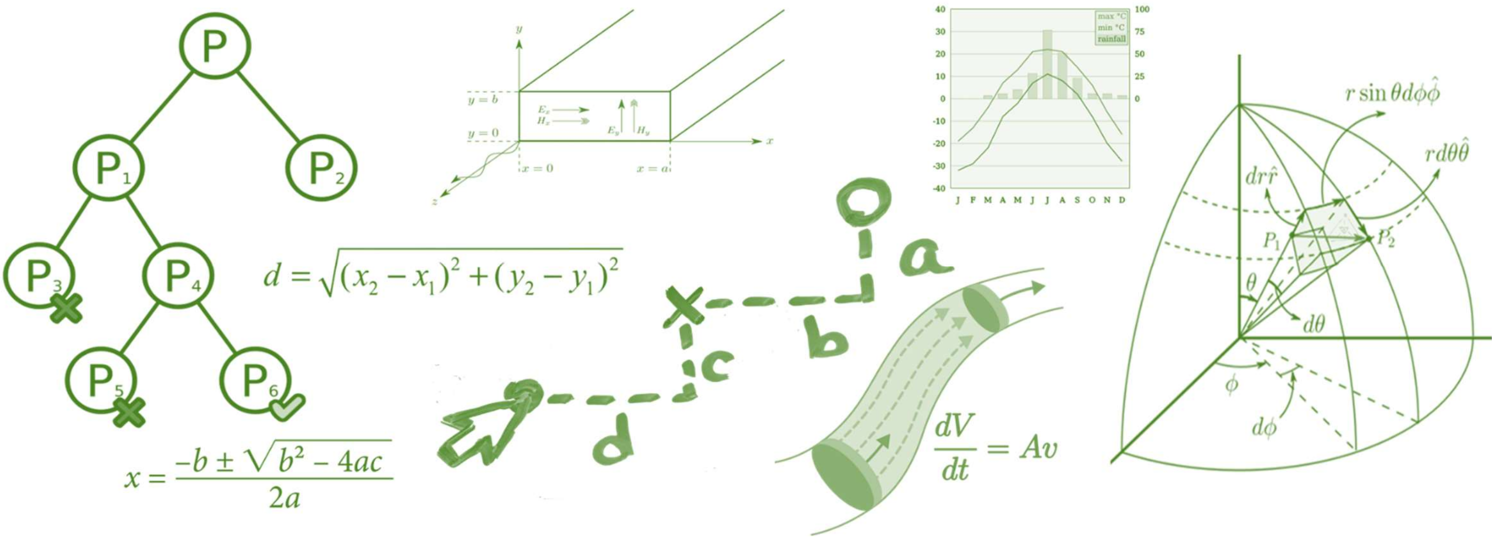
Implementing a set of strategies to meet food challenges under conditions of water constraints is necessary (Li et al., 2018). In this way, the present work addresses the environmental optimisation of food production in AU through different water strategies. First, the use of mixtures of different elements to improve the physical and chemical characteristics of the substrates used or different cultivation techniques to reduce the detrimental effects of the lack of water on the crops (Lu et al., 2015; Tomadoni et al., 2020).

The reduction of environmental impacts through efficient water management is explored by contrasting 3 strategies (conventional management with 30% leaching, management with recirculation and convectional management of 30% leaching, and recirculation with reduced irrigation). Data were obtained in the rooftop greenhouse of the Institute of Environmental Science and Technology.

Finally, a water demand model was developed based on climatic data from a rooftop greenhouse with a tomato crop. This work aims to build a tool to estimate water amounts in UA conditions. To better control the required water inputs, the losses associated with management should be reduced. These losses are associated not only with water as a resource but also with the nutrients that are applied through the fertigation system.

Part II

Materials and methods



Chapter 2.

Materials and Methods

Chapter 2 presents the materials and methods used in the present dissertation , including: description of the study site and the auxiliary systems, as well as the environmental and agronomic analysis employed. Additionally, all the data gathering such as climatic information and the statistical analysis used are also described.

This chapter is structured as follows:

- Study site and system description
- Description of agronomic analysis and general greenhouse management
- Water balance and flows
- Yield and biomass determination
- Life Cycle Assessment (LCA)
- Statistical modelling of water demand
- Data collection
- Climatic variables and Sensors required

2. Chapter 2: Materials and methods

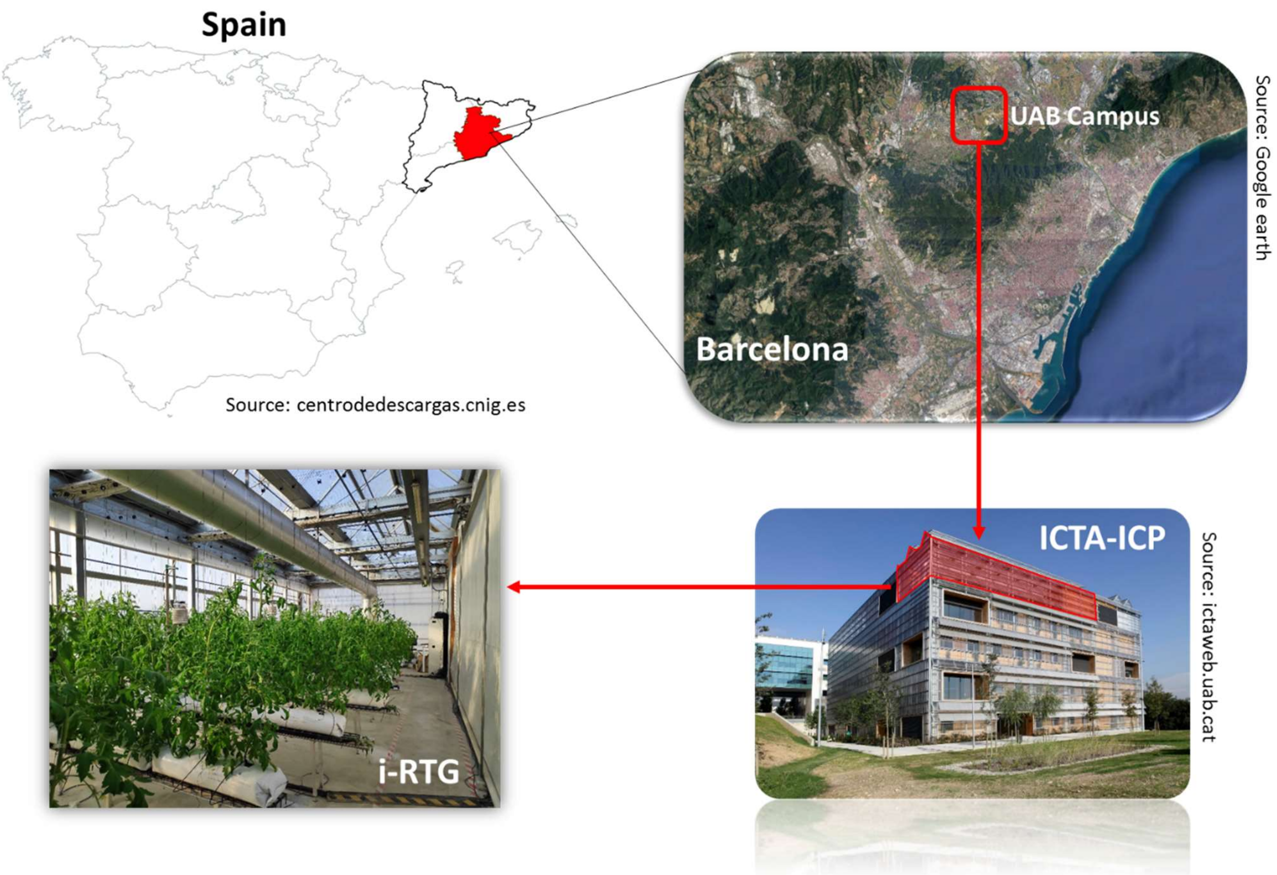
Materials and methodologies used in the thesis for the collection of information analysed in this research. In order to carry out the environmental and agronomic analysis of this work, a series of materials and methodologies were used, which will be described in the following section. Table 2.1 presents a summary of the general methodologies applied. **Chapter 3** relates the water demand with climatic variables measured inside the greenhouse using a statistical analysis for the determination of a simple water demand model. Within **Chapter 4**, a life cycle analysis (LCA) is conducted, contrasting the environmental impact of three irrigation strategies implemented under two systems (one linear and two with leachate recirculation). Finally, **Chapter 5**, focuses on the optimization of water resources through the implementation of restrictive irrigation management and the use of different organic substrates

Table 2.1 Methodologies and analysis applied in each chapter.

	Chapter 3	**Chapter 4**	**Chapter 5**
Agronomic analysis	x	x	x
Water optimization	x	x	x
Field experiments	x	x	x
Chemical analysis			
Life Cycle Assessment			
Data bases management		x	x
Statistical modelling	x		
Statistical analysis	x	x	x

2.1. Study site: integrated rooftop greenhouse of ICTA

All the studies were developed in the integrated Rooftop Greenhouse (i-RTG) of the Institute of Environmental Science and Technology of the Autonomous University of Barcelona (ICTA-UAB) (4594364.95 N, 425599.00 E, 31T). This building is located on the campus of Universitat Autònoma de Barcelona (Catalonia, Spain), in the outskirts of the city of Barcelona.



Source: centrodedescargas.cnig.es

Source: Google earth

Source: ictaweb.uab.cat

Figure 2.1 Description of the study site.

2.2. Agronomic analysis

A general description of the system, considering the most important water flows, is presented in this section. Subsequently, how the direct monitoring of the greenhouse was carried out, considering the data collection. A general description if the greenhouse its monitoring and fertirrigation system are presented.

Furthermore, there are also describes the pest management and simple and analysis methodologies.

2.2.1. System description and general greenhouse management

The experimental and analytical methodologies were developed in the urban agriculture laboratory 1 and 2 (LAU-1 and LAU-2, respectively) of the integrated rooftop greenhouse (i-RTG - Figure 2.1). LAU-1 has a south-east exposure, getting the best hours of radiation (morning and midday). In contrast LAU-2 has a South-west exposure, with the best hours of radiation only in the afternoon (More details Table 2.2).

Table 2.2 General description of Laboratory of Urban Agriculture 1 and 2.

Item	Unit	LAU1	LAU2
Total area	[m^2]	128.0	125.0
Effective area	[m^2]	84.3	70.0
Harvesting area	[m^2]	63.5	64.0
Crop	-	Tomato	Lettuce
Crop tray	-	Single	Double
Cultivar	-	Arawak	Oakleaf
Plants per bag	[Nº]	3.0	4.0
Nº of seasons	[Nº]	3.0	3.0
Season duration	[Date]	1) 10-01-2018 to 30/07/2018	1) 19-03-2018 to 26-04-2018
		2) 14-01-2019 to 02/08/2019	2) 03-05-2018 to 04-06-2018
		3) 17-02-2020 to 31/07/2020	3) 19-06-2018 to 18-07-2018

*The effective area is considered as the space without the elements that are not part of the greenhouse, such as ventilation systems, work tables, lockers, among others. The harvest area is considered as the specific space used for the development of the crop, where the benches and the interior paths between these elements are contemplated.

The tomato plant used in LAU1 was *Solanum lycopersicum* L. cultivar Arawak. Each season lasted from 6 to months (from January to July), with approximately 170 tomato plants distributed amongst 57 perlite substrate bags (40 L, granulometry of 0-6 mm). The plant density was 2.7 plant·m^{-2} within a frame of 0.33 x 1.1 m, as shown in Figure 2.2. Both laboratories have an irrigation system, which consists of a centrifugal pump, two fertiliser dosing units (Dosatron ® at 1%) and two rainwater containers of 300 litres each. In the case of LAU1, since 2019 the recirculation system has been added, where a centrifugal pump was added to distribute the leachates, a 300 litres tank to accumulate them (for more details of equipment see Table 2.3). In particular, LAU1 present two irrigation sectors, used to perform different water management.

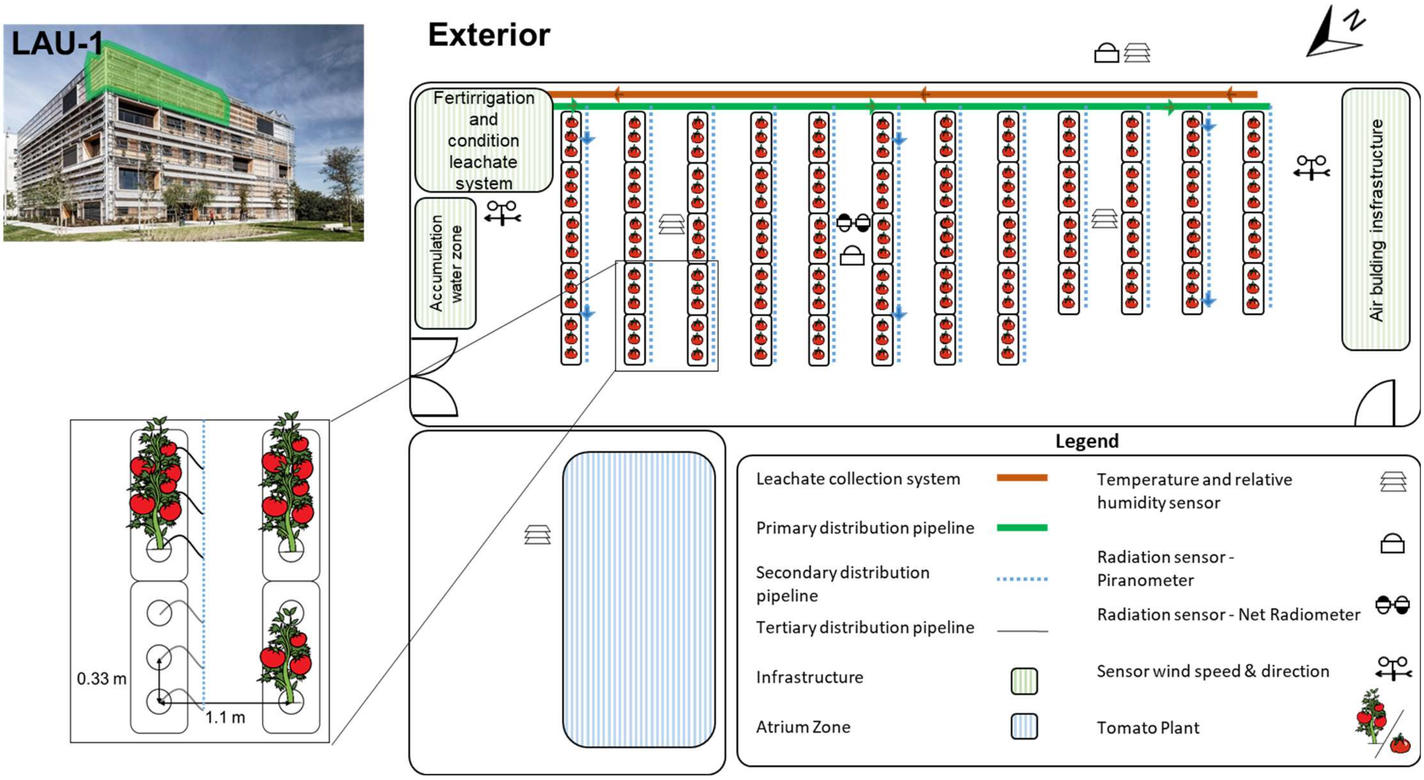


Figure 2.2 Distribution of plants, irrigation systems and sensors (LAU-1).

The atrium area is a construction-free zone within the building, which allows for interaction between all floors above ground level. This allows a better use of the building's thermal inertia, for more details it is possible review (Muñoz-Liesa et al., 2020), who fully describes the energy flows in the whole building. On the other hand, the sites described as infrastructures are spaces for equipment, greenhouse irrigation (Fertirrigation and condition leachate system, and accumulation water zone) or ventilation of the building (Air building infrastructure).

Table 2.3 Description of irrigation and leachate systems (LAU-1 and LAU-2).

	LAU1		**LAU2**
	Irrigation System	**Recirculation System**	**Irrigation System**
Pump horizontal	Prize, model 10-4M, 0,6HP	Prize, model 10-4M, 0,6HP	Prize, model 10-3M, 0,5HP
Pump Submersible	-	2 Calpeda, model GXRM9, 0,34HP	-
Filters Physical	1 Mesh filter 3/4" (200 mesh)	1 Sand filter with backwashing (diameter 0.5 - 1 mm)	1 Mesh filter 3/4" (200 mesh)
		2 Mesh filter 3/4" (200 mesh)	
Filters Biological	-	UV Filter	-
Containers 300 L	2	1	2
Containers 80 L	2	2	2
Programmer	Hunter ® X-Core (4 station, 3 canals)		

The lettuce used in LAU-2 was Oak leaf lettuces (*Lactuca sativa* L. cultivar Crispa). Each season (approx. one month) featured 176 lettuces distributed in 44 perlite substrate bags (40L, granulometry of 0-6 mm). The plant density was 2.8 plant·m^{-2} (with a frame of 0.4 x 0.25 m) as shown in Figure 2.3.

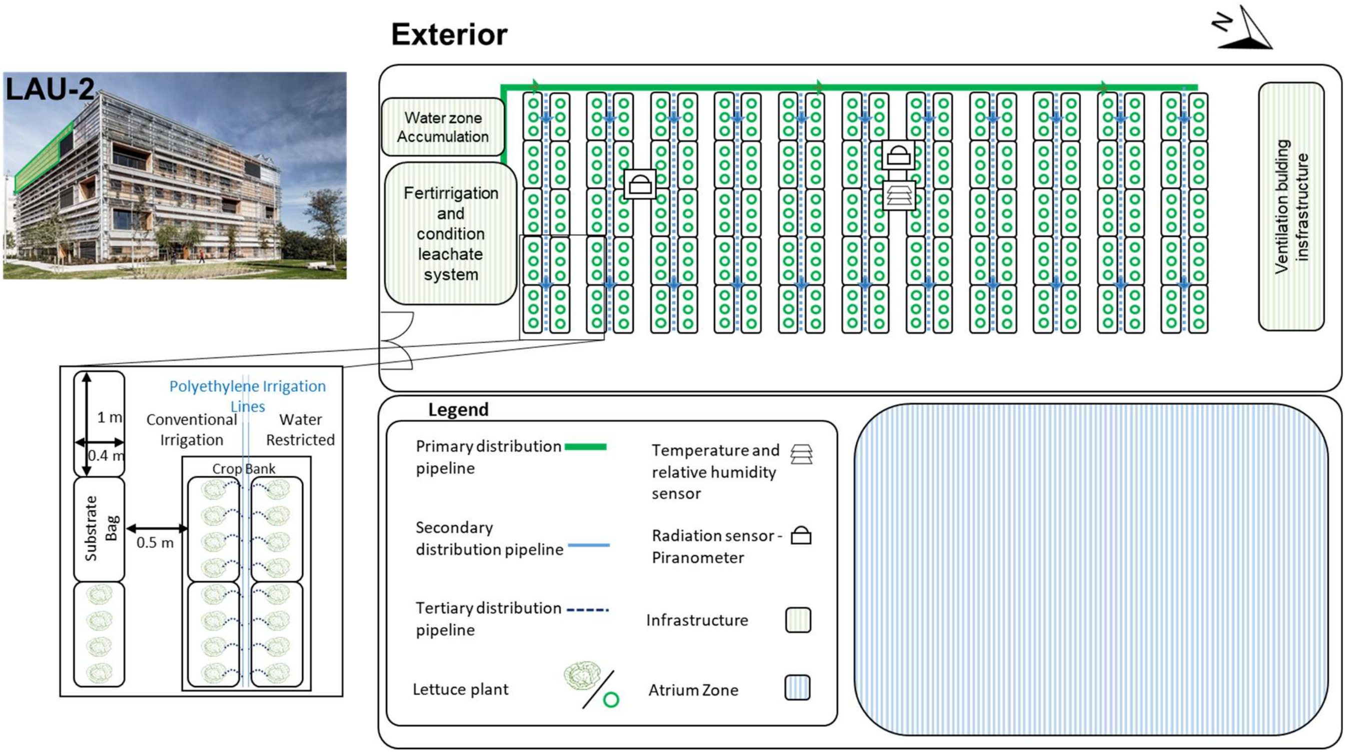


Figure 2.3. Distribution of plants, irrigation systems and sensors (LAU-2).

2.2.2. Water balance and flows

For LAU1, two methodologies were used to determine the water flows: one by estimating the general leachate from the laboratory and the second by measuring the leachate through flowmeters. In 2018, a metering system was implemented, measuring the amount of leachate produced by 3 rows to estimate the overall leachate of the laboratory. From the 2019 campaign onwards, a recirculation system was implemented where all leachate was collected, and new water flowmeters were incorporated. These elements improved the data representativeness and accuracy.

In both cases (2018 and 2019/2020), the inflows and outflows were determined and are detailed in Figure 3.2. For the lettuce seasons in LAU-2, flowmeters were used to determine the amount of water irrigated daily. For the determination of volume leachates, 10 L collection tanks located at the end of the rows were used daily.

The recirculation system used any partial or total leachate generated by the crop. In the season carried out in 2019, a part of the leachate produced by the tomato crop was used in an alternative lettuce crop, as detailed in **Chapter 3**. In the 2020 season, purges of the recirculation system were performed due to the increase in electrical conductivity beyond the critical value of ~4 dSm^{-1}. A dilution of the leachate was carried out, where the maximum volume to be diluted was 50% in a 300 L container, with the remaining 50% removed and refilled with rainwater. All water outflows were accounted for in the daily water balance (Equation 2.1):

$$\mathbf{I} = \mathbf{ET}_{\boldsymbol{c}} + \mathbf{L}_{\boldsymbol{e}} + \mathbf{P} \qquad \text{(Eq. 2.1)}$$

Where I is the input irrigation water, ET_c is the water consumed by the plants or crop evapotranspiration, L_e represents the leachates collected, P represents losses following purges, and E is the evaporation from the perlite bag which was not considered due to its marginal value in relation to daily water demand. All values are presented in [mm·day^{-1}·m^{-2}].

2.2.3. Daily monitoring

Daily monitoring in LAU1 and LAU2 included three basic aspects: flowmeter registration, water flow quality (irrigation and leachate), and crop status.

After recording the values shown on flowmeters (registration) the water flows (inflows and outflows) were determined through the daily differential. The water flow quality is characterized by two parameters: electrical conductivity (EC) (Band: XS, Model: G-CONDT5) and pH (Brand: XS, Model: G-PHT1, and Brand; Hanna Instruments, Model: HI98128).

Finally, the crop status was carried out, checking the state of the plants, with emphasis on any physiological disorder, presence of any pathology or pest. In order to prevent any kind of yield loss within the crop.

2.2.4. Sampling

To monitoring the crop nutrient status, in all of the essay, 3 times per week (Monday, Wednesday and Friday), was collected irrigation and leachates samples (for the rainwater only 1 time per week due this value do no change drastically over the time).

2.2.5. Fertirrigation

The irrigation water was distributed by a pumping system with a drip rate of 2 L·h^{-1}. The fertilizer was applied according to the level of need throughout the cropping season (Table 2.4). In, a summary of the fertirrigation applied in the seasons is presented (for more details see Appendix 9.1-B). The amount of nutrients was adjusted according to plant requirements (developmental stage).

Table 2.4 Average patron solution for tomato and lettuce fertirrigation.

Nutrients [meq·L^{-1}]	LAU2	LAU1		
	2018	2018	2019	2020
$NO_3^{=}$	8.1	10.1	8.0	8.8
P	1.0	1.2	1.5	1.1
SO_4^{-}	2.6	1.9	1.8	2.2
Cl^{-}	3.5	3.5	2.1	2.3
Na^{+}	0.5	0.1	0.1	0.1
K^{+}	8.1	6.5	5.9	6.4
Ca^{++}	3.7	4.1	3.6	4.0
Mg^{++}	1.4	1.9	1.0	1.0

Each LAU featured 2 containers with fertilisers (macro and micronutrients) to avoid the generation of precipitation due to low solubility of the salts present in the containers (Table 2.5). In this sense the injection rate was ~1%.

Table 2.5 Distribution of stock solution.

Container 1	**Name**	**N**	**P** **[%]**	**K**	**Comments**
H_2KPO_4	Mono-Potassium Phosphate	0	52	34	
KNO_3	Potassium Nitrate	13	0	46	
K_2SO_4	Potassium Sulphate	0	0	53	
Container 2					
$Ca(NO_3)_2$	Calcium Nitrate	16	0	0	
$CaCl_2$	Calcium Chloride	0	0	0	50% CaO_2
$Mg(NO_3)_2$	Magnesium Nitrate	11	0	0	16% Mg^{++}
Hortrilon ®	-	0	0	0	Micronutrients
Sequestrene ®	-	0	0	0	Micronutrients

2.2.6. Pest management

As mentioned in general management, daily checks of the LAUs were carried out together with preventive measures for the most common pests/diseases, Figure 2.4 Examples of pest and distribution of biocontrol. shows examples of the pest present in the laboratories. Due to the location of the greenhouse on the roof and its integration with the rest of the building, the range of products applied were smaller than what is typically needed in a conventional greenhouse. The commonly used products are those listed in Table 2.6.

Table 2.6 Products used for pest control.

Product	Plague Control	Concentration [%]	LAU
Sulphur Powder	Eriophyid	0.5	1
Heliosoufre S®	Eriophyid	0.6	1
Potassium soap	Aphid	2-4.	1 and 2
Neemazal ®	Aphid	0.3	1

At the same time, populations of *Macrolophus caliginosus* were introduced into LAU1 each season as a complementary biological control for Trips and Whiteflies. Macrolophus colonies were positioned with food (Entofood - Koppert) to ensure successful establishment and were distributed in 8 points inside LAU-1.

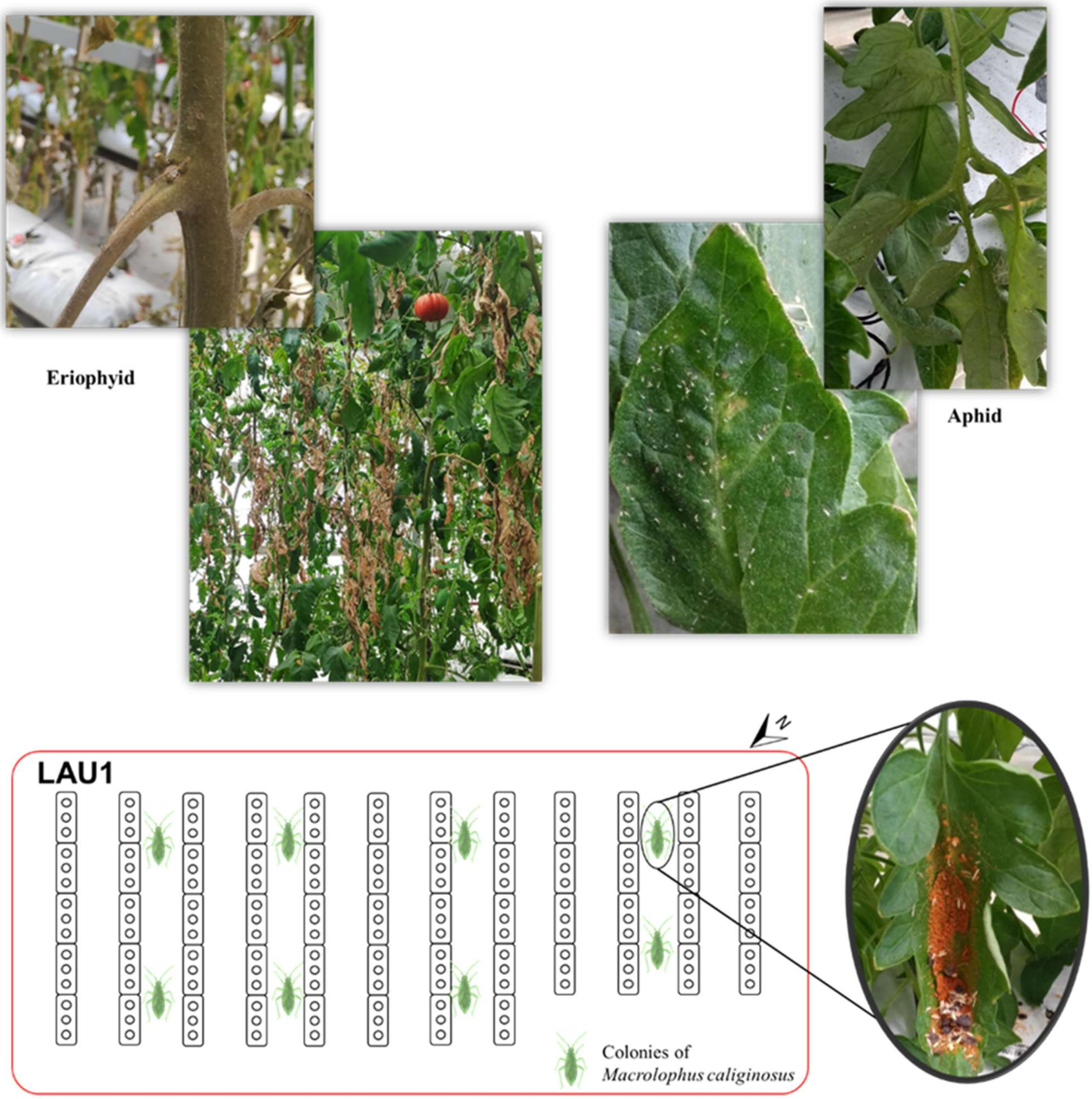


Figure 2.4 Examples of pest and distribution of biocontrol.

2.2.7. Yield and biomass determination

For the LAU1, within each sector, two weekly harvests were carried out, normally on Tuesdays and Fridays, where the yield per row was counted and then aggregated for yield quantification. For the harvesting index, tomatoes were harvested when reaching the colour pink (USDA, 2005). For each harvest, at least five tomatoes were saved to be processed. The samples were oven-dried to constant weight at 65° C and then, three tomatoes was selected, and ground to be analysed composite and send to laboratory. Composite samples were made by taking 3 tomatoes at random from each weekly harvest (fortnightly integration, 2 weekly samples = 1 fortnightly composite sample).

Pruning residues were considered as biomass and were counted per row each time pruning was carried out inside the greenhouse. Samples were taken to be sent for analysis at least once per season. They were dried in an oven at 65º C until constant weight. Yield data, such as pruning biomass [in kilograms], were stored in a computer inside the greenhouse for later analysis. For lettuces in LAU-2, at harvest, the fresh weight of the plant (g of the marketable part) was determined. five lettuces were considered at random for each row of each treatment.

2.3.Nutrient flow analysis

For the nutrient flow analysis different methodologies were implemented. Sampling for water flow is described in the previous sections (Sampling and Daily monitoring). Table 2.7 shows a summary of the methodologies implemented.

Table 2.7. Methodologies of elemental and nutrient analysis.

Element	ICP-OES [Optima 4300DV by PerkinElmer]	Ion chromatograph [ICS-2000 Dionex]	Elemental analysis [Flash 2000 CHNS by Thermo Scientific]
N		I / L	B
P	I / L / B		
K	I / L / B		
K	I / L / B		
Ca	I / L / B		
Mg	I / L / B		
S	I / L / B		B
H			B
C			B

Irrigation water (I), Leachates (L), Biomass and Yield (B)

2.3.1. Irrigation water and leachates

For the determination of the element (nutrients) in the irrigation samples and leachate, two methodologies were used. Firstly, for nitrogen, all samples were stored at -20ºC, then filtered (0.2u nylon) and placed in 1,5ml vials. The aim is to condition the sample to avoid blockages in the column inside the ion chromatograph (ICS-2000 by Dionex), with a column for anion analysis. This device gave the concentrations of nitrite (NO_2^-) and nitrate (NO_3^-). The levels of macro nutrients and other nutrients (P, K, Ca, Mg, and S) were measured by an external service (Chemical Analysis Service of the Universitat Autònoma de Barcelona) through inductively coupled plasma optical emission spectroscopy (ICP-OES, Optima 4300DV by PerkinElmer).

2.3.2. Yield and biomass

For the analysis of yield composite samples, two methodologies were used. The first one for elemental analysis of C, H, N, and S, using the elemental analyser Flash 2000 CHNS by Thermo Scientific. For the elements P, K, Ca, Mg and S, ICP-OES was used (Optima 4300DV by PerkinElmer) in the chemical analysis service of the UAB.

2.4. Life Cycle Assessment (LCA)

The LCA methodology (ISO, 2006) was applied in **Chapter 4** to contrast the environmental performance of the different irrigation strategies, within the i-RTG production system for all the stages of tomato production. The i-RTG production sub-system was separated in two systems: Operation and Infrastructure (Figure 2.5).

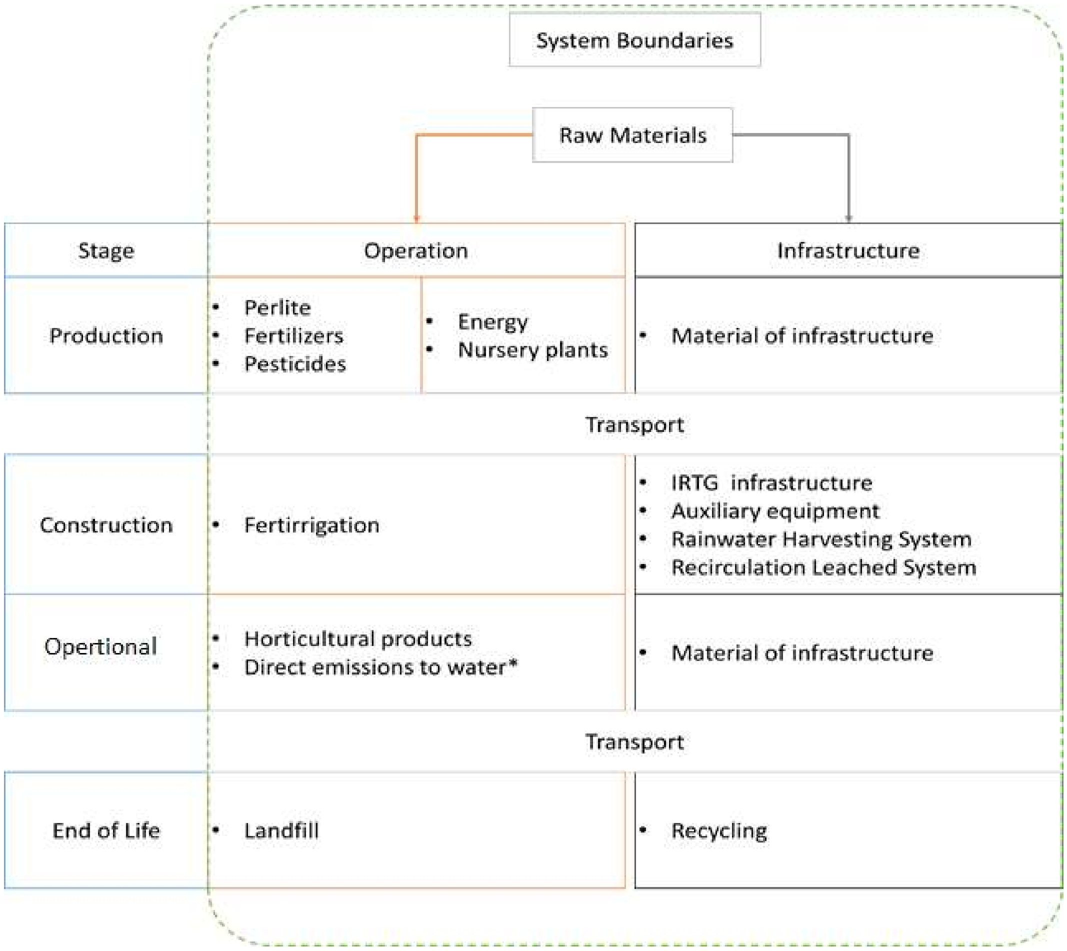


Figure 2.5 Description of system Boundaries for i-RTG System boundaries.
(Green dotted line, Orange: Operation phase, black: Infrastructure, light-blue: Stage.)

2.4.1. Life cycle inventory (LCI)

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

The emissions in the leachate were considered to be directly emitted to the aquatic environment and were determined through the NO_2^- and NO_3^-leachate content. The LCI is available in the Appendix 9.3-C - **Chapter 5**. An impact allocation procedure based on rainwater volume consumed was applied to estimate the impacts of the rainwater harvesting system and fertilizers, due to the different water uses of this system element.

2.4.2. Life cycle impact analysis

Simapro 9 software was used to determine the impact assessment using the Ecoinvent v3.5 database (Wernet et al., 2016) for background data on processes. The life cycle impact assessment (LCIA) was developed using the Recipe 2016 method (Hierarchist) at the midpoint level (Huijbregts et al., 2017), considering a cut-off criterion to estimate the environmental impacts (it was assumed that the secondary product receives the impacts and benefits of the recycling process). The functional unit for the LCA is 1 kg of edible tomatoes. The impact categories considered in this study are described in Table 2.8.

Table 2.8 Life cycle assessment impact categories used in the dissertation.

Name	Acronym	Units	Description
Global Warming Potential	GWP	kg CO_2 equivalent	Amount of additional radiative forcing integrated over time caused by an emission of 1 kg of GHG relative to the additional radiative forcing integrated over that same time horizon caused by the release of 1 kg of CO_2
Terrestrial Acidification	TA	kg SO_2 equivalent	Terrestrial ecosystem damage due to acidifying emissions.
Freshwater Eutrophication	FE	kg P equivalent	Phosphorus emissions to fresh water.
Marine Eutrophication	ME	kg N equivalent	Nitrogen emissions to the marine water.
Fossil Resource Scarcity	FRS	kg oil equivalent	Ratio between the energy content of fossil resource x and the energy content of crude oil.
Ecotoxicity	ET	kg 14-DB equivalent	Factor of human toxicity and ecotoxicity accounts for the environmental persistence (fate), accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. Addition of marine terrestrial and freshwater ecotoxicities.
Cumulative Energy Demand	CED	MJ	Is the energy use throughout the life cycle of a good or a service

2.5. Statistical modelling of water demand

The modelling was carried out through a statistical process which contemplated the development of different models. Using Generalize additive (GAM) and generalize linear (GLM) models, statistical models were built for the prediction of water demand by means of climatic variables measured within the i-RTG. These methodologies were selected because they considered the interaction of the different climatic variables at the time of modelling. This process is conducted without initially considering the limitations of the classical linear models.

2.5.1. Data collection

The data was collected using Campbell's PC200 and PC400 software (Campbell Scientific®). A program was developed which took information every minute and stored the average of the data recorded every 10 minutes. All this information was stored in the servers of the SOSTENIPRA group.

2.5.2. Climatic variables and Sensors required

Different climate sensors were used for the data acquisition dissertation, which are listed and described in Table 2.9.

Table 2.9 Climatic Campbell sensors used in the present dissertation

Variable	Sensor Model	Amount [Nº]
Net Radiation (2 pyranometers + 2 pignogeometers)	NR01	1
Photosynthetic Active Radiation	SKP215	2
Radiation (incident)	LP02 (TR)	6
Substrate moisture	CS655	8
Surface Temperature	110PV	4
Temperature	107	31
Temperature and Relative Humidity	CS215	8
Wind speed & direction	03002-5	3

Figure 2.6 presents a summary of the sensors. For more details to the location sensors see (Appendix 9.1-A). Water demand was determined through daily water balances (Equation 2.1) explained in detail in **Chapter 5**. Different statistical models of higher and lower complexity were built and water demand was compared with climatic conditions measured inside the i-RTG. Each model was evaluated through statistical indicators, such as Pearson's correlation coefficient (r), Akaike Index Criterion (AIC), and Bayesian Index Criterion (BIC). With the above information, the model with the best performance and the least amount of climatic variables was selected for the prediction of water demand within the i-RTG.

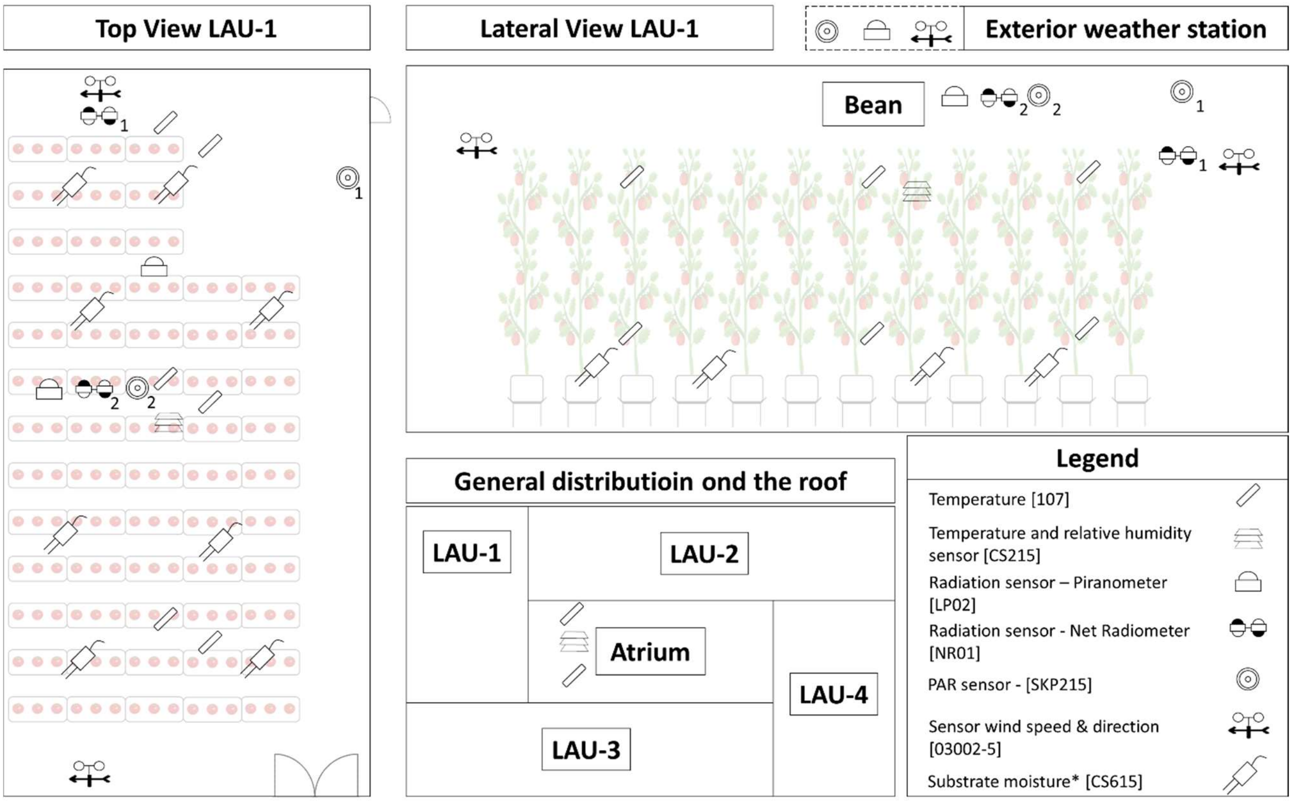
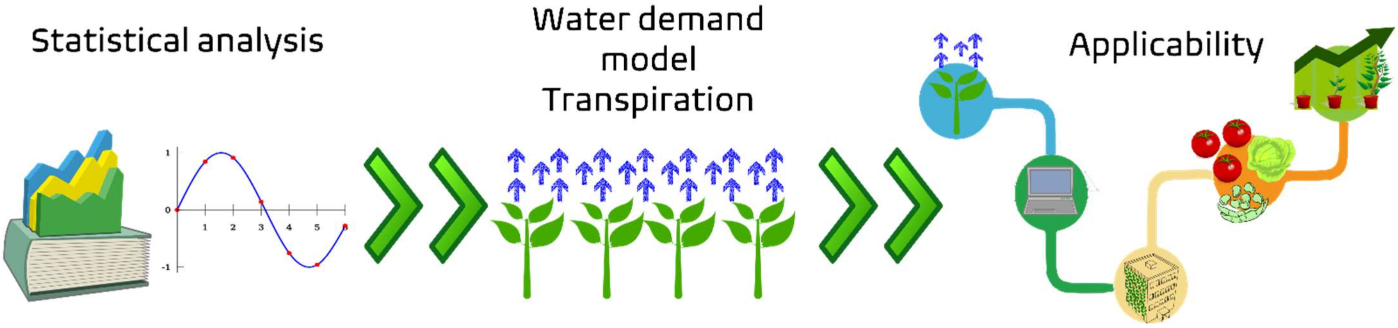


Figure 2.6 General distribution of the sensors into i-RTG on the 4th floor.

Part III

Results



Chapter 3.

Modelling water demand in a rooftop greenhouse for tomato cultivation

3. Chapter 3: Modelling water demand for tomato cultivation in a rooftop greenhouse

This work had the follow collaborators:

Parada F., Arcas-Pilz V., Rufí-Salís M., Muñoz P., Villalba G., Muñoz J., Gabarrell X.

3.1.Abstract

Currently, water availability for food production is decreasing due to various factors such as rising temperatures and droughts. These are the main drivers of water scarcity in the Mediterranean and other areas. Urban agriculture (UA), using rooftop greenhouses (RTG), is a productive solution because it engages underutilized spaces within cities. To improve water management for UA, a statistical model was developed to predict demand based on conditions needed for urban food production. This study explored the relationship of evapotranspiration in an RTG with its internal climatic variables. Barcelona was selected as the study location, and tomato was selected as the crop. The crop evapotranspiration (ETc) was determined by water balances, and the potential evapotranspiration was adjusted by the crop coefficient Kc. The 2018 and 2019 cropping cycles were used to generate the model base, and 2020 was used for validation. Flexible generalizations of linear models, such as generalized linear models (GLM) and generalized additive models (GAM), were used to develop the proposed model. The most significant climatic variables were determined through a process of back draw selection; of these, radiation and internal greenhouse temperature were the most important. The results were compared with those of other models, which are listed in the bibliography. The proposed model (i-RTG) presented a Pearson correlation coefficient (r) of 73%, similar to the McCloud model; these models had RSME values of 2.97 and 2.38, respectively. The Abtew model, on the other hand, had an RMSE of 0.71, followed by the Jensen model. The i-RTG model can be applied to other conditions, but like any statistical model, a prior calibration must be performed to verify that the results are within acceptable ranges of variability.

Keywords: Urban evapotranspiration model, Penman-Monteith, Water management, water optimization.

3.2. Introduction

The steady growth of the human population and the increasing density of urban areas (expected to reach 70% by 2050) (United Nations, 2019a) will result in higher demands for basic resources in cities, such as food, energy, and water. Freshwater availability is a growing global concern; the depleting water supply is further exacerbated due to climate change (IPCC, 2021). Rising temperatures and reduced rainfall are expected to cause droughts entailing extended periods of severe fresh water scarcity in Mediterranean ecosystems and similar areas (Cramer et al., 2018). Urbanization leads to an increase in the use of urban resources, which strains the environment. This notion is exemplified by the current food production chain, for which most production falls outside urban areas, thus increasing transportation-related costs. UA is a possible solution for promoting self-sufficiency in cities due to certain advantages, such as employing underutilized spaces for food production and reducing consumption chains and transportation. UA has developed different typologies, and rooftop greenhouses have much potential for agricultural production. While resources such as sunlight and rainfall are directly available for crop production on rooftops, the installation of greenhouses can offer further advantages such as protecting crops from unfavourable climate conditions, supporting crop production, and offering better temperature control (Eigenbrod and Gruda, 2015).

These productive improvements at the greenhouse level also translate into enhancements in water and nutrient use efficiency. Traditionally, irrigation management uses schedules/fixed-time to determine the amount of water to apply without considering on-site variables (Pratt et al., 2019; Zotarelli et al., 2009). This type of configuration can lead to a series of problems, such as low-efficiency levels of water and nutrients, that contribute to environmental pollution. Maximizing the efficiency of this resource is essential for the development of sustainable agriculture in the context of water scarcity (Gruda et al., 2019; Montero et al., 2009; Parada et al., 2021b). Previous research has focused on reducing the impacts of food production as a way to improve agricultural production system sustainability; these studies include substrate resilience to drou

ght, strategies for water recycling, and accurate models for water demand determination (Alayu and Leta, 2021; Mason et al., 2019; Parada et al., 2021a). Among these, the case-specific model chosen for predicting the daily water demand of an entire crop can directly affect site-specific management strategies.

Various physical and empirical models have been developed to model potential evapotranspiration. Physical models describe the relationship of physically measured variables and explain and predict the quantity of the water demand (Fazlil Ilahi, 2009). These models are based on energy balances, and combinations of different methods are used to estimate and determine climatic variables. One of the most studied models is the Penman–Monteith model (Allen et al., 2006), which has been widely used to determine reference evapotranspiration (ET0) and to validate other models (Jo and Shin, 2021; Qiu et al., 2013a).

On the other hand, empirical models consider few parameters to explain ET0 and are associated with specific weather conditions; they also consider fewer variables to estimate the water demand. Typically, a constant value absorbs the local influence of the parameter not considered. Two of the most commonly used empirical models are Hargreaves-Samani and Priestley-Taylor (Mahmoodi-Eshkaftaki and Rafiee, 2021). The most common parameters are radiation, temperature, relative humidity, and wind speed (Gong et al., 2020).

Moreover, characterizing the city's production conditions, which can vary considerably from traditional ones, is essential to better predict its water flows. Complex models demand data for variables that are not always available to nonspecialized greenhouse managers. In this regard, research has focused on the use of simplified equations (Katsoulas and Stanghellini, 2019) to contribute to water resource efficiency. These equations can provide better water management and contribute to better estimations of water demand at both small and large scales.

In UA, since complex models are also employed to characterize the effects of plant evapotranspiration on building-integrated agriculture (Ledesma et al., 2020), simplified models specifically developed for urban environments can facilitate their implementation and deliver better energy estimations. In turn, they can aid in improving energy and resource-use efficiency in urban crops to better estimate energy resource circularity in integrated greenhouses, including in this case study (Muñoz-Liesa et al., 2020).

In this work, we propose a simplified model to predict water demand for urban agricultural hydroponic systems in rooftop greenhouses that requires the internal temperature to predict the water demand. The methods to create the model have been developed with the data generated by two cropping cycles of tomato plants. Experiments were conducted at the Institute of Environmental Science and Technology on campus of the Autonomous University of Barcelona (ICTA-UAB). The integrated rooftop greenhouse (i-RTG) was located approximately 40 metres above sea level. Greenhouses are equipped with passive ventilation, which maintains thermal stability and reduces building energy consumption. We show how this method predicts crop evapotranspiration better than the existing conventional models and is thus a tool to significantly reduce the amount of water needed for urban agricultural hydroponic systems.

3.3.Materials and Methods

This section describes the methodologies used, together with all the elements required for the development of measurements. The study site and cultivation methods are detailed. In addition, the determination of water balances and the modelling and validation of the water demand model were developed.

3.4. Study Site, Crop/System Description, and Experimental Design

This study was performed in a hydroponic system located inside an integrated rooftop greenhouse (i-RTG) on the ICTA-ICP building on the campus of the

Universitat Autònoma de Barcelona (Catalonia, Spain). The building has a passive climate control system; through a monitoring system of climatic variables inside the building and internal programming, the passive climate control system is able to determine whether to open or close the double façade windows (Nadal et al., 2017).

Two systems were used for this work. The first, starting in 2018, was a linear or open system where the leachate generated by excess irrigation water was dumped into the sewer. From 2019 onwards, a leachate recirculation system was implemented, which allowed the recovery of excess irrigation applied. The composition and quality of the leachate collected were monitored to avoid interference with transpiration due to excess salinity. In 2018, an open irrigation system was used, where the leachate was discharged into the sewage system. From 2019 onwards, the leachate was recirculated. Flowmeters were used to measure the amount of water used for irrigation (freshwater and recirculated irrigation) during all crop seasons. In 2018, 3 15-litres containers were used to estimate the leaching of the field; 3 plants per container were measured (9 in total out of 171 plants). For more details, see Appendix 9.1-A, which shows the description of the cycle and the material used.

For all the cropping cycles, irrigation water was obtained from a rainwater harvesting system with a tank of 100 m^3 (900 m^2 of harvesting surface). Tomato crops were planted (*Solanum Lycopersicum* L., cultivar Arawak) with a density of 2.7 plant m^{-2} (frame of 0.33 x 1.1 m). The growing media used were 40-litres bags of perlite , with 3 plants per bag. The tomato plants were trained by a vertical system to ~3 m in height. Figure 3.1 shows the plant distribution and trained system, and Figure 3.2 shows and scheme of each system.

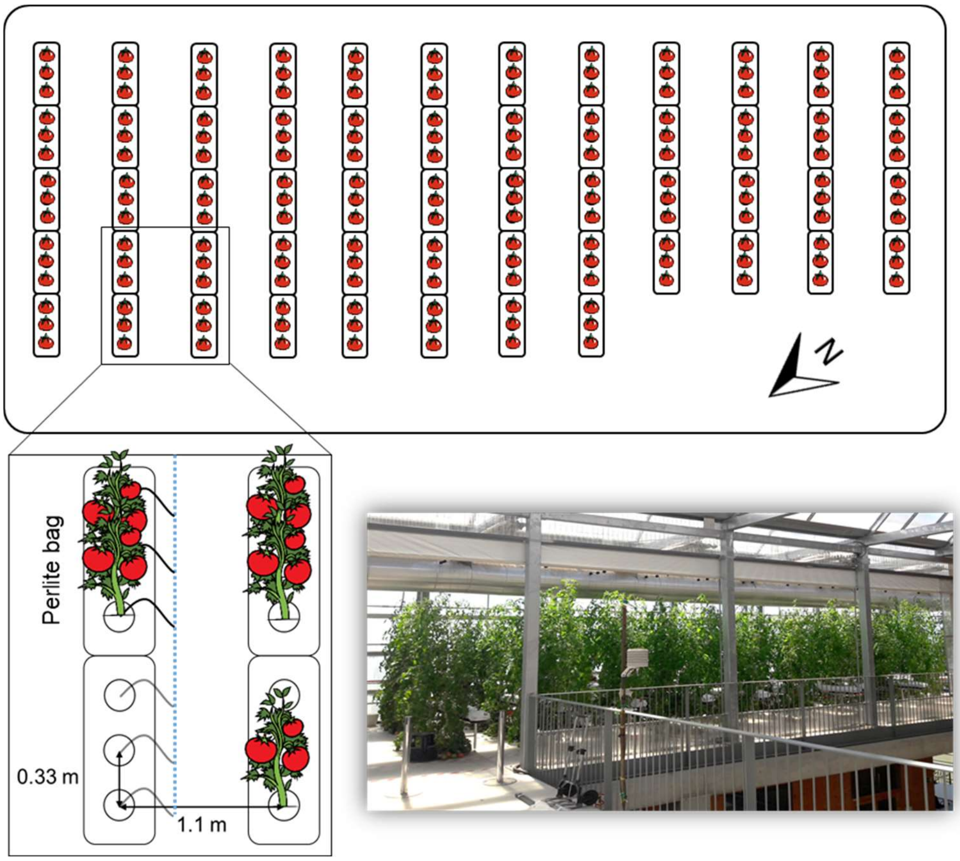


Figure 3.1. Plant distribution on the Laboratory of Urban Agriculture (LAU-1). Tomato plants were planted at a density of three plants per substrate bag of perlite.

The drip irrigation system used was 2 L h^{-1} drips, one for each plant. The nutrient solution was adjusted based on crop requirements (Appendix 9.1-B). Daily monitoring was performed to control the crop conditions, including electrical conductivity, pH, and nutrient content in the irrigation flow and leachates.

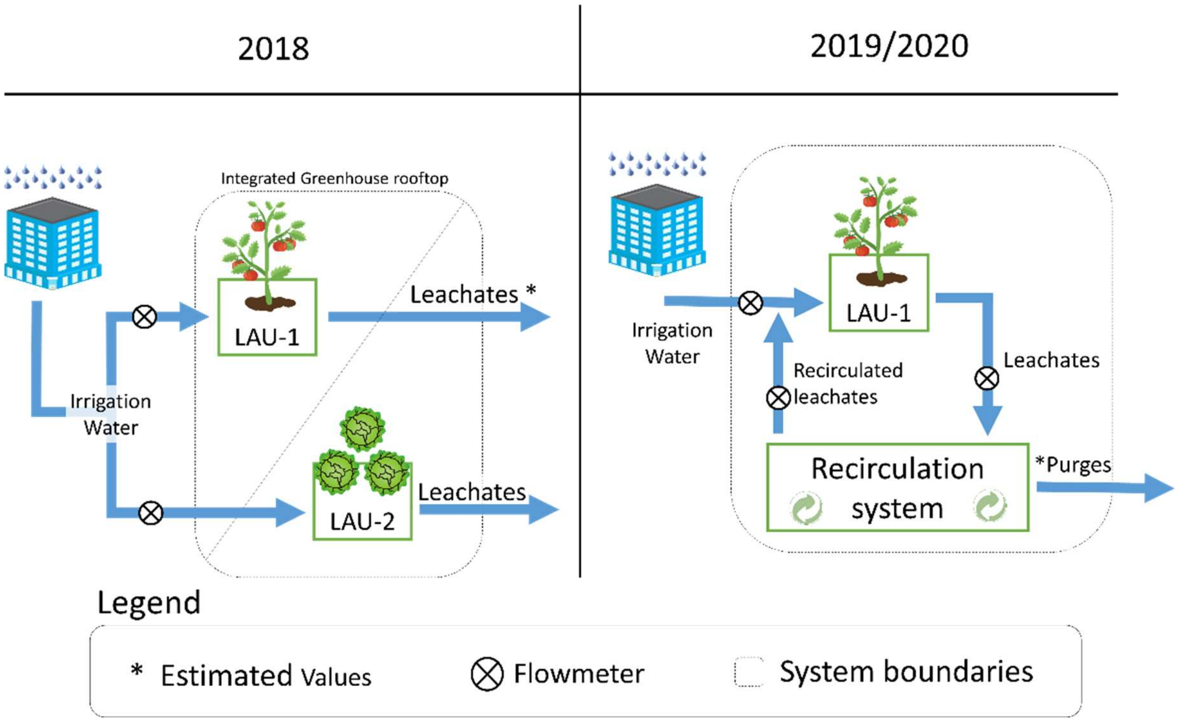


Figure 3.2. System boundaries of the water balance.

For all crop cycles, temperature, relative humidity, total radiation and PAR were measured (CS215, Pyranometer Hukseflux LP02, and Quantum PAR SKP215, respectively). Starting in 2019, a net radiation sensor (NR01) was installed, and in 2020, soil moisture sensors (CS655) were added. The resulting data were recorded through a CR3000 datalogger (Campbell Scientific). For missing data (radiation), a weather station near the laboratory (8 km to northeast) was consulted to the Meteorological Service of Catalonia (Ruralcat, 2019).

3.4.1. Water balance

The water consumed [mm·day^{-1}·m^{-2}] ([L·day^{-1}·m^{-2}] equivalent units) can be used as the evapotranspiration value of the crop (ET$_c$). In each cropping cycle, a daily water balance was performed with Equation 3.1.

$$\mathbf{ET}_c = \mathbf{I} - \mathbf{L} - \mathbf{E} - \mathbf{P} \qquad \text{(Eq. 3.1)}$$

where I is the input irrigation water [mm·day^{-1}·m^{-2}], L represents the leachates collected [mm·day^{-1}·m^{-2}], and E is the evaporation from the perlite bag, which in our case is insignificant because the evaporation zone associated with the hole where the plant is located is minimal. Finally, P is the water purged during the cropping cycles; the recirculated leachates exceeded ~4 dSm^{-1} of salinity.

For irrigation in 2018, the leachate amount was estimated by measuring the daily drainage of three leachate trays (volume of leachate collected/volume irrigation applied) and was assumed to be representative of the greenhouse at large. A value of approximately 30% of the leachate rate was selected and maintained. A recirculation system was implemented in 2019. This system permitted the input (new water and the reapplied leachate) and output water (leachates) to be calculated through flowmeters and remain at the same rate.

3.4.2. Modelling Evapotranspiration for i-RTG systems and statistical analysis

Two cropping cycles were used to develop the model (2018–2019), and one cropping cycle was used to validate it (2020). To obtain the evapotranspiration (ET$_0$) (Qiu et al., 2013), Equation 3.2 was used.

$$\mathrm{ET}_0 = \frac{\mathbf{ET}_{\boldsymbol{c}}}{\boldsymbol{K}_{\boldsymbol{c}}} \qquad \text{(Eq. 3.2)}$$

The crop coefficient (K$_c$) is an adjustment factor of ET$_0$ to a typical crop in the reference grass field (Allen et al., 2006). Each crop has its own K$_c$ (defined by its different growth stages or phenological stages). It is used to correct the ET$_0$ value to an actual transpiration condition based on the current crop stage. The K$_c$ values obtained from the previous work of Gallardo et al., (2013) were used for a long-cycle tomato crop in a Mediterranean climate, and these values were adjusted by biomass pruning. (Figure 3.2)

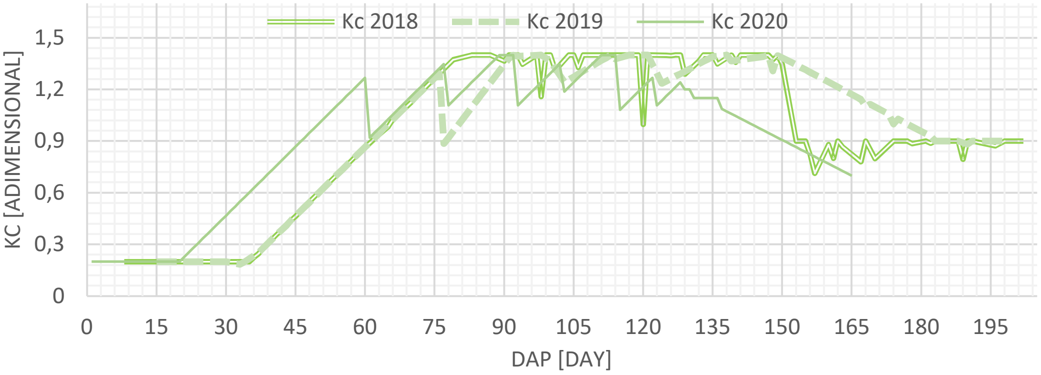


Figure 3.3. Crop coefficient used per year to adjust the ET_0.

The evapotranspiration reference – ET_0 (response variable, Eq. 2) as the amount of water transpired adjusted by the coefficient crop K_c was analysed. Climatic variables (explanatory variables) were used as bases to predict ET_0. An integration of variables, such as vapour pressure deficit (VPD, defined as the differential between the vapour pressure at saturation and the actual vapour pressure) or average value (AVG: sum of maximum and minimum value divided by 2), was also used. All the data that were out of range were removed for all the variables measured (e.g., temperature values below 0 °C inside the greenhouse, for more details Appendix 9.1-C).

For this study, a statistical approach was implemented, in which diverse models were tested: Generalized Additive Models (GAM), Generalized Linear Models (GLM) and Lineal Models (LM) (Ohana-Levi et al., 2020; Zuur et al., 2009). GLM was used to estimate evapotranspiration, with an inverted gamma family distribution as a link function, due to continued data and always nonnegative values.

A back draw selection criterion was implemented to contrast the performance of different models. The Akaike information criterion (AIC) and Bayesian information criterion (BIC) were used to support the selection. This methodology allows comparison of the different models chosen, preventing overparameterization (use of many variables to predict ET_0). The AIC and BIC criteria are widely used to evaluate model performance; we compared the quality of our models to them (the lower the value of the indicator, the better the model) (Zuur et al., 2009). An important characteristics of the BIC is that it penalizes complexity and greater numbers of variables; in other words, to maintain the indicator constant, a significant increase in explainability to compensates for the inclusion of another variable is necessary; otherwise, the inclusion of more variables will negatively impact the evaluation of model performances. In parallel, a selection of variables was made through an analysis of covariance, employing the Pearson correlation index (*r*), which has multicollinearity and is the most relevant at the physical level.

3.4.3. Model validation and model comparison

To validate the models, we compared their predicted values with the measured values of ET_0 within the i-RTG in 2020.

In addition, the selected statistical models were compared with previous models in the bibliography to determine crop evapotranspiration and to contrast and analyse whether different levels of inputs present similar performances. Table 3.1 shows the external models used to contrast ET_0.

Table 3.1 Models used and the parameters for the implementation.

Model	Acronym	Parameters	Equation	Source
Abtew^{1}	AB1	R_s	$ET_0 = 0.52 \cdot \frac{R_S}{\lambda}$	Abtew, 1996
Abtew^{2}	AB2	T and R_s	$ET_0 = \frac{1}{56} \cdot \frac{T_{max} \cdot R_S}{\lambda}$	Abtew, 1996
Ahooghalandari^{1}	AH1	T, HR and R_a	$ET_0 = 0.29 \cdot \frac{R_a}{\lambda} + 0.15 \cdot T_{max}(1 - HR_{internal\,mean}\%)$	Ahooghalandari et al., 2016
Ahooghalandari^{2}	AH2	T, HR and R_a	$ET_0 = 0.252 \cdot \frac{R_a}{\lambda} + 0.221 \cdot T_{mean}(1 - HR_{internal\,mean}\%)$	Ahooghalandari et al., 2016
Allen	ALL	T and R_a	$ET_0 = 0.003 \cdot \frac{R_a}{\lambda} \cdot (T_{AVG} + 20) \cdot (T_{max} - T_{min})^{0.4}$	Droogers and Allen, 2002
Baier	BA	T and R_a	$ET_0 = 0.157 \cdot T_{max} - 0.109 \cdot \frac{R_a}{\lambda} + 0.158 \cdot T_{AVG} - 5.39$	Baier and Robertson, 1965
Hargreaves^{1}	HG1	T and R_s	$ET_0 = 0.0135 \cdot \frac{R_s}{\lambda} \cdot (T_{mean} + 17.8)$	George H. Hargreaves, 1975
Hargreaves^{2}	HG2	T and R_a	$ET_0 = 0.0023 \cdot \frac{R_a}{\lambda} \cdot (T_{AVG} + 17.8) \cdot (T_{max} - T_{min})^{0.5}$	Allen et al., 2006
Irmak	IR	T and R_s	$ET_0 = 0.149 \cdot R_s + T_{mean} \cdot 0.079 - 0.611$	Irmak et al., 2003
Jensen	JE	T and R_s	$ET_0 = \frac{R_s}{\lambda} \cdot (T_{mean} \cdot 0.25 + 0.08)$	Jensen and Haise, 1963
Makkink	MA	R_s	$ET_0 = 0.7 \cdot \frac{R_s}{\lambda} \cdot \left(\frac{\Delta}{\Delta + \gamma}\right) - 12$	Makkink, 1957 cited by Celestin et al., 2020
McCloud	MC	T	$ET_0 = 0.01 \cdot 1.07^{T_{mean}}$	McCloud, 1955 cited by Jacobs et al., 2001, Augustin, 1983
Penman-Monteith$^{1,\,2}$	PM	Combined	$ET_0 = \frac{0.408 \cdot \mathrm{R}_n \cdot \Delta \cdot + \gamma \cdot \left(\frac{628 \cdot VPD}{T_{mean} + 273}\right)}{\Delta + 1.24 \cdot \gamma}$	Allen et al., 2006 fixed by Qiu et al., 2013b
Romanenko^{1}	RO1	T	$ET_0 = 4.5 \cdot \left(1 + \frac{T_{mean}}{25}\right)^2 \left(1 - \frac{e_a}{e_s}\right)$	Romanenko, 1961 cited by Oudin et al., 2005
Romanenko^{2}	RO2	T and HR	$ET_0 = 0.0018 \cdot (T_{mean} + 25)^2 \cdot (100 - RH)$	Romanenko, 1961 cited by Djaman et al., 2015
Talaee	TAL	T and R_a	$ET_0 = 0.0031 \cdot \frac{R_a}{\lambda} \cdot (T_{AVG} + 17.8) \cdot (T_{max} - T_{min})^{0.5}$	Tabari and Talaee, 2011
Trajkovic	TR	T and R_a	$ET_0 = 0.0023 \cdot \frac{R_a}{\lambda} \cdot (T_{AVG} + 17.8) \cdot (T_{max} - T_{min})^{0.424}$	Trajkovic, 2007

ET0 is in mm day−1, Rn: net radiation [MJ m-2 day−1], Ra: extraterrestrial radiation [MJ m-2 day−1], Rs: incident solar radiation [MJ m-2day−1]. γ: psychrometric constant [kPa °C−1], es and ea: saturation vapour pressure and actual vapour pressure [kPa], respectively, Δ: slope of the saturation vapour pressure [kPa°C−1], Tmean is the mean daily air temperature [°C], Tmin minimum daily temperature [°C], Tmax: maximum daily temperature [°C], RH is the mean daily relative humidity [%]. Penman–Monteith1: Internal radiation. Penman–Monteith2: External radiation.

3.5.Results

This section presents the experimental, analytical, and statistical results of the relationship between water balance and climatic variables measured in the i-RTG. This model is contrasted with previous models described in the literature. First, we describe the general climatic conditions in the greenhouse and the results of the water balance and ET_0 calculations. Second, we perform an analysis of the annual water balance. Third, we select critical variables and the best-suited models based on the i-RTG information. Finally, we compare and evaluate the ET_0 prediction performance of the i-RTG model.

3.5.1. Environmental variables Measured

Temperature

Within the greenhouse, thermal stability was observed (Figure 4-B) in comparison with external conditions. Within the periods evaluated, measurements ranged between 15 and 24 degrees. From 168 Julian Day (June) onward, the mean daily temperature increased until the end of the study period. Outside, temperature values were generally lower, falling between 5 and 10 °C below. The temperature control of the building allowed for a stable temperature throughout the productive cropping cycle, which can highly affect the difference between the actual water demand and that which can be predicted through empirical models. The outside temperature progressively increased, starting from Julian Day 30 in all cropping cycles until the end of the cultivation period, Julian Day 100.

Relative Humidity (RH)

Indoor RH presents a range of between 50 and 70% for all years analysed. These values are lower than those outside the greenhouse. In addition, the greenhouse receives a supply of waste air from laboratories located immediately below. These are at approximately 25 °C and 45% relative humidity. On the other hand, the external RH was stable between 60 and 80% during the 3 seasons, although there were some singularities; for example, in 2018, on Julian Day 84, the values were below this range. In general, a stable trend is seen.

Vapour pressure deficit (VPD)

The interior VPD was stable within all cropping cycles, with a value of 1·kPa (in a range of 0.5 and 1.5·kPa). In the 2019 cropping cycle, a slight increase of approximately 1.2 kPa occurred.

Radiation

The interior radiation presents values between 5 and 10 MJ·day^{-1} (within the 3 season), whereas from Julian Day 100 onward, exterior and interior radiation markedly increased. A relationship between these parameters was seen, where the value inside the greenhouse is close to 41% (± 3%) of the external radiation.

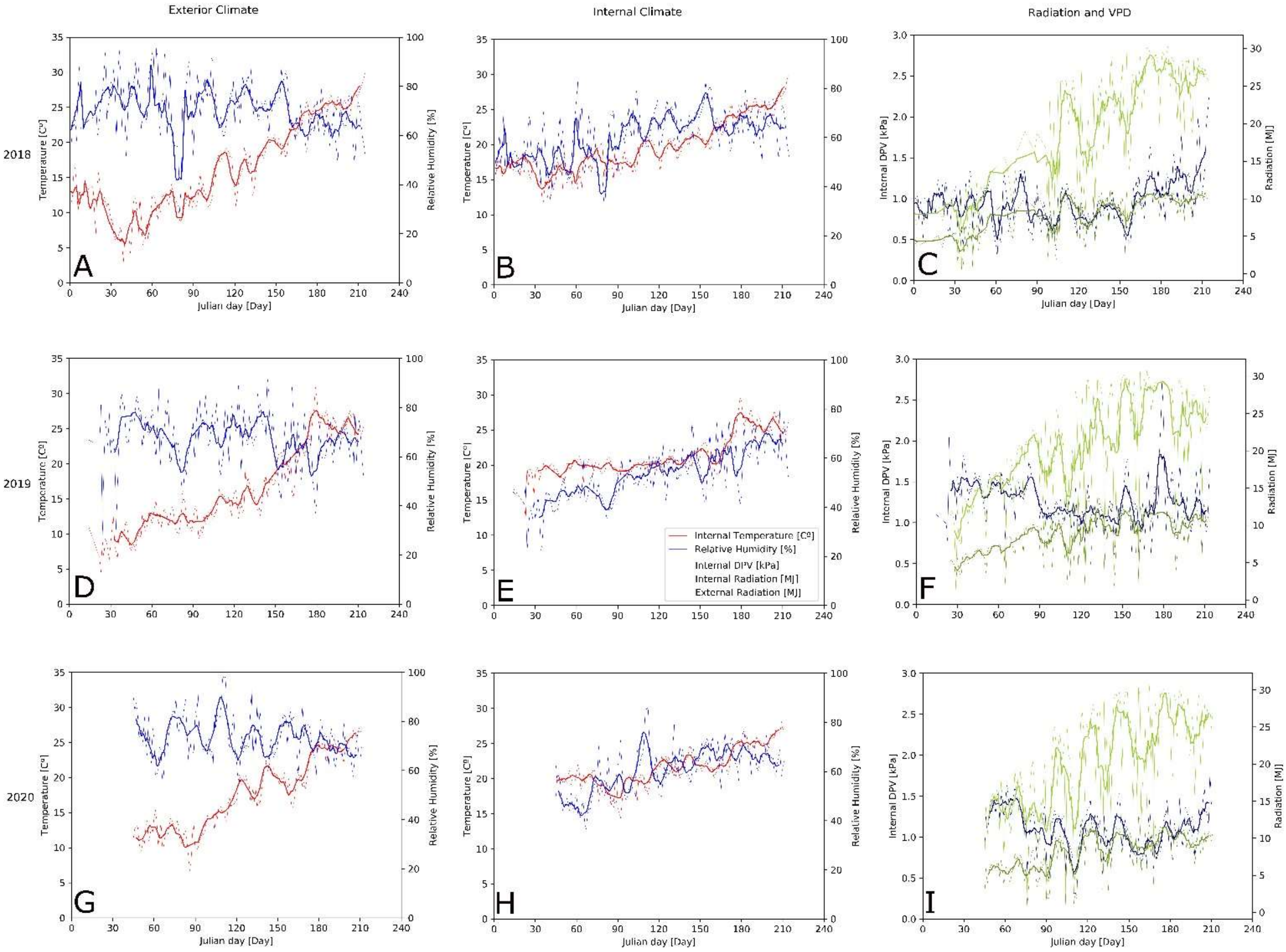


Figure 3.4. The weather conditions in the greenhouse for all of the years.
External clime in chart A, D G; Internal clime chart B, E, H; Temperature (red); Relative humidity (blue); VPD (deep blue); Internal radiation (green); External radiation (light green) chart C, F, I. The VPD was calculated following the methodology proposed by FAO (Allen et al., 2006).

3.5.2. Crop evapotranspiration and water balance

Figure 3.5 shows the result of water balance, in terms of ET_c, related to the Julian day. A similar trend is shown for 2018 and 2019. In 2020, the ET_c showed a decrease associated with the decrease in the wind speed inside the greenhouse. The decrease in transpiration is shown by the drop in the slope in Figure 3.5 in 2020 (0.0138), with values of 0.0358 and 0.0313 for 2018 and 2019, respectively.

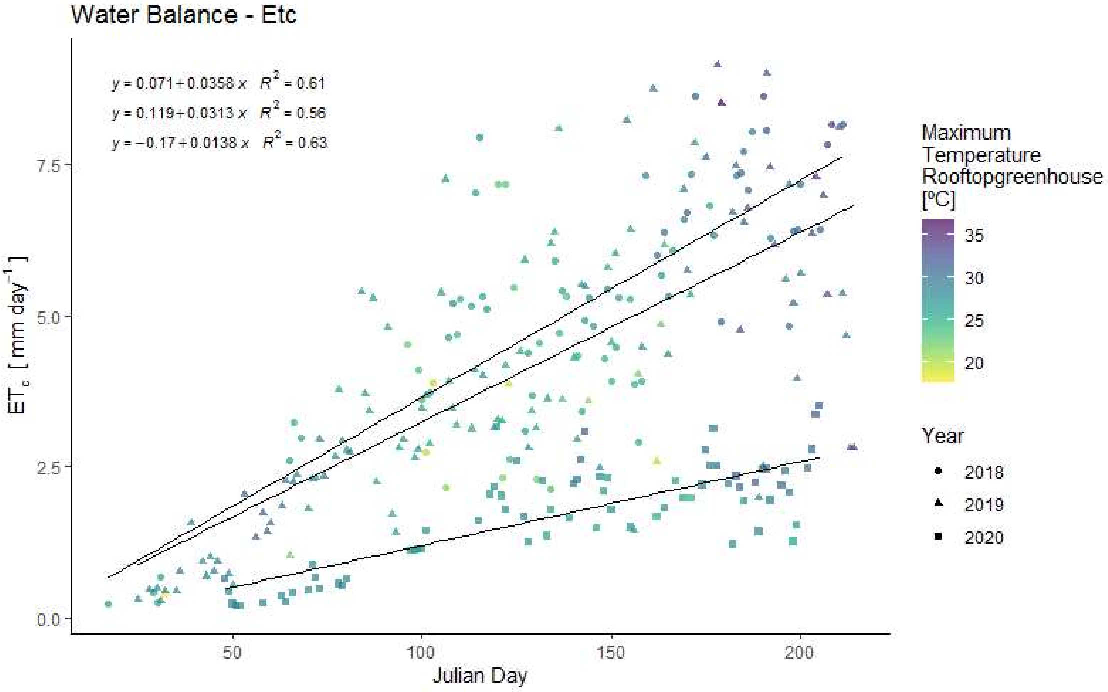


Figure 3.5. Water balance per year for crop evapotranspiration.

3.6. Model development

3.6.1. Variable selection – i-RTG Model

Through a back draw selection method, models of evapotranspiration were used to determine the water demand inside the greenhouse. The models developed are based on the selected variables presented in Table 3.2 (For all models - Appendix 9.1-D).

Table 3.2. Summary of the best i-RTG model and variables required.

Internal				External				Nº variables	Acronym	Type of model	AIC	BIC	RMSE	r
Tº	RH		Radiation	Tº		RH	R							
Mean	Max	Min		Mean	Min	AVG								
x	x	x	x	x	x	x	x	8	G_8	GAM	660	711	0.28	0.69
				x			x	2	$G_2T_eR_e$	GAM	676	720	0.3	0.65
x			x					2	$G_2T_iR_i$	GAM	691	718	0.32	0.6
x							x	2	$G_2T_iR_e$	GAM	688	727	0.31	0.61
x								1	G_1T_i	GAM	693	717	0.32	0.58
x								1	i-RTG model	GLM	720	730	0.35	0.5
x								1	L_1	LM	763	773	1.52	0.47

T° represents the temperature [°C], RH represents the relative humidity [%], and radiation represents the daily radiation [MJ day^{-1}]. Mean is the daily mean, Max and Min represent the maximum and minimum values, respectively, and AVG is the average value from Max and Min. AIC is the Akaike information criterion, and BIC is the Bayesian information criterion. The RMSE is the root mean squared error, and finally, *r* is the coefficient of correlation of Pearson (measure of linear dependence between two quantitative variables). Its value is independent of the scale of measurement of the variables. The range of this index is -1 to 1).

The i-RTG model for 2020 used mean daily temperature only (generalized lineal model, AIC: 720, BIC: 730, RMSE: 0.35, *r*: 0.5). The mean daily temperature model had a lower performance than other models, such as the ones used for radiation and temperature exterior ($G_2T_eR_e$) or temperature and relative humidity internal (not shown in Table 3.2). The measurement of the mean temperature is a widely used parameter; therefore, its implementation is straightforward. In addition, several authors recommended keeping the modelling simple; thus, it was the preferred choice.

In parallel, two more i-RTG models were also considered, one with the minimum number of variables for the maximum *r* (8 climatic variables – G_8 Table 3.2). A second model considered only the mean temperature and external radiation of the building ($G_2T_iR_e$) because these variables were easily accessible; for these cases collinearity not considered.

For the implementation of the model, only the mean greenhouse temperature was needed to obtain the predicted value (μ determined by the gamma link function). The default link for a gamma GLM is the inverse link, which is determined by the following equation (Equation 3.3).

$$\mu_i=\beta_1+x_i\beta_2 \qquad \text{(Eq. 3.3)}$$

The results from the fitted i-RTG model are that β_1= 0.733367 and β_2= -0.022568.

3.6.2. Evaluation of ET_0 models

The results of the calculated potential evapotranspiration (ET_0) were contrasted with 15 models described in the literature. The best five modes were selected (PM, AB2, JE, BA, MC) to contrast with the three models proposed (G_8, $G_2T_iR_e$, and i-RTG Model), with the best *r* presented in Figure 3.6 and Table 3.3.

Table 3.3 Coefficients of RMSE, Pearson coefficient (r), and MAE.

Model	Name	Variable	RMSE	*r*	MAE
Penman-Monteith^2	PM	Combined	7.14	0.56	6.64
Abtew^2	AB_2	T and R_s	0.71	0.58	0.57
i-RTG ET0 Model [8 Variables]	G_8	Combined	5.79	0.59	5.04
Jensen	JE	T and R_s	1.05	0.59	0.91
Baier	BA	T and R_a	2.59	0.69	2.51
i-RTG ET0 Model [2 Variables]	G_2	T and R_s	3.20	0.70	2.98
McCloud	MC	T	2.38	0.73	2.25
i-RTG Model	**i-RTG Model**	**T**	**2.97**	**0.73**	**2.87**

***In bold the model proposed**

The i-RTG model and McCloud's model presented *r* 73%, followed by the proposed 2-variable model (mean temperature and external radiation) and the Baier model. The models with the highest *r* (69 and 73%) were those with the highest RMSE (2.38-3.20) (Baier, i-RTG Model [1 and two variables], McCloud). In contrast, models with a medium r presented a low RMSE value, which was similar to the Jensen or Abtew^2 models. The RMSE minimum values obtained by the Abtew model and Jensen model were 0.71 and 1.05 mm day$^{-1,}$ respectively, which were similar to the value obtained by Gong et al., (2019) (0.44–0.63 mm·day^{-1}).

Figure 3.6 shows the relationship between ET_0 modelled and ET_0 measured. For the Penman–Monteith model (FAO56), the proposed i-RTG model presents an r of 64%, and $G_2T_iR_e$ presents 81%.

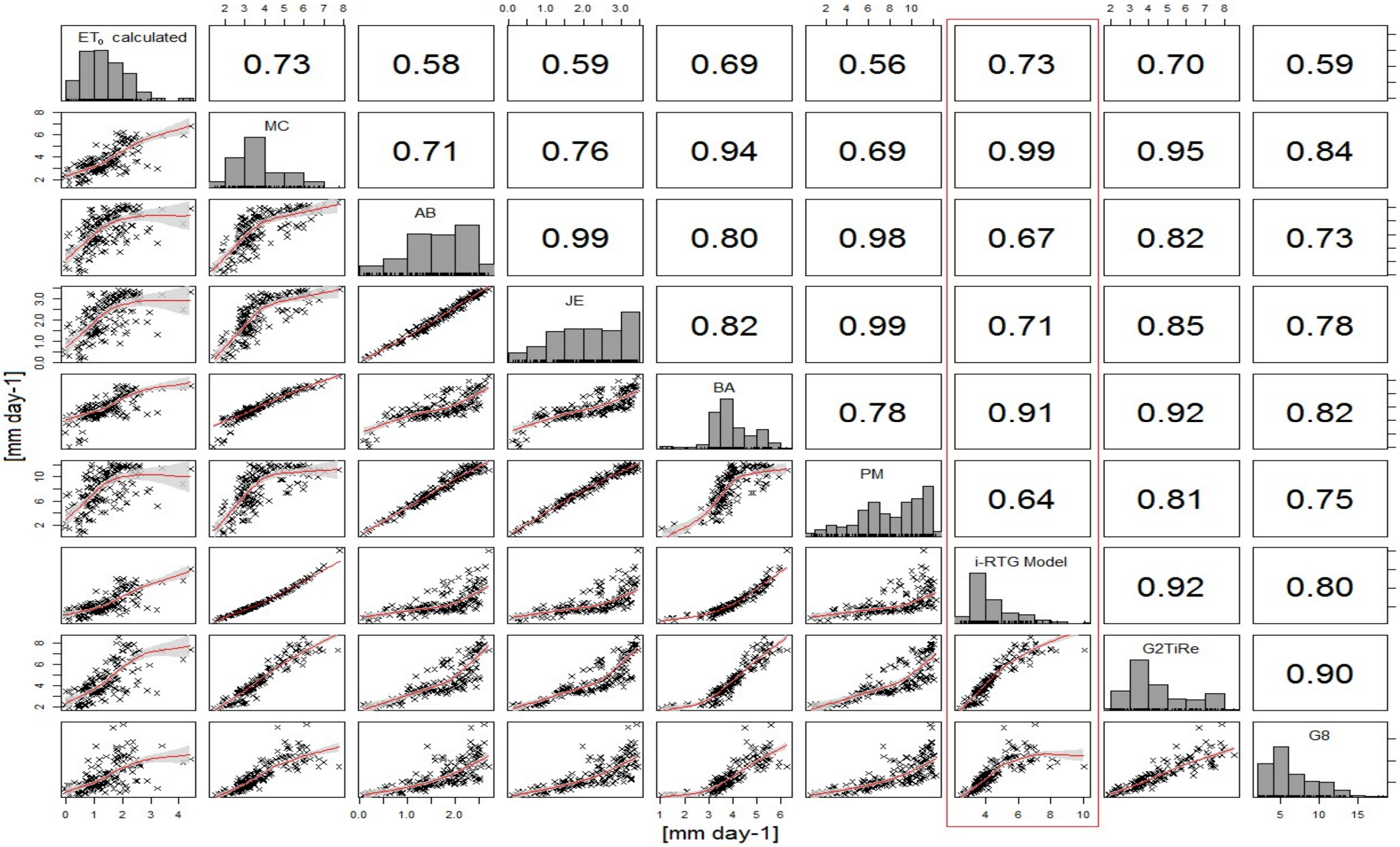


Figure 3.6 Correlation ET₀ calculated vs ET₀ modelled.
Values represent the Pearson coefficient (r). The i-RTG model proposed is highlighted in red.

Figure 3.7 shows the relation between the i-RTG model and the other models evaluated in this work. The Penman–Monteith model presents a greater variation from the 5 mm estimation. Data ranging from 0 to 5 mm represent approximately 75% of the contrasted information. At temperatures above 25 °C, the variability of the response increased, which is associated with the last month of cultivation, with August being the warmest period of the experiment.

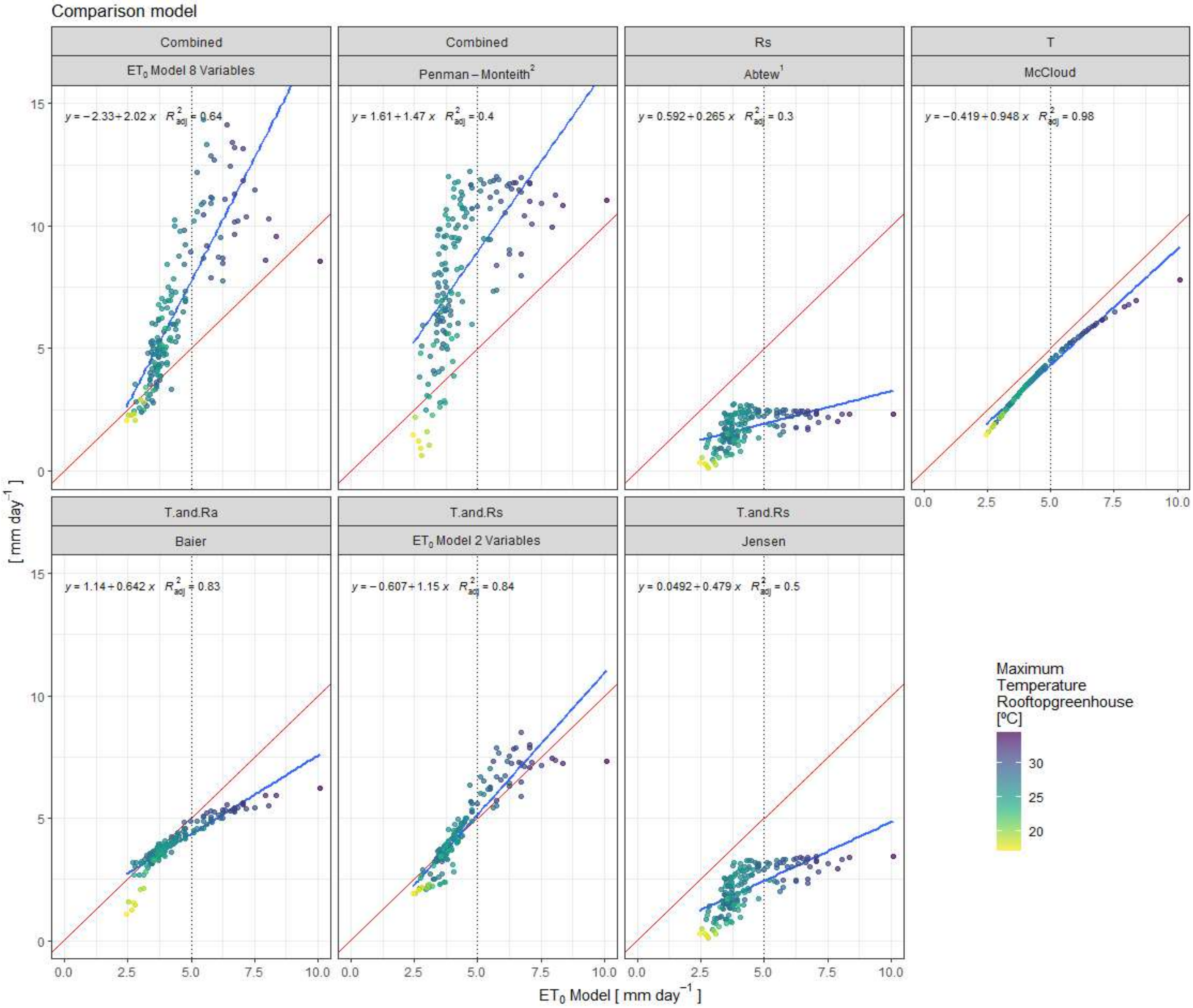


Figure 3.7 Comparison of proposed models vs. previously published models.
The dotted line is located at 5 mm.

3.7. Discussion

In this section, the internal relationships between climate variables will be discussed, as these measurements most determine evapotranspiration. Reducing the number of measured variables allows for consideration of those that are both the most important and the easiest to measure. Hence, the highest representation can be obtained with the lowest input of information. Second, the model performance is discussed, contrasting its accuracy with previous models referenced in the literature. The variables that most influence each model (both its own and those previously published) are determined. It is important to highlight the way these models can most apply to rooftop greenhouse conditions. Finally, the applicability of the model for estimating the water consumption of different stakeholders and at different scales is discussed.

3.7.1. Climate interaction and predictability

Intensive greenhouse production relies on different protective strategies to provide a better growing environment for crops. In this sense, the i-RTG presents a stable environment, which makes it a suitable site for modelling water demand. Our results show that below a daily maximum of 27 °C, the model performs well; the greenhouse falls within this parameter approximately 75% of the time the greenhouse is in this condition.

Temperature, a covariable of radiation, was selected as the main variable for the proposed i-RTG model. This allows for an accurate way of modelling the water demand (transpiration) inside the greenhouse. In addition, the passive climate control of the building helps stabilize the internal variables (temperature, relative humidity, and radiation). A control system that opens or closes windows depending on the internal climatic conditions employs a pre-programmed control system. This allows the system to maintain a stable temperature condition in intermediate situations (<25 °C on average). The i-RTG has a stable internal clime condition (Figure 3.4); therefore, creating a reliable model is possible.

A particular characteristic of the i-RTG, which can be found in different typologies of UA (Sanyé-Mengual, 2015a), is the height of the greenhouse; in our case, the LAU is located 27 metres above the ground. This condition affects the ventilation level of the greenhouse due to the positive relationship between height and wind speed (Muñoz-Liesa et al., 2019). During the warmer seasons, the windows remain open 24 hours a day, while in winter, they are permanently closed to hold in the heat generated by the building beneath the greenhouse. These conditions are windy and warm, leading to an expected increase in water demand. Based on these parameters (temperature and humidity), Allen et al., (2006) determined in the field that the crop coefficient can vary between -0.1 and 0.05 (considering wind speed from 0 to 4 ms^{-1}), solely by changing the wind and relative humidity conditions. Within a conventional greenhouse, wind speed is normally assumed to be close to 0 or values close to <0,1 m s^{-1} (Wang et al., 1999), and relative humidity conditions are expected to be high (Piscia et al., 2015). In contrast, the i-RTG has a high turnover rate due to the aforementioned wind and altitude conditions (Parada et al., 2021). Fuchs et al., (1997) conducted studies in multi-span greenhouse and reported that increments of 0.5 ms^{-1} (ranging from 1.9 to 2.6 ms^{-1}) could double the air turnover rates inside the greenhouse.

As shown in Figure 3.8, in 2019, there was a higher wind speed inside the greenhouse, which translated into a higher water demand. On the other hand, in 2020, the average wind speed in the greenhouse was lower, so this phenomenon would partially explain the lower water demand for that year. Möller and Assouline, (2007) presented a study on greenhouses in which they used a shading screen to reduce wind speed and radiation (40% less radiation and 50% less wind, compared to the outdoor condition), which translated into 38% less ET_c, where radiation was the main driver, followed by wind speed. Wind speed was not included in the parameters evaluated within the models, as the information was not available for 2018. Future approximations should consider this parameter since, based on our results, it shows an important influence on ET_c.

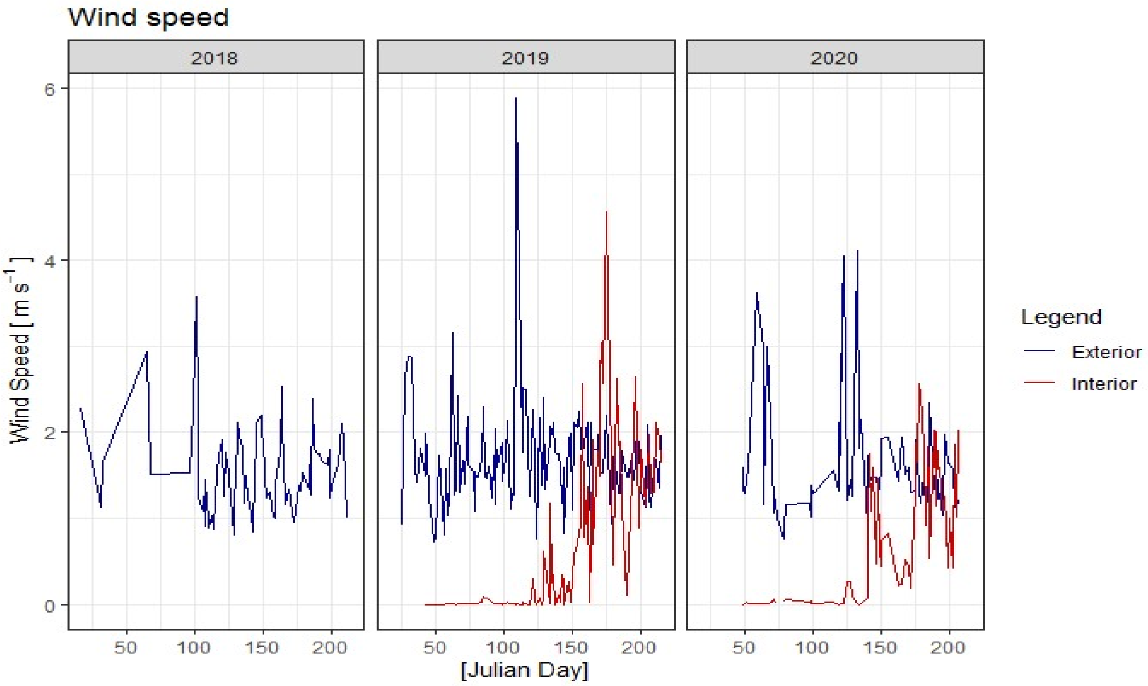


Figure 3.8 Internal and external wind speed per year.

In this work, a back draw selection process was implemented, where statistically less significant variables were discarded. The $G_2T_iR_e$ model considered internal temperature together with external radiation. This latter parameter was widely accessible and the main driver of evapotranspiration (Gong et al., 2019). The inclusion of this variable increased the r^2 by 11%, causing it to be relevant. Therefore, this variable would be an alternative for the proposed model. In addition, internal relative humidity was analysed together with temperature and internal radiation. The results of this model showed that relative humidity was not statistically significant. The r^2 increases by 1%, so the inclusion of this variable does not significantly improve the predictability of the model. Although this parameter is used for water modelling, in our case, it was such a stable parameter over time that it was not statistically significant enough to be included in the final model.

3.7.2. Model performance

The i-RTG model shows a good correlation up to the 5 mm range with PM, one of the most broadly used models, in contrast with other models validated in different studies.

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Figure 3.6 shows the correlation to ET_0 calculated in 2020 and the models tested (by a bibliography and proposed). With an increase in the confidence interval from the values 3 and 4 mm, the theoretical models present a lower sensitivity in this range. Regarding the PM model (FAO-56), the proposed i-RTG model presents an *r* of 64%, and the $G_2T_iR_e$ model (daily mean internal temperature and external radiation) presents an *r* of 81%. In contrast, in the 8-variable Model (G_8), *r* decreases because the weight of constants assigned by the statistical model is not necessarily similar to those assigned by the Penman model. The inclusion of more variables does not necessarily improve the prediction of ET_0. Thus, when including the external radiation variable, we have a better performance than when including 8 variables. Previous experiences have shown that for specific sites, it is possible to reduce the number of variables without having an important loss in prediction quality. An example of this is the Hargrave and Samani model recommended by FAO (Allen et al., 2006), where only temperature variables were used to estimate evapotranspiration with results similar to the Penman–Monteith equation. On the other hand, for some situations, calibrating simple models is desirable to better adjust for the evaluated climatic conditions.

Models such as those proposed by Ahooghalandari et al., (2016) are built in a tropical arid condition (very low relative humidity condition), which would explain the inclusion of relative humidity. J. Shuttleworth and S. Wallace, (2009) researched different sites in Australia, where they also considered relative humidity as a relevant parameter in estimating evapotranspiration. Models such as FAO (Allen et al., 2006) consider relative humidity indirectly through the vapour pressure deficit (VPD), which is defined as the difference between saturation vapour pressure and actual vapour pressure. Therefore, this parameter should not be discarded in future research.

Other research has shown that PM has the best performance for modelling potential evapotranspiration in both greenhouses and open air (Fernández et al., 2010; Villarreal-Guerrero et al., 2012). In this study, the PM model, although it showed an acceptable performance, was not among the best. The MC and the proposed i-RTG models demonstrated better predictability for the 2020 data. Other studies conducted outdoors that compared models showed similar trends, where PM was not the model with the best fit (Liu et al., 2017). Both the AB and JE models presented acceptable values for r

(0.67 and 0.71 Figure 3.6); both models could be adjusted for one factor intrinsic to the model, or an external factor could be added to improve the accuracy of the model. This is because they both use temperature and incident radiation prediction variables. (Daily Max temperature in the case of AB and Daily Mean Temperature for JE).

3.7.3. Applicability i-RTG model

Other crop validation

To validate the proposed i-RTG model, a lettuce (*Lactuca sativa* cultivar Maravilla) assay was implemented in LAU- 2 (SE exposition) between 01/09/21 and 02/10/21, with a planting density of 10 plants·m^{-2}. The K_c used was obtained from Suárez-Rey et al., (2016). For the determination of ET_0, the same methodology was used as presented in Appendix 9.1-C Criterion to cured data modelling.

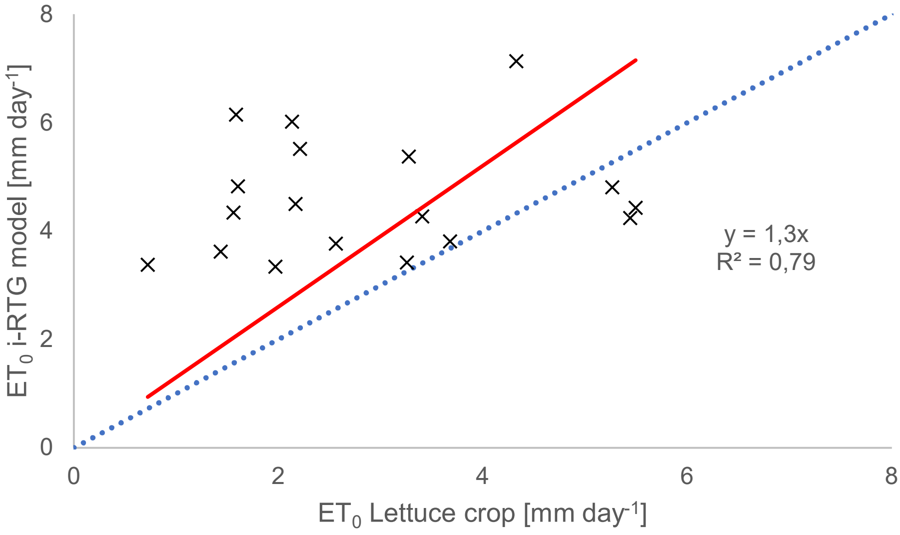

Figure 3.9 10 Relationship ET_0 lettuce crop obtained vs. ET_0 i-RTG model.
The red line represents the slope, and the blue dotted line represents the relation 1:1.

Figure 3.9 shows the water demand relationship . A correlation coefficient (*r*) of 0.79, and an overestimation of approximately 30% are shown. The results are consistent with those obtained previously under similar crop conditions (LAU-1). The proposed model overestimates ET_0 values up to 5 mm. From 5 mm onwards, little information is available, but an underestimation can be seen. In this sense, the results of this validation are in accordance with those of the 2020 tomato crop, where there is an overestimation of the water demand.

Replicability

The proposed model can be applied in other UA conditions due to the internal characteristics of the laboratory setting, its structure and distribution. The structure, a new building, had to follow the construction standards of Spain. Multiple required elements, such as beams and support structures (elements that generate greater resistance for the greenhouse), produce many shadows. This shading reduces the overall efficiency of the greenhouse, as not all the incoming radiation is used by the plants. The potential use of this model is supported by its simplicity, applicability, and replicability. First, it uses only one variable, which is the average daytime temperature, to estimate the water demand. This variable is integrative of the radiation and relative humidity conditions that occur inside the greenhouse. Second, because the model is simple and requires only one variable, it is accessible to a wide range of stakeholders, including researchers, home users, and businesses. These stakeholders can determine water needed for irrigation, potential flows, and ways to reduce of irrigation, among others. Third, the model is replicable under conditions similar to those under which it was built in terms of temperature, elevation, and wind. For other conditions, we recommend pretesting to calibrate the model to reach a better fit. At the scientific level, it is possible to use this model to estimate the amount of irrigation to be applied, but it is necessary to take into account the high RMSE value that the model currently presents, which can affect the estimates, leading to errors. In this case, it is always advisable to validate the model, either with empirical values obtained or with already validated models. In our case, when comparing PM with the i-RTG model, the i-RTG model presents a low variability up to approximately 5 mm per day at 27°C of maximum temperature. For similar conditions, acceptable predictability would be expected, but it would be necessary to adjust the model because it tends to overestimate the predicted values for PM.

Regarding overestimation, for commercial conditions that consider using the i-RTG model over large areas, the implementation of complementary technologies, such as moisture monitoring sensors, is recommended. The irrigation decisions were extended to the whole area through the information reported by the model and validated by the irrigation sensors. Finally, for domestic users, the i-RTG model represents a simple and useful tool that requires minimal information to quickly estimate how much irrigation water is needed. With basic knowledge, responding to local conditions, as opposed to seasonal ones, is possible. This allows for more effective management of water resources at a domestic user level.

3.8.Limitations and potentials

The proposed model has some limitations. First, it is necessary to validate it under different conditions or locations and integrate this information into the initial structure of the model to determine what factors should be considered for implementation. For the general additive model (GAM), potential sites locations should be added for validation. Second, as a recommendation, a verification process of the model's response should be performed before it is used directly.

3.9.Final remarks and conclusion

The objective of this study is to generate a simple tool so that those different stakeholders can, through 1 or 2 variables, determine the amount of water applied. Previously proposed potential uses include the application of this model as a reference base for determining water consumption for different UA conditions. Additionally, using the i-RTG model for water management of crops in a city greenhouse determines the irrigation times necessary for adequate irrigation. The estimation of reference amounts also contributes to the determination of restrictive management. Zotarelli (et al., 2009) presents research that considers irrigation at 80% of ET_0, which showed an increase in water use efficiency in tomato crops without compromising the final yield. In this sense, developing agriculture that seeks efficiency in the use of resources is essential for the sustainable development of agriculture.

Chapter 4.

Comparison of organic substrates in urban rooftop agriculture, towards improving crop production resilience to water stress in Mediterranean cities

4. Chapter 4: Comparison of organic substrates in urban rooftop agriculture, towards improving crop production resilience to water stress in Mediterranean cities

This work is based on the follow Journal paper:

Parada F., Ercilla-Montserrat M., Arcas-Pilz V., Lopez-Capel E., Carazo N., Montero J.I., Gabarrell X., Villalba G., Rieradevall J., Muñoz P.

Wiley Journal: Science of Food and Agriculture - https://doi.org/10.1002/jsfa.11241

4.1. Abstract

Urban agriculture contributes to meeting the growing food production demand in cities. In the context of low water availability, it is important to consider alternatives that are able to maintain production. Through a circular economy vision, this study aimed to assess the use of substrates made from local materials as an alternative for urban agriculture in periods of low water availability, due to water supply cuts. The substrates used were coir commercial organic substrate, vegetable compost from urban organic waste, perlite commercial standard substrate, and a mixture of the urban compost and perlite (1:1) were used for 3 consecutive crop cycles of lettuce (Lactuca sativa L. var. crispa). The crop cycles were performed in the spring and summer periods of 2018 to observe the performance during warmer periods of the year in an integrated rooftop greenhouse near Barcelona. Each substrate was assessed under conventionally irrigation (0-5 kPa) and water restricted conditions (irrigation stopped until the water tension reached -20 kPa perlite). In terms of yield, our results show that the compost and mixture were similar to those obtained from perlite (11.5% and 3.7% of more production in a restricted water condition). Organic substrates increased the crop's resilience to water restriction in contrast with the perlite. In particular, water lost took longer in coir (1 and 2 crop cycle); however, when dryness began, it occurred quickly. The vegetable compost and the substrate mixture presented tolerance to water restriction when water restriction reached -20 kPa.

Keywords: Circular economy, sustainable cities, soilless system, water stress resilience, water restriction, urban agriculture.

4.2. Introduction

Currently, the increase in population within cities has created a concern due to an increased demand for resources such as energy, water, and food. This situation is exacerbated by the advance of climate change, causing persistent droughts, one of the biggest problems to be addressed in agriculture due to the high water demand for food production (Cramer et al., 2018).

Urban agriculture (UA) is an alternative to satisfy the increasing demand, contributing to food production's sustainability by reducing different production chain elements, such as energy in distribution and used packaging (Sanyé et al., 2012). UA can be carried out from different scales such as home to community gardens, with different degrees of sophistication such as the use of irrigation systems, special substrates, outdoor production or through greenhouses. Even on different levels of a building, both inside and outside, in this sense buildings integrated roof greenhouses contribute to sustainable and Food Security city strategies; where both circular economy and the use of food-energy-water approaches are used (Eigenbrod and Gruda, 2015). The advantage of rooftop greenhouses is access to unutilized spaces, increasing current local food production, and reducing the environmental load associated with food production and the buildings that sustain it (Nadal et al., 2017). The evaluation of unoccupied roof spaces for greenhouse found that these are usually small and well-ventilated and have a very low relative humidity. This leads to a condition with high water consumption by plants and, therefore, a propensity for crops to suffer hydric stress (Montero et al., 2017).

Barcelona is an example of a Mediterranean city area, where droughts have been repeated cyclically for the past two decades. This situation has led to creating a management plan that aims to prioritize water uses in cities, especially during emergencies. UA is considered as a green space amenity activity rather than an agricultural activity in Spain, hampered by the legal restrictions applied to these areas. As an example, tap water irrigation of private gardens and city parks was forbidden during water shortages in 2008 (Decreto 84/2007, 2007) . This highlights the importance to develop alternatives to alleviate drought conditions of urban crop systems and maintain food production. There is a need to study strategies and technologies that allow the development of crops in water-limiting conditions, such as irrigation optimization, reuse of leachates, and soilless culture systems (SCS). SCS is frequently used to establish crops in an artificial medium to produce food under different growing conditions (Barrett et al., 2016). Within food production in the UA, the supply of water is essential for its development, water cuts can be generated by different reasons (electricity or water supply), this can negatively affect crop yield. It is necessary to generate strategies that mitigate the effect of low water availability and contribute positively to the production of food. Considering the above, it is desirable to use substrates that present characteristics such as a large amount of water retention, and it is available over time. In this sense, the use of substrates reduces the risk in a situation of water stress, in the event of a problem with electricity or water supply. It is understandable that, in the event of a very prolonged water cut, there is no guarantee that this will prevent the problem completely, and the reduction in performance will be strongly affected. The objective is to generate alternatives that mitigate the effect of low water availability, and the use of local organic substrates is one of these. A variety of organic and inorganic substrates could be suitable for crop production under restricted water availability in urban settings.

One of the most used substrates is perlite, an inorganic substrate characterized by its capacity for aeration, drainage, and optimum water retention. However, a high amount of energy is required for its production and transportation. Organic alternative substrates widely use include coir and compost (Savvas et al., 2013). These present desirable substrate characteristics, such as high water holding, cation exchange, that are comparable to perlite). Coir is an agricultural waste and, therefore, a renewable resource. However, it must be noted that coir is a material from a tropical crop produced in geographical areas far from maximum horticultural use and present the same perlite problem on transportation. Compost is an alternative to coir (Ulm et al., 2019), since it is possible to obtain it locally, avoiding transportation. Compost can be produced from different local organic waste, such as domestic waste, municipal pruning, restaurant waste, among others, which is highly available at city levels. Its use as a substrate contributes to the recovery of organic waste resources and reduction of dependency on non-renewable substrates, such as perlite. The recent increased interest in urban agricultural activities highlights the timely need to investigate low environmental impact substrates. Alternative urban organic substrates need to be easy to manage and available, financially feasible, have a low environmental impact, show high moisture retention, and have nutrients that are readily for produce high quality crops (Gruda, 2019).

Organic substrates have been widely studied for their use in the horticultural industry (Roehrdanz et al., 2019; Urrestarazu et al., 2001; Verdonck et al., 1984) but not in the UA circular economy context. There is an urge in both horticultural industry and gardening to study organic materials derived from agricultural, industrial, and municipal waste streams. The disposal of such organic (also referred to as biodegradable) waste materials is an environmental problem (European Commission, 2020), and their reuse as substrates might provide a suitable solution (Hogg et al., 2002). Compost from municipal organic waste would specifically target reduction of urban organic waste to landfill and reuse, towards a short-chain circular economy and contributing to sustainable development goal (SDG) 11 (sustainable cities and communities) and SDG 2 (sustainable food production) (UN., 2015) Considering a future scenario of low water availability, which can be addressed from the use of organic substrates, the need arises to study the behaviour of these substrates under more restrictive conditions, in such a way, to generate strategies that allow maintaining food production in situations where the use of water is restricted in urban communities.

We hypothesize in a context of water scarcity, where the water supply can be affected, it is essential to have local substrates, which avoid dramatic drops in crop yields. Within urban agriculture, the use of compost for food production is a viable alternative in terms of maintaining yield under conditions of reduced water, concerning conventional substrates such as perlite. The objectives are to determine the agronomic feasibility of using alternative substrates for perlite in an RTG in the context of UA and characterize the behaviour of a green leaf crop as an indicator of the substrates' crop production performance under conventional and restricted irrigation conditions

4.3.Materials and methods

4.3.1. Study site

The experiments were conducted in the rooftop greenhouse laboratory (i-RTG Lab), a cropping system representing other UA projects developed (Ercilla-Montserrat et al., 2018). It is located in the Environmental Science and Technology (ICTA-UAB) building on the campus of the Universitat Autònoma de Barcelona. Protected cultivation is performed under a steel and polycarbonate greenhouse structure. The climate conditions in the i-RTG Lab were passively controlled.

4.3.2. Substrate characteristics

The study focused on three substrates. These consist of perlite as control substrate, coir, green compost, and a (1:1) mixture of the green compost and perlite. Substrate physical and chemical properties as shown in Table 4.1. Analytical methods and tables of the result are provided in the Appendix 9.2-A. The green compost used was derived from municipal pruning waste, which is chipped and mixed for 3-4 weeks and irrigated 4 times per month with rainwater (3 months of composting process in open-air piles). When the composting process is finished, the material is sieved to 10 mm and packed. The green compost used present a 57.9% of organic matter, an EC of 2.77 $dS \cdot m^{-1}$, and a pH of 7.79.

Table 4.1 Substrate physical and chemical properties.

Substrate	Total Porosity	Granulometry	pH	Electric Conductivity	Organic Matter	Origin
	%	mm		dS·m^{-1}	%	
perlite	95.8	0 to 6*	7*	0.09*	1.1	Inorganic. Expanded clay, chemically inert
coir	92.2	-	6	0.45	85	Coir and coco dust
compost	87.2	0 to 10	8	2.77	60	Municipal pruning waste, composting process takes up to 3 months to finish on open-air piles
mixture	91.4	0 to 10	7	1.43	30	-

*perlite`s physical and chemical properties were provided by the commercial company provider (OTAVI, S&B ®). The total porosity of growing media was estimated based on the content of organic and mineralogical matter of each of the substrates. (For more details see the Appendix 9.2-A).

4.3.3. Experimental design

The experiment consisted of monitoring substrates performance during three crop growing cycles between spring and summer of 2018 in order to include warmer seasonal periods. Internal and external meteorological conditions of the i-RTG were recorded (Datalogger model CR3000; Campbell Scientific Inc., USA), a summary of the information is given in Table 4.2.

Table 4.2 Temperature and relative humidity conditions of the i-RTG.

	Crop Season	Temperature C°			Relative humidity %		
		Avg.	Max.	Min.	Avg.	Max.	Min.
Inside	1	19.6	31.7	11.3	43.9	68.0	9.2
	2	20.5	29.9	14.4	60.5	86.2	25.2
	3	26.0	35.8	18.6	53.6	83.2	19.2
Outside	1	13.2	23.0	1.5	69.5	100.0	17.3
	2	18.3	25.5	8.4	71.4	100.0	30.4
	3	24.49	30.8	17.9	62.72	100.0	30.3

The three crop cycles are considered independent (Table 4.3). The three substrates selected were tested under conventional irrigation (supplying all water requirements) and water restricted conditions (cut the irrigation to reach -20 kPa) in triplicates during each three crop cycle, except perlite, which was tested in duplicates: two under conventional conditions and the other water restricted conditions.

Table 4.3 Crop cycle schedule greenhouse.

Date		Test						
		1		2		3		
Transplanting		19/3/2018		3/5/2018		19/6/2018		
Harvest		26/4/2018		4/6/2018		18/7/2018		
Growing season		43 days		33 days		29 days		
Treatments		No stress	Restriction	No stress	Restriction	No stress	Restriction	Restriction
		0 to-5 cbar	-20 cbar	0 to-5 cbar	-20 cbar	0 to-5 cbar	-10 cbar	-20 cbar
Hydric restriction	Start		6/4/2018		22/5/2018		9/7/2018	9/7/2018
	End		20/4/2018		31/5/2018		13/7/2018	16/7/2018

A 70 m^2 study area within the 125 m^2 i-RTG facility was used. Growing bags' dimensions were 0.4 m x1.0 m, and they had a volume of 0.04 m^{-3}. Each plant was planted at distances of 0.2 m x 0.4 m resulting in 4 plants per substrate bag, three bags per row, and 0.5 meter distance between rows, as shown in Figure 1.1. Oak leaf lettuces (*Lactuca sativa* L. var. crispa) seedlings were planted in the four substrates. Crop growth was monitored, and growing conditions controlled, following conventional agronomic guidelines for lettuce production. During the growing periods, the diseases and deficiencies were monitored and controlled.

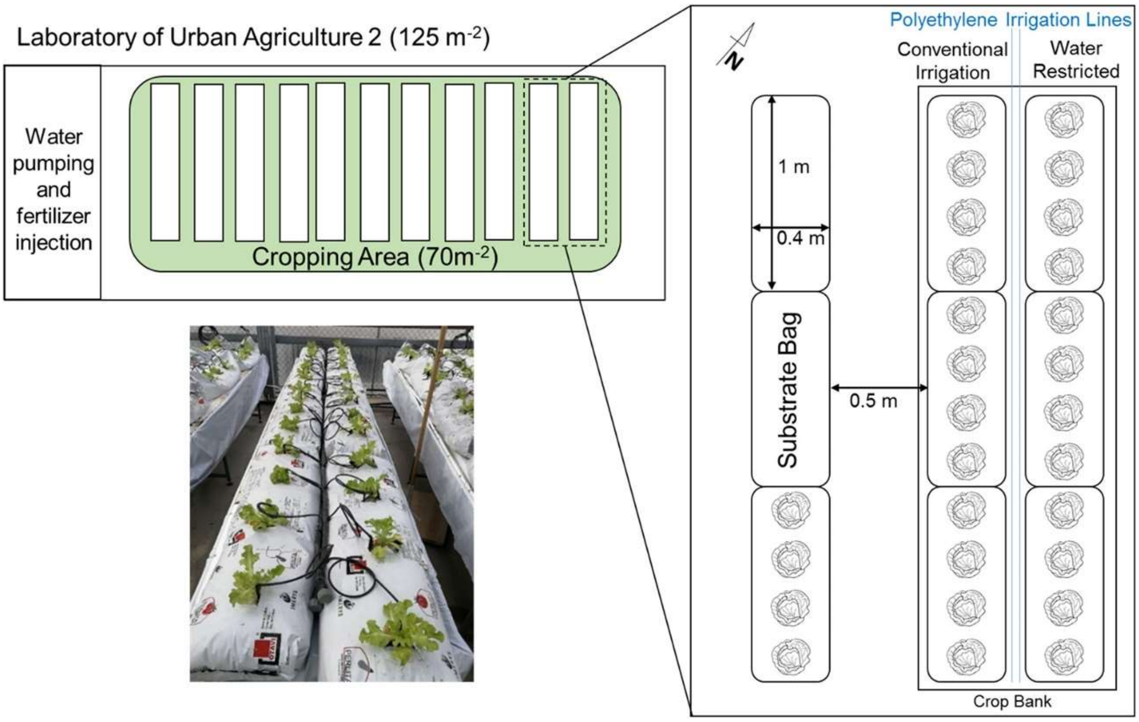

Figure 4.1 Diagram of experimental design of lettuce cultivation system.

4.3.4. Irrigation management

The nutrition solution was provided to the lettuces via a drip fertigation system. The nutrient solution contained: HNO_3 0.063 g·k^{-1}, KPO_4H_2 0.136 g·k^{-1}, KNO_3 0.101 g·k^{-1}, K_2SO_4 0.174 g·k^{-1}, $Ca(NO_3)_2$ 0.164 g·k^{-1}, $CaCl_2$ 0.111 g·k^{-1}, $Mg(NO_3)_2$ 0.148 g·k^{-1}, and microelements 0.0001 g·k^{-1}.) Irrigation volumes were adapted and optimized to the needs of lettuces grown in the control substrate (perlite). They ranged between 0.0003-0.00045 m^3·day^{-1}plant^{-1}. Induced water restriction took place 20 days after transplanting to make a late temporary drought when the plants were fully developing and required a higher water and nutrient supply following the methodology proposed Kerbiriou et al., (2013). This restriction was applied by completely stopping irrigation until the perlite bags reached -20 kPa. At this time, irrigation was re-established for all the water restricted rows. Water tension in the substrate was determined with an analog 12 cm tensiometer (irrometer® MLT) through the hydric potential variation, with a range of 0 to -40 kPa. Also, in the third crop cycle, a second hydric restriction was performed. This second restriction consisted of the same irrigation stoppage, but it was only maintained until the tensiometers in the control substrate perlite reached -10 kPa.

4.3.5. Crop system monitoring conditions; irrigation data collection and substrate physicochemical analysis

To the water flow characterization, a daily sampling was performed in each repetition of the crop cycle, and the amount of irrigated water, the leachates drained, and its electrical conductivity was measured (Table 4.4). The physical characterization of the substrate was assessed with 2 randomly samples per row of each substrate (n=12 substrates and n =8 to control - perlite) evaluated bulk density, pore space or porosity, and dry matter and moisture content (Volumetric amount of water) at the start and end of the complete crop cycles by the ring method (USDA et al., 2001). It was also shown the differential of the water content in each substrate between the conventional irrigation treatment and the restriction irrigation treatment (θ %W-θ %S).

Table 4.4 Physical characterization of substrates.

Substrates	Irrigation	Bulk density (Mean±SD)		WC (Mean±SD)		Differential at the end of the study	Electrical Conductivity Leachates	
		Start	End	Start	End		Start	End
		kg·m^{-3}		θ % (Vol water / Vol soil)		θ%C- θ%R	dS·m^{-1}	
vegetable compost	R	0.23 ±0.02^{a} (n=4)	0.29±0.04 (n=6)	31.62 ±0.99^{b} (n=4)	38.12±17.92^{d} (n=6)	25.48	4.03	2.27
	C		0.29±0.03 (n=6)		63.60±4.27^{ab} (n=6)		3.60	1.94
coir	R	0.09 ±0.00^{d} (n=4)	0.09±0.02 (n=6)	81.76 ±1.71^{a} (n=4)	38.35±6.79^{d} (n=6)	32.8	1.59	1.84
	C		0.10±0.01 (n=6)		71.15±5.41^{a} (n=6)		1.67	1.74
mixture	R	0.17 ±0.00^{b} (n=4)	0.18±0.03 (n=6)	25.29 ±8.46^{bc} (n=4)	31.26±4.58^{d} (n=6)	17.87	2.27	1.90
	C		0.17±0.03 (n=6)		49.13±4.23^{c} (n=6)		2.77	1.59
perlite	R	0.11 ±0.01^{c} (n=4)	0.12±0.01 (n=4)	14.43 ±15.96^{c} (n=4)	34.92±1.96^{d} (n=4)	21.96	0.83	1.92
	C		0.12±0.03 (n=4)		56.89±4.88^{bc} (n=4)		0.86	1.50

R: Restricted (-20cbar), C: Conventional, WC: water content, and EC: electrical conductivity in the leachates. SD standard deviation. The letters represent the significant differences detected between substrate and treatments.

4.3.6. Crop sampling

At time of harvest, plant fresh weight was determined (g of the commercial part of lettuce, as fresh yield, Table 4.5). For the sampling, five lettuces were taken randomly from different repetitions of each treatment (for each of the three rows of each treatment n= 15, except the control, which was two rows with n= 10 lettuce in total). At the end of the crop cycle, when the crop was harvested, the final yield was determined (g of the commercial part of lettuce, Table 4.5). The mature index used to cut the lettuce is based on head compactness. A compact head which can be compressed with moderate hand pressure is considered ideal maturity. A very loose head is immature and a very firm or hard head is overmature (Cantwell and Suslow, 2002).

4.3.7. Statistical analysis

The crop measurements were expressed using average values and standard deviations. "R" version 3.1.2 software (R Development Core Team, 2014) was used to determine significant differences between the different substrates and the effect of water restriction. The significance was tested using a one-way analysis of variance (ANOVA). Before the statistical analysis, the assumptions of ANOVA were checked by a Shapiro-Wilk (normal distribution) and Levene test (Variance homoscedasticity). Multiple comparisons of the means were determined by a post hoc Duncan test. When the data were not normally distributed or present variance heteroscedasticity, a Kruskal-Wallis test was used.

Table 4.5 Evolution of the crops during the three tests.

Month	Treatment	Compost	Mixture	Coir	Perlite	Compost	Mix	Coir
		g·plant^{-1}				Variation regarding Perlite [%]		
April	Conventional -irrigated	445.7 a	427.1 a	422.7 a	445.0 a	0.1%	-4.0%	-5.0%
	Restricted -20	322.6 b	249.2 c	277.5 c	259.3 c	24.4%	-3.9%	7.0%
May	Conventional -irrigated	423.9 b	477.2 ab	453.7 ab	490.0 a	-13.5%	-2.6%	-7.4%
	Restricted -20	320.2 c	323.5 c	348.5 c	340.7 c	-6.0%	-5.0%	2.3%
July	Conventional -irrigated	408. 7 ab	418.4 a	370.3 c	381.8 bc	7.0%	9.6%	-3.0%
	Restricted -10	336.3 ed	350.3 cde	358.9 cd	322.4 f	4.3%	8.6%	11.3%
	Restricted -20	285.0 g	295.2 g	276.1 gh	245.7 h	16.0%	20.1%	12.4%
Average 3 cycle				**Conventional -irrigated**		3.4%	3.7%	3.2%
				Restricted-10		4.3%	8.6%	11.3%
				Restricted -20		11.5%	3.7%	7.2%

4.4.Results and Discussion

The commercial production and the crop development were analysed, and a difference was detected between the lettuces in the different substrates by comparing the first tests to the second crop cycle. Within the third crop cycle, it was possible to appreciate a lower variability between the yields of plants irrigated conventionally and with water restriction. In addition, a trend towards a reduction in yield, regarding on the applied water restriction (-10 and -20 kPa).

4.4.1. Substrate characteristics

At the end of the three consecutive experiments coir presented an 81.76% water content, the perlite showed a 14.43% water content, and the vegetable compost and substrate mixture showed 31.62% and 25.29% water content, respectively. The coir showed the lowest value for the BD, with 0.09 kg·m^{-3}, followed by perlite, mixture, and compost, the latter with 0.23 kg·m^{-3} (Table 4.4).

Perlite: In this study, it was not possible to see final compaction of this substrate, which was possible in all the other substrates as the compost, where it was possible to perceive a reduction in the volume and substrate inside the bag, being in the last crop cycle a denser material (Table 4.4). The leachates electrical conductivity in the conventional irrigation ranged between 0.86 $dS{\cdot}m^{-1}$ and 1.50 $dS{\cdot}m^{-1}$ depending on the percent drainage, or the water consumption plants.

Coir: The amount of water at the end of the assay for the conventional irrigation coir was 71.17% (Table 4). Compared to the conventionally irrigated perlite (56.89%), there was a 14% higher WC in the coir. Additionally, the coir showed the smallest BD of all the substrate used in this assay, with 0.1 $kg{\cdot}m^{-3}$. In other word present a very low weight and high water retention, characteristic desirable in a substrate. The electrical conductivity in coir treatment was constant throughout the study, ranging between 1.67 $dS{\cdot}m^{-1}$ and 1.74 $mS{\cdot}cm^{-1}$.

Vegetable Compost: The electric conductivity on the first day of the first crop cycle was 3.60 $dS{\cdot}m^{-1}$, which decreased over time. At the same time, it is possible to see how the substrate changed from the initial condition to the final, where densification occurred, due to an increase in BD (initial 0.23 kg m^{-3}, end 0.29 kg m^{-3} for both treatments conventional irrigation and management with water restriction). In this sense, this process could be explained due to the management implemented, which was carried out based on previous experience with perlite. In this sense, as result of the irrigation management carried out, this has generated a rearrangement of the particles in time, which generated densification of the substrate, increasing the apparent density.

Mixture: The substrate mixture indicated values ranging between compost and perlite, for the EC`s leachates (2.77 $dS{\cdot}m^{-1}$) and the BD (0.17 $kg{\cdot}m^{-3}$), indicated in Table 4. During the experiment, the leachate’s EC had the same decreasing tendency reported in the compost substrate. Besides, to understand the behaviour over time, the final water content (WC) was evaluated together with the measures obtained daily with the tensiometers placed in each substrate.

Effect of temporary water restriction on the substrates

The coir showed a 32% higher water content (θ % conventional irrigation treatment - θ % restricted water treatment); in this sense, the mixture showed poor performance, at 18%. The vegetable compost and perlite had a performance of approximately 25% and 22%, respectively.

Due substrate's different hydric curves (Appendix 9.2-A), the point of restriction was not the same for all of them (the minimum hydric potential reached in each substrate was different) because the period of no irrigation was the same in all the substrates (Figure 2). For example, during the first crop cycle, when the perlite presented 19 kPa, the coir and compost presented -23 and 4, respectively. The restriction period was different throughout the three crop cycle s (Table 3) due to the temperature increase during the study, with each crop cycle showing higher temperatures than the previous crop cycle. This induced the same drought stress levels in less time.

Perlite: Focusing on the tensiometers, the perlite water holding capacity (WHC) remained constant through the 3 crop cycle s, with a progressive release of water content over time. When water restriction was induced, the percent drainage variation occurred in hours compared to the other substrates, which took approximately 2 days. Moreover, it was detected that the major differences in the leachate electrical conductivities of the conventional irrigated and restricted perlite bags were related to the duration of the restriction periods and not just to the hydric tension of the substrate. As previously explained, the temperatures increased throughout the second and third crop cycle s, reaching the limiting - 20 kPa in shorter periods. Lower EC values in the second crop cycle (9 days without irrigation) and the third crop cycle (7 days without irrigation) compared to the first crop cycle (14 days without irrigation) once irrigation was restored.

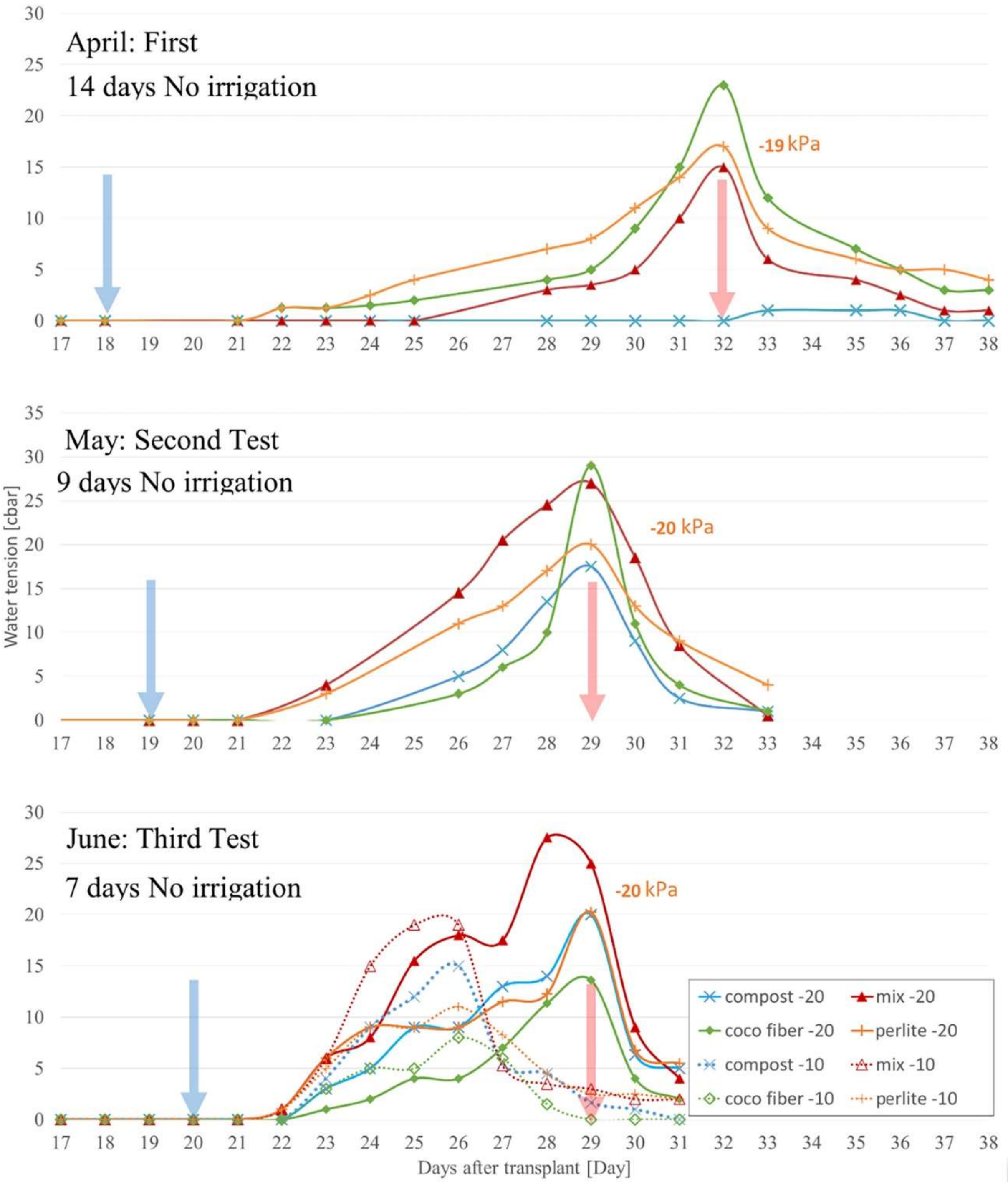

Figure 4.2 Water tension inside each substrate's bags under study.
After inducing water restriction up to −20 kPa (tests 1, 2 and 3) and −10 kPa (test 3).

Tested substrates: vegetable compost, a mixture (mix in the Figure) of compost and perlite in a 1:1 volume, coir, and perlite (the control substrate). The blue arrow shows the beginning of cut of irrigation. The red arrow shows the reincorporation of irrigation.

Coir: In crop cycles 1 and 2, the coir showed a slow response to water restriction, but when the matrix potential ranged between 5 and 8 kPa, it decreased rapidly. The results obtained using the water retention curve, a high percent easily available water (23.07%). Its water loss was more progressive than the perlite since perlite has 8.6% easily available water. Moreover, the stress response measure decreased in the last crop cycle with the same hydric demand, and the substrate presented less tension in the pore system. It can explain by the collapse of coarse porosity through the different processes of irrigation and drought in the test, creating a more complex porosity with a normalized pore distribution, which would explain its behaviour during test number 3. The treatment with restricted water presents a constant EC throughout the study, and no differences were detected in the conventionally irrigated substrates.

Vegetable Compost: Through monitoring with tensiometers, the compost showed a low response to hydric potential in crop cycles 1 and 2 (4 and 17.5 kPa). In the last crop cycle, the compost had similar behaviour to perlite in both water restrict treatments (-10/- 20 kPa, with 15 and 25 kPa for compost and 11 and 20 kPa for perlite, Figure 2). The restricted compost's final water content was similar to that of perlite and the water content when the compost was conventionally irrigated. The increase of BD (0.23 to 0.3 $kg \cdot m^{-3}$) can be explained by the general irrigation management of the test was adjusted to the perlite demands. This could have meant a higher irrigation input during crop cycles 1 and 2, which could have favoured particles' arrangement, and for concomitance, the increment of the bulk density. Moreover, when irrigation was stopped, no leachates were detected, and after the water restriction period, the EC was the highest among the substrates.

Specifically, in the first test, the leachates were detected 6 days after irrigation was re-established, and the electrical conductivity was 4.93 $dS \cdot m^{-1}$. Nevertheless, this finding highlights that at the end of each crop cycle, the leachates' EC was the same in the restricted crops as in the conventionally irrigated crops.

Mixture: For hydric potential, the mixture showed an intermediate performance between the compost and the perlite in the water restricted treatment during the first crop cycle, while during the second and third crop cycles, it showed a high response to hydric potential, with a lower value (27 kPa) compared to the control (perlite with 20 kPa) (Figure 2). This is consistent with results obtained in the water retention curve easily available water ranged between the values obtained in the compost and the perlite (20.58% and 14.83%, respectively). This could be explained by the mixture having a poor water content performance. The conventionally irrigated and restricted mixture substrates had the lowest WC values (31% and 49%, respectively, compared to the perlite, at 34% and 51%, respectively), confirming the relationship of low water content and low hydric potential (a lower value more strongly strengthens the stress due to the fact that the hydric potential is tension). The BD remained constant over time, being unaffected by the irrigation treatment, and showed an average value of 0.17 kg·m^{-3}; the BDs of the compost and perlite at the start of the crop cycle were 0.23 and 0.11 kg·m^{-3}, respectively. In the end, the compost showed slight compaction (0.29 kg·m^{-3}), but this was not the case in the mixture. The EC was similar, but its behaviour was closer to that of the perlite than the compost. The mixture had the same pattern as the compost in the electric conductivity. For example, at the beginning of the crop cycles s, the EC was 2.27 dS·m^{-1} (crop cycle 1), 2.30 dS·m^{-1} (crop cycle 2), and 1.80 dS·m^{-1} (crop cycle 3). Nevertheless, as shown, the differences between the conventionally irrigated treatment and the restricted treatment are smaller than those of the compost.

4.4.2. Crop production

The crop yields ranged from 245.7 to 490.0 g·plant$^{-1,}$ and some differences were detected due to the substrates, the effect of water restriction, and the meteorological conditions. It is important high light that water supply is key to adequate food production, however there are studies have shown that the water content of a media has a direct influence on the fresh weight gain by lettuce plants (Valença et al., 2018). With our results it is possible to appreciate that when the hydric restrictions are generated losses of yield, in general, the smaller this loss, the greater tolerance to the hydric deficit the substrate presents. The main result is that in all three alternative substrates studied, commercial productions were obtained; therefore, they could be used in UA. As expected, when the crops suffered under a water restriction period, production decreased, but the magnitude of these losses was different among the substrates.

Conventional irrigation

During the first crop cycle (April), when the crops were irrigated appropriately, no significant differences ($p<0.05$) in the yield were observed among the substrates. The yield obtained ranged between 422.7 and 445.7 g·plant^{-1}. Crop cycle 2 present a different behaviour, with the conventional irrigation, crops grown on the mixture and coir substrates obtained statistically the same production as the control (which is the substrate with the highest production: 490.0 g·plant^{-1}), and the compost presented the lowest production (423.9 g·plant^{-1}, 14% less weight). In 3 crop cycle, the best results in the conventional irrigated crops were obtained with compost (408.7 g·plant^{-1}) and mixture (418.4 g·plant^{-1}). Compared to the substrate with the highest obtained weight (mixture), the coir presented the lowest production (370.1 g·plant^{-1}), -11.5% less. The behaviour of the compost was notably different from those of the other substrates. The lettuce grown in the compost presented successive decreasing weights with the three consecutive crop cycles (Table 5). This difference could be due to the fact that in the first crop cycle, the compost is used for the first time, being able to contribute a large amount of nutrients to the lettuce. However, throughout the trials, nutrient depletion was detected by measuring the electrical conductivity of the leachates, as noted in the previous section. Furthermore, a compaction of the substrate was detected, which could be a further reason for the production decrease (Mastouri et al., 2005).

Water stress effect on the yield

Some differences were detected when the crops were under water restriction. Compared to the control, the mixture, and the coir substrates in the first crop cycle, the plants grown in the compost reached higher weights (322.6 g·plant^{-1}). These results demonstrate that vegetable compost from urban green waste is a competitive agronomic option for use in UA. Thus, the compost was able to provide some buffering capacity to the temporary drought. The coir did not reduce stress in the lettuce as much as expected based on the material's high water-retention capacity. Previous studies have suggested that the yield decrease could have been due to excessive osmotic stress from the combined effects of the drought and the high salinity of the media, which would not have been reflected in the tensiometer readings, as these only report matric potential (not osmotic) (Wallach, 2008).

In the second crop cycle, in all the treatments, compared to the conventional irrigated crops, the water restricted crops' production decreased and was statistically the same between treatments. In this case, the compost results were worse than expected. First, the lettuce presented the same weight as the other substrates, and the benefits detected in the previous crop cycle were not detected here. Second, because the other three restricted substrates presented an increase in production compared to the first crop cycle (25-30%), compost's production was similar to that in the first crop cycle (320 g).

Compared to the previous crop cycles, during the third crop cycle, the higher temperatures induced a more rapid appearance of water stress (Figure 2). Whether the water restriction reached -10 kPa or -20 kPa, the lowest production was obtained in the perlite bags. When the restriction reached -20 kPa, the mixture and the compost substrates presented the best results (295.2 and 284.9 $g \cdot plant^{-1}$, respectively). Nevertheless, when the restriction did not exceed -10 kPa, the crops grown in the coir, and the mixture reached the highest production values (358.9 and 350.3 $g \cdot plant^{-1}$). These results could have been perceived when analysing the water loss curves of the different substrates. As shown in the previous section, in the first crop cycle, the coir took a long time to lose water; however, when dryness begins, water loss occurs very quickly and can damage crop production.

4.4.3. Relevance in UA

The consumption model within cities is characterized by being unidirectional, where inputs and outputs flow prevail (World Economic Forum, 2018). Firstly, diverse externalities are generated by an extractives model that feeds on natural resources, and secondly, it increases new spaces for agricultural production to satisfy the city's requirements. From a circular economy perspective, favour exchanges of flows between urban subsystems are part of the solution to migrate to sustainable cities (Lucertini and Musco, 2020). The use of compost and the mixtures of substrates derived from it, responds to these needs since at the city level 1; it reduces and values municipal solid waste (MSW), 2; favours the recycling of nutrients, 3; as a substrate to improve physical, chemical and biological properties of the culture medium.

(1) By using organic matter from MSW its amount will be reduced and, therefore, the greenhouse gases emitted in landfill disposal (Lou and Nair, 2009). In this sense, the advantages can be seen at the UA level and interact with more elements within the city (De Corato, 2020). Other Research presents a study in Belgium about the opportunities and barriers of compost at the farm level, where they recommended 5 measures towards using compost (Viaene et al., 2016). However, the study is carried out for farm conditions, the recommendations are applicable in a circular economy context in the city. The third recommendation refers to searching for new alternative sources of biomass from other industries to produce compost. It is possible to find different stakeholders at the city level that can regularly provide biomass, such as greengrocers and coffee shops, among others. The integration of agricultural production in the city would maintain a stable compost production over time due to its possible interconnections to other industries. Furthermore, research has been made on composting with common inorganic waste from the city, which has shown good results, such as disposable diapers and biochar, among others (Colón et al., 2013; Espinosa-Valdemar et al., 2014; Guo et al., 2020).

(2) By composting the organic matter, it stabilizes, and the nutrients are available again to produce new vegetables (Harrison, 2008; Jack and Thies, 2006). Since nutrients are a limited resource, reincorporating and reusing them in the production system is vital for the UA's sustainable development.

(3) The incorporation of compost (total or partially) as a replacement for commercial substrates can decrease the CO_2 emissions, depending on the origin of the replaced substrate. As an example, for this, in Spain, close to 80% of the perlite used comes from Turkey, South Africa, Greece, Uganda, and United Kingdom (35%, 18%, 10%, 8%and 8% respectively), where the reduction in the transport item could result in an environmentally better process. Studies suggest that under proper compost management, environmental impacts are reduced (Martínez-Blanco et al., 2010).

In the present study, the vegetable compost and the mixture of vegetable compost with perlite are suitable substrates in horticulture, especially in RA. Besides, it has been observed that these substrates have better characteristics for preventing hydric stress in summer, despite previous studies showing that compost production could decrease due to salt concentrations (Mastouri et al., 2005).

The yield was markedly competitive and higher than that of perlite in April and July. Lettuce is a moderately sensitive crop to salinity, similar to most of the RA crops: pepper, tomato, and spinach, among others. Therefore, the results obtained in this study could be directly applied to other horticultural crops

4.5.Conclusions

This analysis quantified lettuce's agronomic performance grown in organic substrates, including their resilience to water restriction. In the circular city context, the study of the agricultural performance of environmentally friendly substrates (the recycled organic municipal waste in cities) can contribute to RA implementation in Mediterranean urban areas. Our results show that the studied organic substrates, coir, as a commercial substrate, and vegetable compost alone or in a substrate mixture with perlite 1:1, could be used in UA, as they obtained similar or higher production than the control substrate (perlite). In summer, the best results were obtained with vegetable compost alone (408.7 $g\cdot plant^{-1}$) and compost mixed with perlite (1:1) (418.4 $g\cdot plant^{-1}$). Nevertheless, a sequential decrease in the fresh lettuce weight grown in compost in the three crop cycles was detected, probably due to the substrate's loss of nutrients.

We found that compared to perlite, the organic substrates improved the conditions against applied water restriction and increased the crops' yield. Specifically, the coir tended to take a long time to lose water; however, when dryness begins, it occurs very quickly, and commercial production decreases if drought induces water stress of -20 kPa, the compost and the mixture of compost and perlite present remarkable agronomic resilience.

These results contribute to UA's knowledge and preventive measures of droughts in Mediterranean cities with quantified data. In the current climate change context, with increasing droughts in summer, commercial systems that utilize compost as a growing media could reduce irrigation frequency, save water without increasing the substrate's salinity, and still produce commercially relevant yields. In parallel, to contribute to the circularity of the city, since it is possible to produce it with the same waste, which is generated from agriculture, closing one of its cycles (Manríquez-Altamirano et al., 2020).

Chapter 5. Optimizing irrigation in urban agriculture for tomato crops in rooftop greenhouses

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This work is based on the follow Journal paper:

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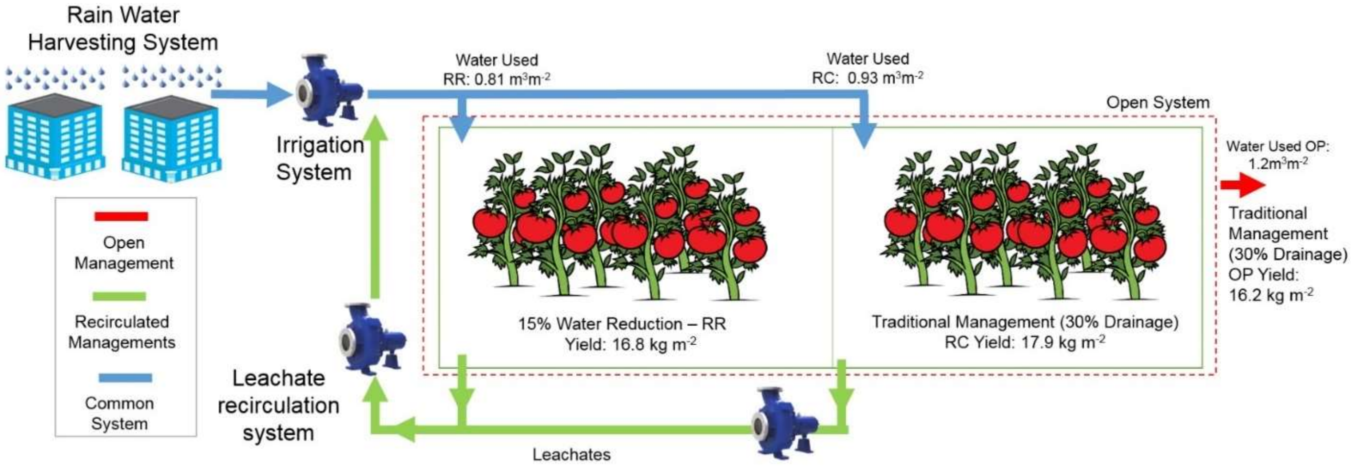
5.1. Abstract

The rising populations in urban areas make it increasingly important to promote urban agriculture (UA), which 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·kg·m^{-2} for OP, RC, and RR, respectively. In terms of water-use efficiency, RR management was the most efficient, requiring 48.7·liters·kg^{-1} of tomato, followed by RC (52.4·L·kg^{-1}) and OP (75.2·L·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.

Keywords: Life cycle assessment (LCA), Water-use efficiency (WUE), reduction water consumption, eutrophication reduction, leachate recirculation, recirculation system.

5.2.Graphical Abstract



5.3.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 non-renewable 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., 2021, 2017; 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 analyse 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 analysing 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 determine 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.

5.4.Materials and methods

5.4.1. 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 x 1.1 m (Figure 5.1) with a total of 171 tomato plants distributed in 57 perlite substrate bags (40 L), making a plant density of 2.7 plant·m^{-2}. The study took place during two consecutive years, 2018 and 2019, where the tomato season lasted approximately 6 months each year.

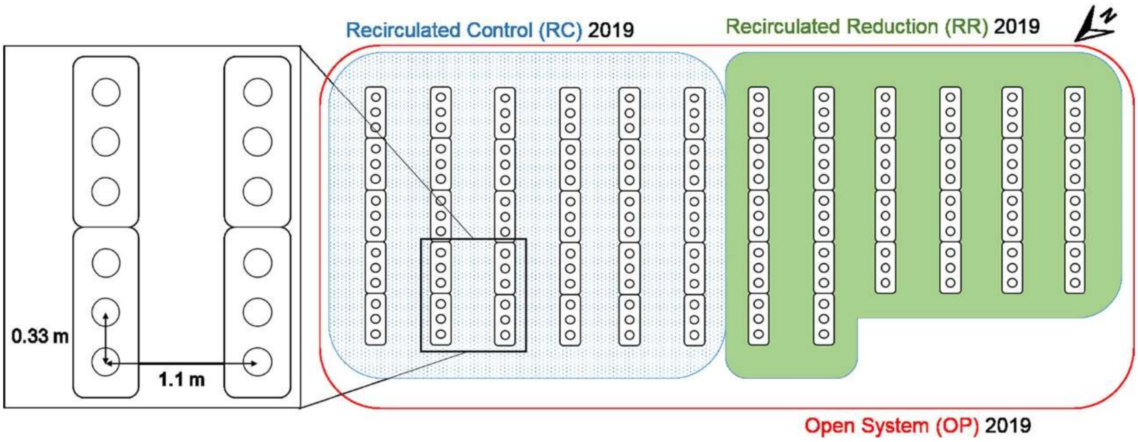


Figure 5.1 Distribution of plants at the ICTA-UAB LAU-1.

A drip irrigation system was used with a 2 L·h^{-1} water flow in which fertilizer was applied according to need throughout the cropping season (Table 5.1).

Table 5.1 Concentration of fertilizers used.

Fertilizers	2018 OP [g·m^{-3}]*	2019 RC [g·m^{-3}]*	2019 RR [g·m^{-3}]*
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

* 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.

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 litres each inside the greenhouse on the top floor of the building.

The leachate was collected in slightly-tilted aluminium 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 aluminium 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 centred on the optimization of fertilizers, energy, and analysis of infrastructure. The three irrigation managements were performed as follows and summarized in Table 5.2: (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 (Figure 5.2).

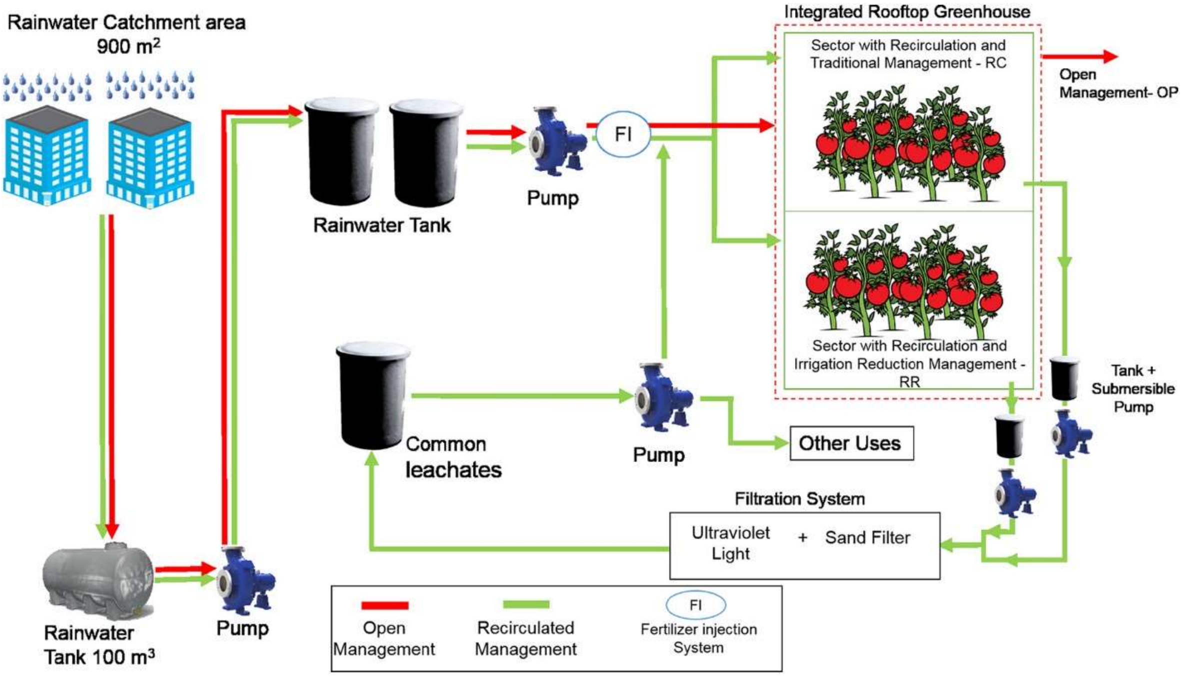


Figure 5.2 The three irrigation schemes, including auxiliary equipment.

The three irrigation schemes, including auxiliary equipment. OP management (red line), recirculated management (green line).

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 5.2. 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				

5.4.2. 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., 2008a). 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 litres) and yield (kg of tomatoes produced) for the entire crop cycle, as shown by Equation 5.1.

$$\text{WUE} = \frac{\boldsymbol{Liters\ of\ added\ water\ to\ the\ system,}[\boldsymbol{L}]}{\boldsymbol{Kilograms\ of\ Tomatoes\ produced\ by\ the\ system}[\boldsymbol{Kg}]} \qquad \text{(Eq. 5.1)}$$

5.4.3. 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.

Equation 5.2 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).

$$\begin{gathered}\text{Total amount of nutrients} \\ \text{From irrigation or leachates [kg]} = \frac{\sum \boldsymbol{X_i *} [\boldsymbol{Nc}]_{\boldsymbol{i}}}{\boldsymbol{10^6}}\end{gathered} \qquad \text{(Eq. 5.2)}$$

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 analysed (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, equation 3 was used, where DM_i represents the partial dry matter of the sample of tomatoes [g $_{\text{dry matter}}$], and $Nc_{DM\,i}$ is the nutrient concentration [mg·g$_{\text{dry matter}}^{-1}$] 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.

$$\text{Total amount of nutrients from biomass and tomatoes [kg]} = \sum \boldsymbol{DM_i} * \ [\boldsymbol{Nc_{DM}}]_{\boldsymbol{i}} \qquad \text{(Eq. 5.3)}$$

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 equation 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.

$$\boldsymbol{X_T = X_L + X_B + X_Y + X_{EA}} \qquad \text{(Eq. 5.4)}$$

5.4.4. 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 Figure 5.3) 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 x 300L), and leachates polyethylene tank (300 L). (For more details see the Appendix 9.3-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.

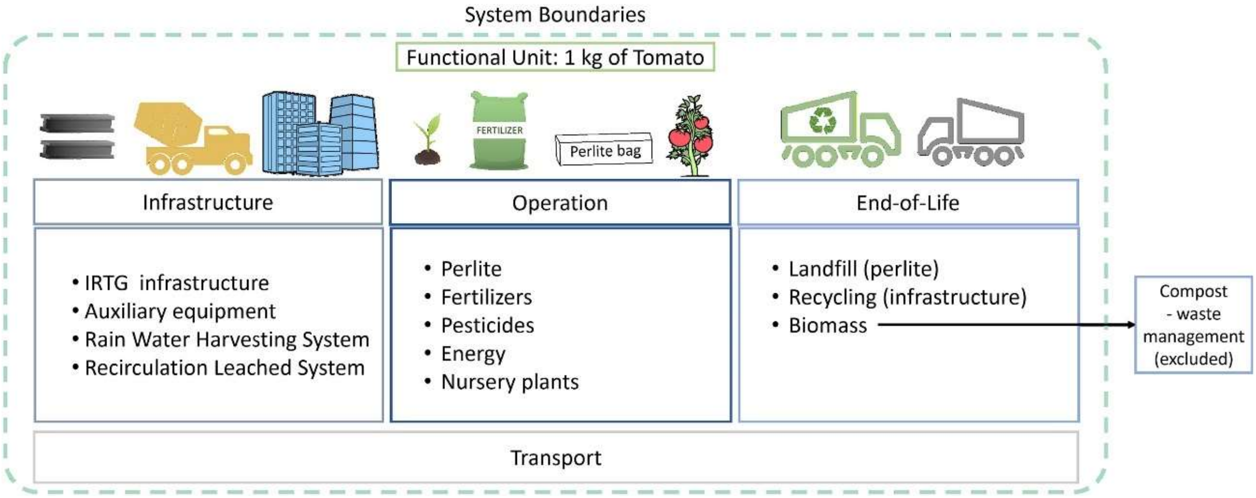


Figure 5.3 Diagram of system boundaries, depicted by the dotted green line.

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).

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 Appendix 9.3-C and Appendix 9.3-D 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., 2020a). 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 cut-off 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.

5.5.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·m^{-2} for open management (OP) to 17.9 kg·m^{-2} for recirculation control (RC), as shown in Table 5.3. 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·m^{-2} in France, and Muñoz et al., (2008), who reported a similar value of 16.5 kg·m^{-2} in Spain.

Table 5.3. Summary of agronomic variables (yield, water used, and WUE).

Parameter	Unit	2018 OP	2019 RC	2019 RR	RC/OP	RR/OP	RR/RC
Yield[1]	kg·m^{-2}	16.2	17.9	16.8	110.2%	103.2%	93.7%
Water Used[2]	L·m^{-2}	1220.7	936.8	815.7	76.3%	66.4%	87.1%
WUE[3]	L·kg^{-1}	75.2	52.4	48.7	69.3%	64.4%	92.9%

[1] Yield considering all tomatoes harvested, divided by effective harvest area. [2] Calculated on a basis of irrigation water added to the system. [3] Water-use efficiency considering liters per kilogram of tomatoes.

WUE was calculated to determine the biomass accumulation (edible yield) per litre 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·kg^{-1}, follow by recirculation control (RC -52.4 L·kg^{-1}) and open system (75.2 L·kg^{-1}) as shown in Table 5.3. Although RR obtained less production, in terms of WUE was approximately 35% more efficient than OP management.

5.5.1. 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 Appendix 9.3-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.

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 Appendix 9.3-E.

5.5.2. Nutrient Balance

Nutrient balance calculations were performed for N, P, and K, and the results are shown in. 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 5.4). 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).

Table 5.4 Mass balance of nutrients by management.

* 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].

		Input [kg]	**Output [kg]**				**Input/Output [%]**				**Total**	**Nutrient-uptake efficiency**	**Nutrient-Use Efficiency**
	Nutrients	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

5.5.3. 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 Figure 5.4. 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.

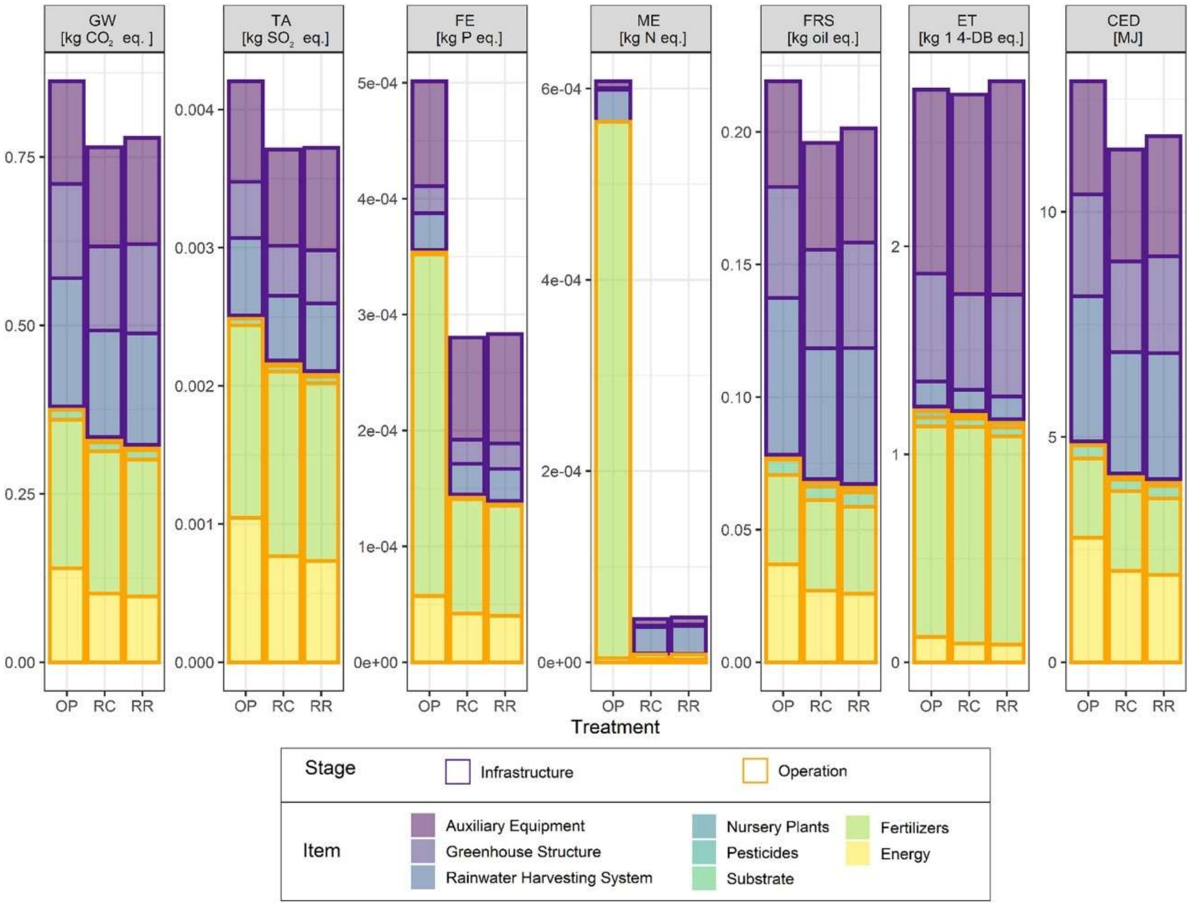


Figure 5.4 Environmental performance per kg of tomato crop.

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 Appendix 9.3-A and Appendix 9.3-B.

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 fibre 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 aluminium and injection molding.

5.6. 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 analyse the potential optimization of the different elements within the operational subsystem and provide recommendations for greenhouse infrastructure.

5.6.1. 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 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 analyse 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 $L\cdot kg^{-1}$ to 65.3 $L\cdot kg^{1}$. 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., 2017) 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 favours 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 defence 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 favour 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 favour adaptive behaviour 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 were 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 (1,400 $g{\cdot}m^{-2}$), requiring a greater structure to support it, in contrast to plastic film with greater flexibility and lower weight (230 $g{\cdot}m^{-2}$) (Castilla, 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.

5.6.2. 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 non-renewable 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 Figure 5.5. 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.

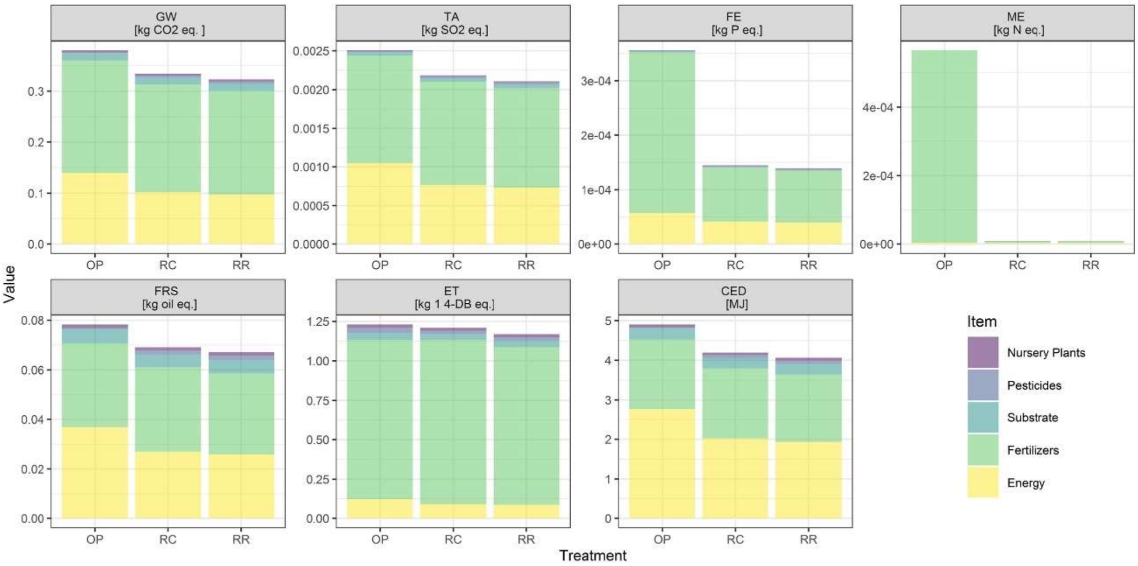


Figure 5.5 Life cycle impacts of the Recirculation and reduction (RR), Recirculation Control (RC), and Open (OP) systems during the operational stage.

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 sulphate. 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 sulphate (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 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 analysed, which are shown in Table 5.4. 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, sulphate ions accumulate over time, creating high concentrations of sulphate 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 sulphur 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.

5.6.3. 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 3,541 and 3,904 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·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 Appendix 9.3-F and Appendix 9.3-G).

Figure 5.6 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 analysing 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.

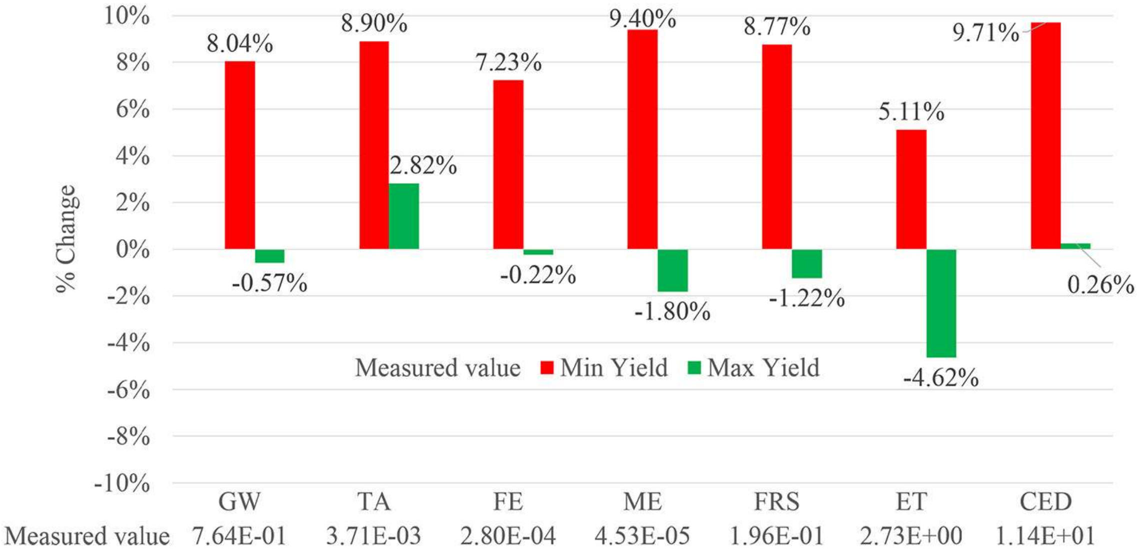


Figure 5.6 Sensitivity analysis with the min and max theoretical yields.

5.7.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 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., 2020a; 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, are 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 litres per kg of harvested tomato, followed by RC (52.4 $L \cdot kg^{-1}$) and OP ($75.2 \cdot L \cdot kg^{-1}$). 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 aluminium 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.

Part IV

Discussion

Chapter 6.

Discussion of the major contributions

Chapter 6

This chapter discusses the major contributions of this dissertation. This section aims to expand and deepen the research developed in the previous chapters. It integrates the different water strategies to improve the environmental performance of food production in a UA rooftop condition.

6. General Discussion

This dissertation focuses on efficient water management as a basis for improving food production in urban rooftop greenhouses, based on crop cultivation experiments and environmental and agronomical analysis. The motivation comes from the water scarcity and need to produce food in cities, in this way, it focuses on three strategies to optimize water use: the first one is modelling water demand of urban agricultural systems, the second one is the use of organic substrate from municipal waste with restrictive water management; and thirdly, the environmental analysis of a rooftop greenhouse food production under contrasting irrigation management (traditional and restrictive). The expected water scarcity in Mediterranean areas, together with the population increase in cities, requires more resource-efficient urban food production systems. These improvements are motivated by the decreasing water availability and the increasing demand for inputs (e.g., fertilizers, fuels, and irrigation water). Figure 6.1, shows the major interaction and contribution of this dissertation.

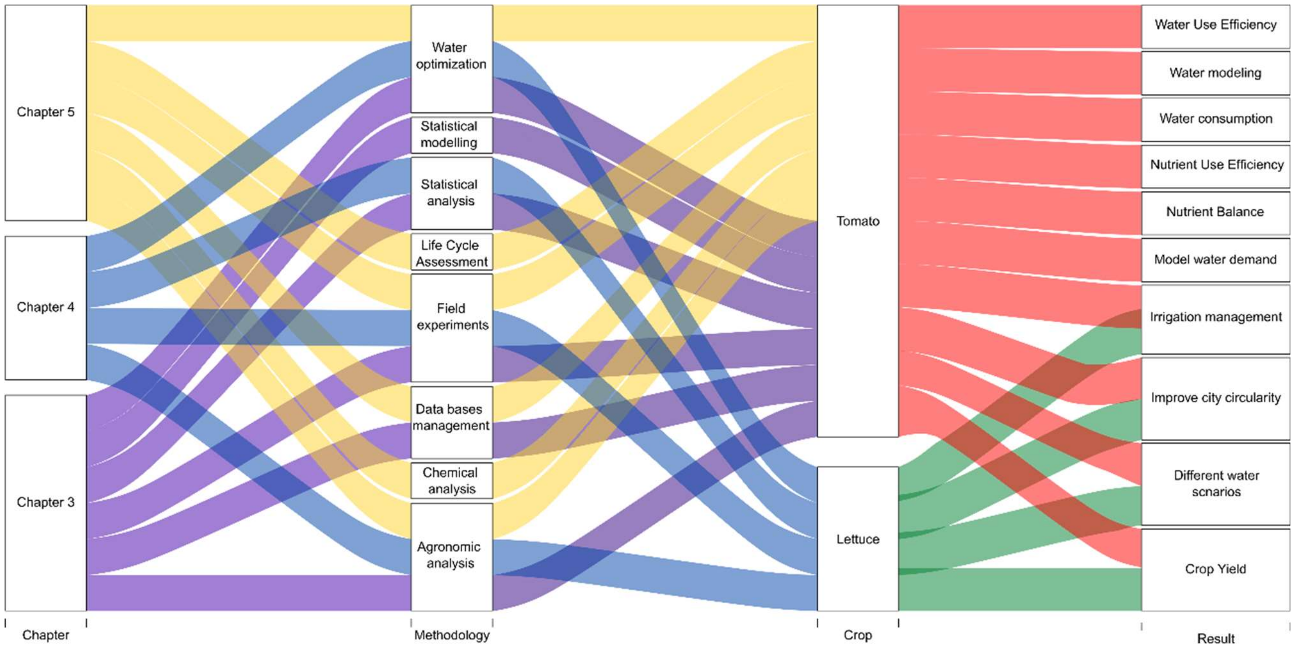


Figure 6.1 Outline of the major contributions of the dissertation

Through the construction of a water demand model under UA (rooftop greenhouse) conditions (**Chapter 3**), more efficient water management was projected. There is evidence that in Mediterranean climates the use of intelligent models or systems, based on climatic parameters, can reduce water consumption (Mason et al., 2019). For conventional agriculture, there is a wide background of water demand models (e.g., FAO Penman-Montieth, Hargreaves and Samani, Priestley-Taylor, each other's). However, for UA there are not specific models to predict the evapotranspiration (ET_0). The statistical methodology, presented in **Chapter 3** (The back draw selection process), allows to determine the most significant variables to predict the ET_0. The model proposed in this dissertation considers internal temperature as the only predictive variable of ET_0, thus explaining 50% of the water demand of the greenhouse (r^2 50%). On the other hand, the application of the $G_2T_iR_e$ model, which considers both internal temperature and external radiation, in our study obtained results similar to those shown by Gong et al. The inclusion of the radiation as predict variable increased the r^2 by 11%. For sites where this information is available, it would be possible to see an improvement in model performance, reducing its RMSE, coupled with the variability of the model for a i-RTG.

The internal relative humidity (Appendix 9.1-D) was also analysed together with internal temperature and radiation. The results of this model showed that relative humidity was not statistically significant. The r^2 increases by 1%, so the inclusion of this variable does not significantly improve the predictability of the model. Although this parameter is used for water modelling, in our case, it is a stable parameter over time, not statistically significant enough to be included in the final model.

This model aims to generate a simple tool to easily access those different stakeholders (urban farmers, companies, and researchers) to determine crop water requirements through a simple climatic variable. Part of a major contribution of this model (**Chapter 3**) is their simplicity, based on the low level of information needed. This simplicity enhances its applicability because the parameter it uses is easily accessible. Finally, the internal conditions of greenhouses in cities will be similar, which allows for replicability. Based on the comparison of previous models, i-RTG model shows similar performance in simple models (McLoud model) in contrast to complex models (Penman-Montieth model) where no substantial improvement with variables were seen. However, it is necessary to take into account the limitations of any model.

For companies it is important to consider possible overestimation associated at i-RTG model, to prevent this situation. It is recommended to implement additional technologies, to complement an efficient water use. A further benefit of the i-RTG model is that it can help domestic users to manage their water with simple information, to estimate the amount of irrigation water needed quickly. By having basic knowledge, it is to possible easily develop a management strategy that is not dependent on calendars. Then, domestic users can thus manage their water resources more effectively. It is established that a simple model can be used to determine the water demand (irrigation) in rooftop greenhouses in UA.

The efficient use of irrigation water also can be transformed into a reduction in different resources, as energy and fertilizers. **Chapter 5** evidenced the irrigation reduction management decrease the water consumption, and shows similar behaviour to the traditional management, even though the yield is show lightly affected. Despite the drop in yield, the input/output ratio (water/biomass) is improved, because the water reduction rate was higher than the loss of tomatoes produced. In that sense, the research presented explores how reductions in terms of water and nutrients affect crops in agronomic and environmental performance. The ratio of inputs applied regarding the number of kilograms of tomato produced presents a positive balance at the environmental level for restrictive water management.

While yield is affected, this drop does not affect environmental performance, in other words, lower yields are compensated by better fertiliser and energy consumption, which makes the variation in environmental impacts similar to traditional irrigation management. In addition, when analysing fertilizers metabolized in terms of inputs (fertilizers kg) and outputs (tomato kg), the field work shows that restrictive water management improves the nutrient use efficiency (nitrogen and potassium) at both the greenhouse system level and plant level when compared to the traditional management. Additionally, there is a significant reduction of nitrogen and phosphorus discharges to the environment, due to the recirculated system implemented.

In a circular economy framework complementary strategies are needed to increase the sustainability of the city. The implementation of water demand modelling and the use of urban organic waste as substrates contribute to reduce the environmental impacts by improving the I/O ratio and enhance the recirculation internal flows into the city..

The waste organic matter can represent a source to produce compost at the city level. Different products and resources can be recycled as substrates and nutrients. The horizontal integration of the production of compost favours the circularity of the city. **Chapter 4** explores lettuce's performance when grown on organic substrates combining organic compost and perlite that favour water and nutrient retention including its resilience to temporary water restrictions.

It was found that these substrates had better characteristics for managing hydric stress under warm conditions. With organic substrates, the crop maintains or increase the yield, and was less susceptible to water restrictions compared with perlite. Particularly, the compost and its mixture with perlite provided agronomic resilience to drought.

A buffer effect can be present in compost, which can help to retain nutrients, which can then be used by the plants, resulting in higher yield. Coir, on the other hand, is a slow loser of water. However, when drought begins, it loses water rapidly, damaging crops. This behaviour must be considered if use coir as a part of organic substrate to prevent yield drops.

Additionally, other horticultural crops could benefit from these results to prevent salinity problems associated with droughts, such as pepper, tomato, and spinach. These crops may be used to maintain food production in UA conditions in case of a water reduction situation.

Chapter 4 discussed how the cities' consumption model consists of a one-way flow of inputs and outputs. As a consequence, this chapter contributes to how compost can support the circulation of urban flows in a circular economy framework, which will facilitate the migration to sustainable cities.

Due to the incorporation of compost to the matrix of the substrate for replacing those with the greatest impacts. In first place this contribute to improves the system, moving it away from linearity (input of inputs - output of waste) to greater sustainability due to circularity (input of waste - output of inputs). In this sense the use of compost is able to reduce greenhouse gas emissions emitted from landfill disposal by using organic material from municipal solid waste. The recovery and re-utilization of nutrients in food production systems, through organic matter, reduce consumption of mineral fertilizers.

Compost could be an additional consideration for reducing CO_2 emissions through replacement of those with greatest impacts with those with less impact by adding it to the substrate matrix. Due to its stability, light weight, and ability to retain water, perlite has traditionally been used. An 80% importation of perlite in Spain would lead to a reduction in the environmental impacts resulting from the reduction in transport.

Municipalities can reduce greenhouse gas emissions from landfill disposal by using compost and composted substrates made from municipal solid waste in place of landfills. Through organic matter, nutrients can be recovered and re-utilized, reducing the consumption of mineral fertilizers in food production systems. Sustainability necessarily involves the reintegration and reuse of these resources within the food production system. The key to sustainability is reintegrating and reusing these resources within the food production systems.

The development of new strategies in the context of low water availability and environmental impacts is a field that presents a huge challenge. **Chapter 5** contributes on agronomic and environmental performance by studying the effect of three irrigation managements (conventional open - OP; conventional with recirculation - RC; reduced irrigation with recirculation - RR) in a rooftop greenhouse (RTG) condition. This shows with the implementation of a recirculation system (water and nutrients) on RTG, how can be reduced the eutrophication impacts related to nutrient discharge and enhance water use efficiency in tomato plants, reducing the water and nutrient supply. In addition, evidence that RR management led to slightly lower tomato crop yields (-6.3%) and used 13% less water than RC.

On the other hand, **Chapter 5** provides water use efficiency values, which can be used for modelling current and future productivity. The results are presented for 2 years and 3 different managements (for tomato crop), which allow expanding the amount of information about productivity (yields, water consumption, fertilizers) developed in UA, considering that it is currently not widely available. In our case, the highest water use efficiency was achieved by RR, with 48.7 litres per kg tomato. Other research, on greenhouses at ground level with the same variety, has found 33.3

litres per kg tomato (Muñoz et al., 2017). Considering the conditions of urban agriculture on roofs, such as increased ventilation, which changes the baseline conditions increasing the water demand. This highlights the idea of further research into alternative management and technology to reduce water inputs in food production systems.

The recirculation system shown in **Chapter 5** can help to solve environmental issues associated with food production, through the reuse of the leachates and recover nutrients. Nevertheless, this is more complicated and expensive to implement because more information, equipment and infrastructure is required. **Chapter 5** reaffirms the idea that it is necessary to implement such recirculation systems (RS) as they enormously reduce nitrogen and phosphorus emissions into the environment (marine and freshwater eutrophication, with 44% and 93% fewer impacts in comparison with open management). By using the RS, nutrients can be reused daily, increasing the efficiency of resource usage, and minimizing the environmental impact caused by adding new fertilizers. Significant life cycle benefits have come as a result of reducing nutrients. For example, the improving use efficiency of some macronutrients, such as phosphorus, which is non-renewable and has slight recycling rates.

The nitrogen-uptake efficiency is not affected by the recirculation and reduction schemes at the crop level. RR reduces the amount of nitrogen applied, causing the increase of the biomass-nutrient ratio. In contrast, phosphorus-uptake efficiency showed a reduction in the recirculated managements compared with the OP system. The ionic imbalance produced by recirculation is an important topic to consider. In this sense, it is recommended to maintain periodical analyses that allow correcting the recirculated irrigation water. In order to prevent excesses or shortages of any type of nutrient, to maximize crop yields.

Contrasting the i-RTG with traditional production systems, these pose fewer environmental impacts, due to less complexity in terms of infrastructure, these would optimize the construction, to favour the entry of light without losing strength in the structure. Research is currently underway to determine the trade-offs of the materials currently in use (Muñoz-Liesa et al., 2021). In this sense, there is necessary to look for new materials for the infrastructure phase. The key is to promote UA at all levels such as domestic, business, and research in an environmentally responsible perspective.

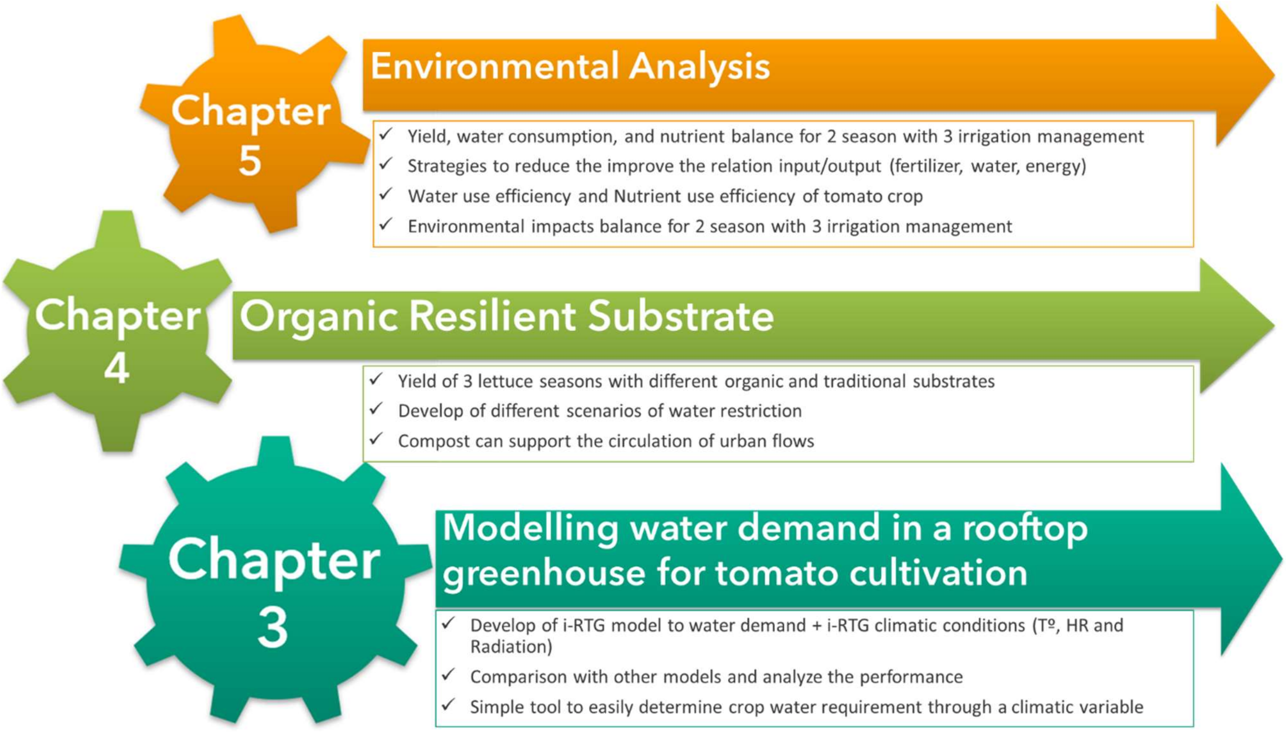
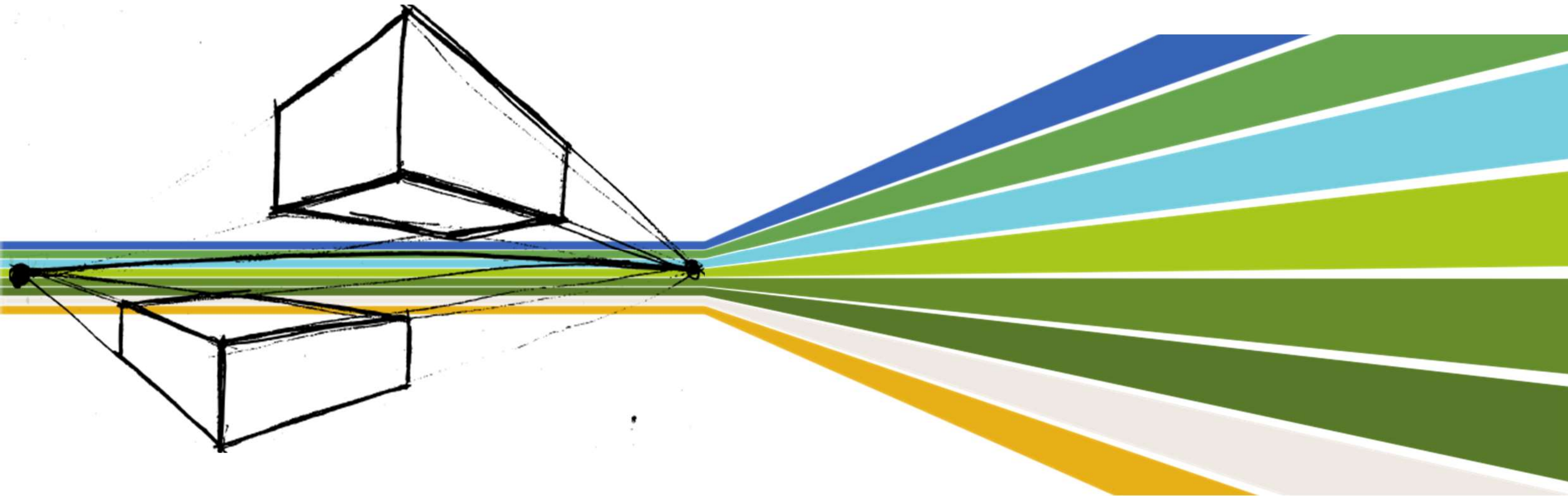


Figure 6.2 Summary of the major contribution of the dissertation.

As mentioned Rufí-Salís, (2020), the implementation of circular strategies has a major influence on the reduction of environmental impacts at UA level, amidst a water shortage and alarming population growth, cities are being overwhelmed by water. In order to meet the needs of the city, new alternatives must be sought. This dissertation develops the application of different circular strategies and their contribution to the development of inner-city food production (Figure 6.2). By efficient water management, it is possible to reduce environmental impacts. Through the development and implementation of a water demand model, it is possible to reduce water consumption by adjusting it to the optimal crop needs, reducing water transport and consumption. In addition, the use of solid organic municipal waste allows the production of compost as a part of the substrate matrix in the UA. It is resistant to water scarcity, keeping production under conditions of water shortages or water stress. Finally, the environmental evaluation of different irrigation management systems showed that the use of recirculating systems improves the environmental performance of food production in UA. It also showed how environmental impacts can be reduced.

Part V

Conclusions and Further Research



Chapter 7.

Conclusion and Further Research

Chapter 7

This chapter show the major conclusion obtained and the answer of the research questions proposed at the beginning of this dissertation. Additionally, ideas about where further research is needed are presented: all within a framework of a circular economy and associated with the development of food production within the city, highlighting how to improve water cycles through different ways, such as water management, waste recycling, and new technologies to be implemented.

7. Conclusions

Water scarcity in urban areas, coupled with population, is an alarming concern. It is essential to look for new alternatives that respond to the water demands of the city as it promotes UA. This dissertation provide integral solutions, which allow food production, improving productive efficiency (reduction of inputs and food losses). Using crop water management to reduce the environmental impact of UA is the main objective of this dissertation. Through three research lines, first by using the i-RTG climate data in three tomato campaigns, develop a water demand model. Second, a study was undertaken to determine lettuce's hydric resistance using organic substrates commonly used in UA. And finally, a study the environmental impact of tomato cultivation, comparing different water management approaches, using a life cycle approach.

Question 1: In order to optimise the use of water, based on the climatic characteristics of a rooftop greenhouse, is it possible to develop a simple water demand model?

Based on the results presented in chapter 3, it is possible to build a reliable and replicable water demand model for hydroponic crops. Through the use of the temperature variables alone it is possible to predict the evapotranspiration. Through analysing the different climatic variables, temperature and radiation are the most important for modelling water demand within an i-RTG. Additionally, in comparison with other models from the literature, the proposed model presented an acceptable performance in relation to Penman-Monteith (one of the most widely used) between 2 and 5 mm of demand (being close to 75% of the time in this range). It is noteworthy that above 27 degrees Celsius the variation increases, so the accuracy of the proposed model decreases. In this sense, it is important to highlight the need to generate more information in this area, in order to improve the accuracy of the calculations and reduce the variability of the response.

Question 2: In a circular economy context, is it possible to maintain yields through the use of organic substrates from the city under water deficit management?

As shown in chapter 4, the use of organic substrates maintained and improved lettuce yields, in contrast to perlite under conditions of water restriction. In this sense, the use of organic waste for compost production is an alternative to improve the circularity of the city. Compared to the control, it does not show a statistically significant reduction in yield, and under water stress conditions, it can maintain or even improve yields. In this sense, it is important to highlight that food production with organic substrates would allow productivity to be maintained in the event of water supply cuts. Similarly, it should be noted that the interaction of various city's sub-systems that produce organic matter would improve its sustainability. Through the compost production, as it would allow the closing of production cycles generating nutrient reuse and reduction of waste sent to landfill.

Question 3: It is possible to determine reductions of environmental impacts from a life cycle approach through a reduction on water management of tomato crops?

As shown in chapter 5, it is possible to see the different impacts associated with different irrigation management (open and recirculation). In this sense, it is worth noting that recirculation management obtained less nitrogen and phosphorus emissions to the environment, under the same irrigation conditions. However, there was a higher impact on ecotoxicity due to the origin of certain materials in the infrastructure phase, such as polycarbonate and steel, which made a high contribution. Within the use phase, equipment, in particular, aluminium was a major contributor.

Comparing the recirculating irrigation systems under traditional and restrictive management, it was possible to appreciate that there were no significant environmental differences between these two management systems, even though crop yields were different. The restrictive irrigation management had a slightly higher environmental impact than conventional management, despite using fewer inputs.

In agricultural terms, recirculation management with restriction approach, delivered the highest water-use efficiency (WUE), using 48.7 litters per kilogram of harvested tomato, followed by recirculated with conventional management (52.4 L kg^{-1}) and open management (75.2 L kg^{-1}). Into the recirculated systems, WUE improved by 7% through irrigation reduction compared with the conventional.

8. Further Research

Based on what has been exposed in this research, it is necessary to develop lines of research that support efficient water management in the context of circularity. In this sense, we can highlight 3 necessary lines of research.

8.1. Water demand modelling

The first is related to the estimation of water demand, where it is necessary to validate the proposed model in other UA conditions, in order to make more robust the models, obtaining accurate and reliable values. In the same way, implement new ways of modelling, such as machine and supervised learning. Under stable, production conditions, and under reliable flow measurement conditions, it is possible to make very accurate predictions. In this aspect it is important to emphasise the value of the crop coefficient or Kc, as it can be sources of error, because it is a value that is estimated or extracted from a table. It is recommended to be aware and informed about how to measure it, and to use it at the moment of irrigation.

At the same time, it is necessary to carry out trials under different typologies of UA in order to try to cover the whole range of productive alternatives at city level. In this sense, the focus should not be lost in the search for sustainable alternatives that contribute, on the one hand, to reducing the environmental impacts of food production and, on the other hand, to connecting the different productive subsystems of the city. This favours the circularity of the city, closing internal cycles, reducing the macro-entry of nutrients into the UA.

8.2.Improvements in circularity

In terms of circularity, it is necessary to develop an interaction between all the subsystems of the city, and several examples of sites that can be a constant source of organic matter are mentioned in Chapter 4. In this way, stable production can be achieved over time, in general, the more components a system has, the more stable it will be. In this regard, the challenge is, on the one hand, to collect organic matter and process it so that it can be used in UA, achieving the recycling of nutrients, and closing part of the nutrient cycles. On the other hand, to seek a residue balance that optimises the quality of the compost and ensures a minimum of nutrients.

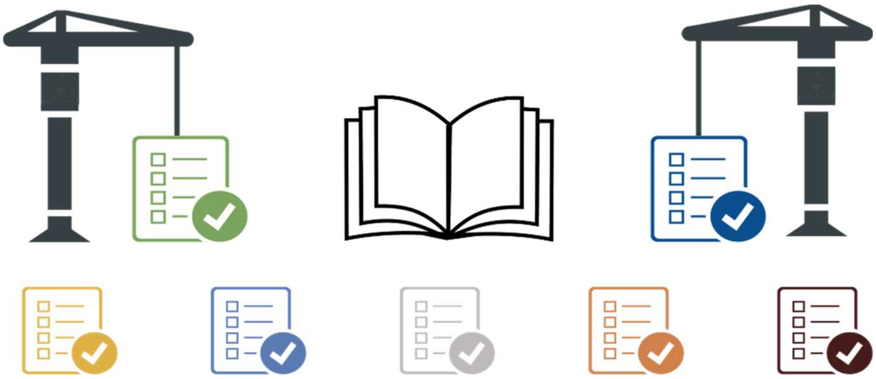
Along the same lines of improving circularity, the search for new sources of water at city level that allow stable production over time. In Mediterranean climates, where rainfall is concentrated in a specific period of the year, it is key to diversify the matrix of water sources. Studies should focus on how to improve the recirculation of effluent from houses and buildings.

Finally, there are still challenges to solve, such as the level of ecotoxicity and global warming potential from some materials, as polycarbonate, steel and aluminium. these contribute most to the environmental burden, and there is a need to find clean materials that take into account the limitations in material performance (Maraveas, 2019). Future studies should focus on finding materials with similar properties to aluminium (weight, strength and durability) with a smaller environmental footprint.

8.3.Agricultural and environmental analysis

The city condition offers a wide range of typologies for food production. From the agricultural perspective, it is necessary to develop research in this new condition, in order to have yields and consumptions for future projections. In addition, it is not possible to lose the environmental vision, considering the question, what do we really need, to produce more or better? In this sense, the present dissertation contributes to a food production consistent with today's demands for cleaner and more socially and environmentally responsible production. The interaction of these two components is key to the development of UA.

Appendix



Appendix. Supplementary information of each Chapter.

9. General Appendix

9.1. Appendix - Chapter 3

Appendix 9.1-A Information collected, and the equipment used.

Years	**2018**	**2019**	**2020**
Items	**Model developing**		**Validation**
Irrigation flow	water flowmeter	water flowmeter	water flowmeter
Leachate flow	Sampling 3 trays	water flowmeter	water flowmeter
Leachate irrigated amount	-	water flowmeter	water flowmeter
System	Open	Close with recirculation	Close with recirculation
Number of Plants	171	90*	90

Appendix 9.1-B Concertation of fertilizers.

Fertilizers	**2018**	**2019**	**2020**
		[g·m^{-3}]	
H_2KPO_4	214	283	234
KNO_3	104	138	193
K_2SO_4	277	367	585
$Ca(NO_3)_2$	403	533	755
$CaCl_2$	100	133	202
$Mg(NO_3)_2$	134	178	223
Hortrilon	8	11	16
Sequestrene	8	11	16

Appendix 9.1-C Criterion to cured data modelling.

Criteria	Formula
Delete rows with low level of confidence	90% > [number of measured values / number of theoretical values (144)]*100
Remove external temperature extremes	[-20> Data used < 50 ºC]
Remove meaningless values of internal minimum temperature	[Data used > 0ºC]
Remove meaningless values for internal radiation	[Data used > 0.2 MJ]
Remove meaningless values for external radiation [<1 MJ] Delete meaningless values for transpiration	[Data used > 1 MJ]
Remove meaningless values for Transpiration - ETc	[1mm day^{-1}> Data used < 10mm day^{-1}]
Eliminate values from weekends where no monitoring was done.	-

Appendix 9.1-D Total evapotranspiration models developed.

Internal										External										Number of variables	Type	AIC	BIC	RMSE	Sigma	R2 adjusted
Temperature				Relative Humidity				Radiation	DPV	Temperature				Relative Humidity				Radiation	DPV							
Mean	Max	Min	AVG	Mean	Max	Min	AVG			Mean	Max	Min	AVG	Mean	Max	Min	AVG									
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	20	gam	663	775	0.26	0.75	0.71
x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	19	gam	663	775	0.26	0.65	0.71
x	x	x	x	x	x	x		x	x	x	x	x		x	x	x	x	x	x	18	gam	663	775	0.26	0.57	0.71
x	x	x		x	x	x		x	x	x	x	x		x	x	x	x	x	x	17	gam	663	775	0.26	0.52	0.71
x		x		x	x	x		x	x	x	x	x		x	x	x	x	x	x	16	gam	661	770	0.26	0.48	0.71
x				x	x	x		x	x	x	x	x		x	x	x	x	x	x	15	gam	660	763	0.26	0.45	0.71
x				x	x	x		x	x	x	x	x		x		x	x	x	x	14	gam	660	758	0.27	0.43	0.71
x				x	x	x		x	x	x		x		x		x	x	x	x	13	gam	659	753	0.27	0.41	0.71
x				x	x	x		x	x	x		x		x			x	x	x	12	gam	658	747	0.27	0.39	0.71
x				x	x	x		x	x	x		x		x			x	x		11	gam	659	740	0.27	0.38	0.70
x				x	x	x		x		x		x		x			x	x		10	gam	660	726	0.28	0.37	0.69
x				x	x	x		x		x		x					x	x		9	gam	659	722	0.28	0.36	0.69
x					x	x		x		x		x					x	x		8	gam	660	711	0.28	0.35	0.69
x					x	x		x									x	x		6	gam	680	741	0.29	0.34	0.65
x						x		x									x	x		5	gam	679	738	0.29	0.34	0.66
x								x									x	x		4	gam	681	714	0.31	0.34	0.65
x								x										x		3	gam	682	710	0.31	0.33	0.65
x								x												2	gam	691	718	0.32	0.33	0.60
x																				1	gam	707	723	0.34	0.34	0.55
x																		x		2	gam	688	726.62	0.31	0.33	0.61
x																				1	glm	693	717	0.32	0.33	0.58
x																				**1**	**glm**	**720**	**730**	**0.35**	**0.35**	**0.50**
x																				1	lm	763	773	1.52	1.53	0.47
x																				1	lm	763	773	1.52	1.53	0.47

Appendix 9.1-E Description of calculation of variables.

Location	Variable	Operation	Formula
Internal, External	Temperature, Relative Humidity	Mean	∑(lecture each 10 minutes in one day) / 144
		Max	Maximum 10 minutes lecture per day
		Min	Minimum 10 minutes lecture per day
		AVG	(Max + Min)/2
	Vapour Pressure Deficit (VPD)	Sum	∑(difference between the saturation (e_s) and actual vapour pressure (e_a) lecture each 10) [1]
	Radiation	Sum	∑(lecture of radiation each 10 minutes in one day)

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[1] Allen, R., Pereira, L., Raes, D., Smith, M., 2006. Crop evapotranspiration. Guidelines for the determination of crop water requirements. Irrigation and Drainage FAO. Y Drenaje No 56.

9.2.Appendix - Chapter 4

Appendix 9.2-A Substrate physical properties analytical methodology.

This section provides a description of the methodology used to determine substrate physical properties. These include water content, water content at different tensions (pF curve), real and dry bulk density.

Water tension at different tensions: Hydric curve (pF curve).

The water content was determined through the methodology described by De Boodt et al., (1974) Where the samples were massed at different tensions within a sand bed. With the information provided, Figure A (Hydric curve or pF curve) and numerical information in Table B.

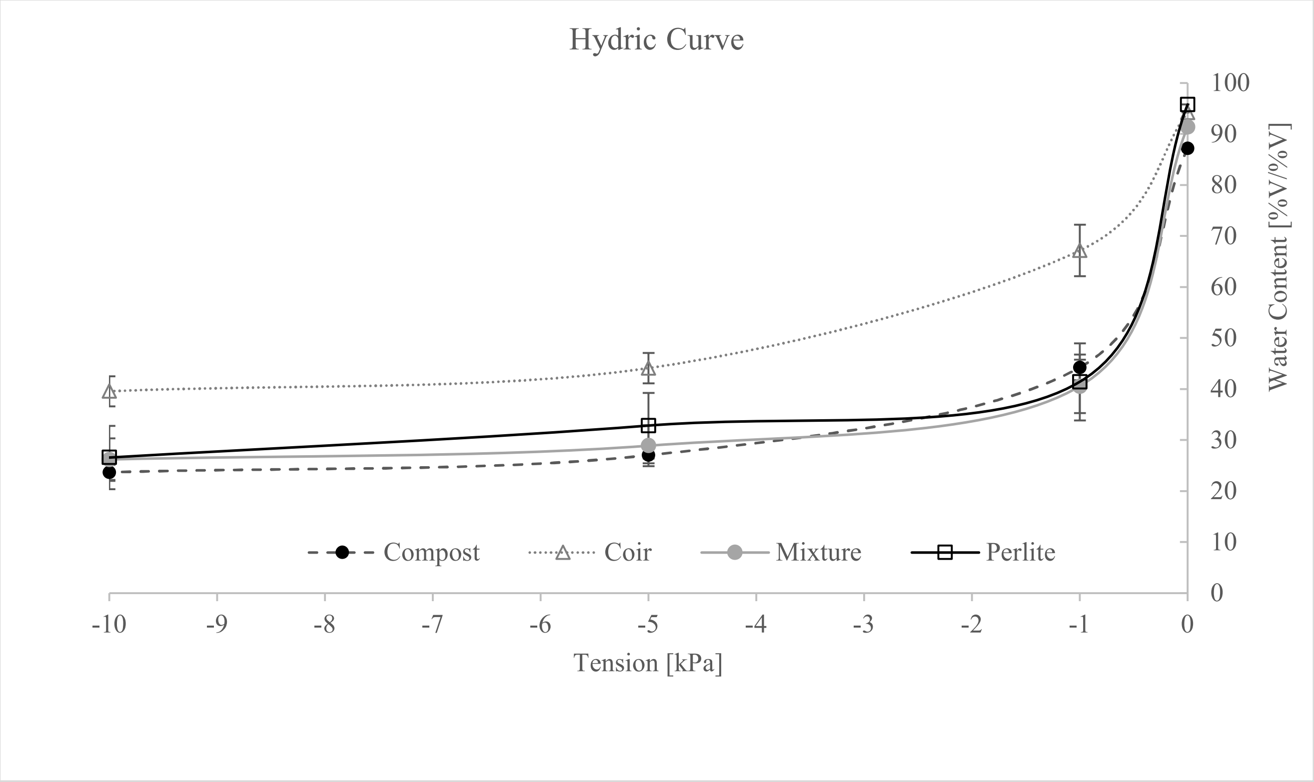

Figure A. Hydric curve of the evaluated substrates. (compost, coir, mixture, perlite)

Table B. Water content to different tensions of the substrate evaluated.

	Water Content [%V/%V]				
	0	**-1**	**-5**	**-10**	**EAW**
Substrate		**[kPa]**			**[kPa]**
Compost	87,16	44,27	27,04	23,69	17,23
Coir	94,25	67,19	44,12	39,59	23,07
Mixture	91,40	40,54	28,92	26,21	11,63
Perlite	95,81	41,43	32,84	26,60	8,60

EAW: Easily Available Water (water content value between tension -1 and -5 [kPa])

Determination of bulk density (ρ_b) and water content (WC)

For the bulk density and water content determined the samples were taken using the cylinder method (or ring method), to be later processed in the laboratory (USDA et al., 2001).

The wet net weight of each sample was measured (without considering the cylinder), subsequently, all the samples were left in an oven until they reached constant weight.

Then water content was calculated with Equation 9.2

$$\boldsymbol{WC}\left[\frac{\boldsymbol{Water_{Vol}}}{\boldsymbol{Soil}_{\boldsymbol{Vol}}}\right] = \frac{\boldsymbol{Weigth\ Substrate\ sample\ wet} - \boldsymbol{Weigth\ Substrate\ sample\ dry}}{\boldsymbol{Weigth\ Substrate\ sample\ dry}} * \boldsymbol{Bulk\ density}^{-1} \quad \text{(Eq. 9.1)}$$

To calculate the bulk density, the value of the dry substrate was used and divided by the volume of the cylinder used.

Determination of total organic matter (TOM) and mineral fraction (MF)

To determine the Total Organic Matter content of each substrate, the weight loss due to combustion of organic matter was used (López Martínez et al., 2009). The results it is possible appreciate in the Table C:

Table C: Total Organic Matter (TOM) and Mineral Fraction (MF) of each substrate.

	TOM	**MF**	**Dr**
Sample	**Mean [%]**	**Mean [%]**	**Mean [kg m^{-3}]**
Compost	57.89	42.11	1.79
Coir	83.90	16.10	1.56
Mixture	41.18	58.82	1.98
Perlite	1.11	98.89	2.63

For the determination of the Total porosity the Equation 8.3 was used. This concept is understood as the space that related bulk density and the real density:

$$\boldsymbol{\varepsilon = 1 - \frac{\rho_b}{\rho_r}} \qquad \text{(Eq. 9.2)}$$

Where ε is the total porosity, ρ_b and ρ_r is the bulk density and real density, respectively.

9.3. Appendix - Chapter 5

Appendix 9.3-A Environmental impacts calculated for Open System, Recirculated Control System, and Recirculated Reduction System per functional unit.

* Negative value represents an increasing of emissions.

Impact Categories		**OP**			**RC**			**RR**		
		Operation	Infrastructure	Total	Operation	Infrastructure	Total	Operation	Infrastructure	Total
GW	kg CO2 eq.	3.80E-01	4.82E-01	8.62E-01	3.34E-01	4.30E-01	7.64E-01	3.23E-01	4.55E-01	7.78E-01
TA	kg SO2 eq.	2.51E-03	1.70E-03	4.20E-03	2.18E-03	1.52E-03	3.71E-03	2.11E-03	1.62E-03	3.72E-03
FE	kg P eq.	3.56E-04	1.45E-04	5.01E-04	1.45E-04	1.35E-04	2.80E-04	1.39E-04	1.44E-04	2.83E-04
ME	kg N eq.	5.65E-04	4.22E-05	6.08E-04	9.07E-06	3.63E-05	4.54E-05	8.80E-06	3.79E-05	4.67E-05
FRS	kg oil eq.	7.83E-02	1.41E-01	2.19E-01	6.91E-02	1.27E-01	1.96E-01	6.72E-02	1.34E-01	2.01E-01
ET	kg 1 4-DB eq.	1.23E+00	1.52E+00	2.75E+00	1.21E+00	1.52E+00	2.73E+00	1.17E+00	1.62E+00	2.79E+00
CED	MJ	4.90E+00	7.99E+00	1.29E+01	4.20E+00	7.19E+00	1.14E+01	4.06E+00	7.61E+00	1.17E+01
		1- RC/OP			**1-RR/OP**			**1-RR/RC**		
		Operation	Infrastructure	Total	Operation	Infrastructure	Total	Operation	Infrastructure	Total
GW	kg CO2 eq.	12.0%	10.8%	11.4%	15.0%	5.6%	9.7%	3.3%	-5.9%	-1.8%
TA	kg SO2 eq.	12.9%	10.1%	11.8%	15.9%	4.7%	11.4%	3.5%	-6.0%	-0.4%
FE	kg P eq.	59.3%	6.9%	44.1%	60.8%	1.1%	43.5%	3.8%	-6.2%	-1.1%
ME	kg N eq.	98.4%	14.0%	92.5%	98.4%	10.2%	92.3%	3.1%	-4.4%	-2.9%
FRS	kg oil eq.	11.7%	10.0%	10.6%	14.2%	4.7%	8.1%	2.8%	-5.9%	-2.8%
ET	kg 1 4-DB eq.	1.7%	0.2%	0.8%	4.9%	-6.6%	-1.5%	3.3%	-6.8%	-2.3%
CED	MJ	14.4%	10.1%	11.7%	17.1%	4.8%	9.4%	3.1%	-5.9%	-2.6%

In Appendix B, the environmental impact categories are represented, highlighting the effect of the fertilizers in FE and ME in the OP, product of the Nitrogen and Phosphorus emissions. The items that contribute the most within these impact categories are Auxiliary equipment, Fertilizers Greenhouse structure, Rainwater harvesting system, and Composting, the last only in RC and RR.

Appendix 9.3-B Results of the environmental impacts separated by infrastructure and operation stage.

Treatment	Impact Categories	Unit / kg tomato	Total	Auxiliary Equipment	Rainwater Harvesting System	Greenhouse Structure	Fertilizers	Nursery Plants	Pesticides	Substrate	Energy
				Infrastructure			Operation				
OP	CC	kg CO2 eq.	8.62E-01	1.52E-01	1.90E-01	1.40E-01	2.21E-01	4.24E-03	6.89E-04	1.49E-02	1.39E-01
	TA	kg SO2 eq.	4.20E-03	7.27E-04	5.63E-04	4.06E-04	1.39E-03	1.32E-05	8.41E-06	4.77E-05	1.05E-03
	FE	kg P eq.	5.01E-04	9.05E-05	3.18E-05	2.32E-05	2.95E-04	9.53E-07	1.37E-06	1.37E-06	5.72E-05
	ME	kg N eq.	6.08E-04	7.18E-06	3.36E-05	1.47E-06	5.61E-04	7.08E-08	9.18E-08	9.32E-08	4.30E-06
	FDP	kg oil eq.	2.19E-01	3.98E-02	5.91E-02	4.19E-02	3.38E-02	1.39E-03	4.10E-04	5.81E-03	3.69E-02
	ET	kg 1 4-DB eq.	2.75E+00	8.85E-01	1.21E-01	5.17E-01	1.01E+00	2.04E-02	3.22E-02	4.41E-02	1.22E-01
	CED	MJ	1.29E+01	2.50E+00	3.22E+00	2.27E+00	1.76E+00	6.87E-02	2.03E-02	2.87E-01	2.76E+00
RC	CC	kg CO2 eq.	7.64E-01	1.47E-01	1.58E-01	1.24E-01	2.11E-01	3.85E-03	3.80E-03	1.33E-02	1.02E-01
	TA	kg SO2 eq.	3.71E-03	6.95E-04	4.69E-04	3.61E-04	1.34E-03	1.20E-05	2.77E-05	4.25E-05	7.67E-04
	FE	kg P eq.	2.80E-04	8.83E-05	2.65E-05	2.06E-05	9.88E-05	8.65E-07	1.99E-06	1.22E-06	4.19E-05
	ME	kg N eq.	4.54E-05	7.02E-06	2.80E-05	1.31E-06	5.03E-06	6.42E-08	7.38E-07	8.30E-08	3.15E-06
	FDP	kg oil eq.	1.96E-01	4.01E-02	4.92E-02	3.73E-02	3.41E-02	1.26E-03	1.60E-03	5.17E-03	2.70E-02
	ET	kg 1 4-DB eq.	2.73E+00	9.60E-01	1.01E-01	4.60E-01	1.04E+00	1.85E-02	1.93E-02	3.92E-02	8.91E-02
	CED	MJ	1.14E+01	2.48E+00	2.69E+00	2.02E+00	1.77E+00	6.23E-02	8.16E-02	2.55E-01	2.02E+00
RR	CC	kg CO2 eq.	7.78E-01	1.58E-01	1.65E-01	1.33E-01	2.03E-01	4.11E-03	4.05E-03	1.42E-02	9.76E-02
	TA	kg SO2 eq.	3.72E-03	7.42E-04	4.89E-04	3.85E-04	1.29E-03	1.28E-05	2.95E-05	4.53E-05	7.33E-04
	FE	kg P eq.	2.83E-04	9.43E-05	2.76E-05	2.20E-05	9.49E-05	9.24E-07	2.13E-06	1.30E-06	4.01E-05
	ME	kg N eq.	4.67E-05	7.49E-06	2.90E-05	1.40E-06	4.83E-06	6.85E-08	7.88E-07	8.85E-08	3.02E-06
	FDP	kg oil eq.	2.01E-01	4.30E-02	5.13E-02	3.98E-02	3.28E-02	1.34E-03	1.71E-03	5.51E-03	2.58E-02
	ET	kg 1 4-DB eq.	2.79E+00	1.02E+00	1.08E-01	4.91E-01	1.00E+00	2.06E-02	2.06E-02	4.19E-02	8.52E-02
	CED	MJ	1.17E+01	2.66E+00	2.80E+00	2.15E+00	1.70E+00	6.65E-02	8.71E-02	2.72E-01	1.94E+00

Appendix 9.3-C Life Cycle Inventory of Infrastructure, and process used in Ecoinvent.

Item	OP	RC	RR	Unit	Comment
Infrastructure					
Auxiliary Equipment					
Material					
Aluminium alloy, metal matrix composite {RoW}| aluminium alloy production, Metallic Matrix Composite | Cut-off, S	8.80E+00	8.63E+00	8.63E+00	kg	Trays, Legs
Bronze {GLO}| market for | Cut-off, S	2.30E-03	3.07E-03	3.07E-03	kg	Manometers
Cast iron {GLO}| market for | Cut-off, S	7.65E-01	1.75E+00	1.75E+00	kg	Pumps, Flow meters
Electronics, for control units {GLO}| market for | Cut-off, S	1.50E-03	2.95E-03	2.95E-03	kg	Time Controller
Glycerine {Europe without Switzerland}| esterification of rape oil | Cut-off, S	2.09E-02	2.71E-02	2.71E-02	kg	Manometer
Inert filler {GLO}| sand to generic market for | Cut-off, S	0.00E+00	2.17E+00	2.17E+00	kg	Sand Filter
Polyethylene, HDPE, granulate, at plant/RER S	5.70E-02	9.39E-01	9.39E-01	kg	Sand Filter, Pipes, Joint, Pump
Polyethylene, high density, granulate {GLO}| market for | Cut-off, S	1.41E+00	2.26E+00	2.26E+00	kg	Water Tank, Leachates Tank, Flowmeters, Stopper
Polyethylene, low density, granulate {GLO}| market for | Cut-off, S	5.34E-01	5.24E-01	5.24E-01	kg	Distribution Pipe
Polypropylene, granulate {GLO}| market for | Cut-off, S	8.80E-02	8.63E-02	8.63E-02	kg	Dosatron
Polyvinylchloride, bulk polymerised {GLO}| market for | Cut-off, S	9.98E-01	9.79E-01	1.15E+00	kg	Drip Tube, Drip, Secondary Pipe, Gripping piece
Steel, low-alloyed {GLO}| market for | Cut-off, S	5.71E-02	6.83E-01	6.83E-01	kg	Pumps
Ultraviolet lamp {GLO}| market for | Cut-off, S	0.00E+00	1.00E+00	1.00E+00	u	Ultraviolet lamp
Processes					
Injection molding/RER S	2.45E+00	4.37E+00	4.37E+00	kg	
Metal working, average for metal product manufacturing {RER}| processing | Cut-off, S	9.78E+00	1.11E+01	1.11E+01	kg	
Transport, van <3.5t/RER S	7.17E+00	7.05E+00	7.05E+00	tkm	

Greenhouse Structure					
Material					
Aluminium, primary, ingot {IAI Area, Russia & RER w/o EU27 & EFTA}∣ aluminium production, primary, ingot ∣ Cut-off, S	5.40E-01	5.29E-01	5.29E-01	kg	Structural Aluminium
Concrete roof tile {GLO}∣ market for ∣ Cut-off, S	1.47E+01	1.44E+01	1.44E+01	kg	Concrete
Glass fibre reinforced plastic, polyester resin, hand lay-up {GLO}∣ market for ∣ Cut-off, S	5.40E-01	5.29E-01	5.29E-01	kg	Polyester
Polycarbonate {GLO}∣ market for ∣ Cut-off, S	1.11E+01	1.08E+01	1.08E+01	kg	Polycarbonate Facade
Polyethylene, low density, granulate {GLO}∣ market for ∣ Cut-off, S	5.40E+00	5.29E+00	5.29E+00	kg	LDPE
Steel, low-alloyed {RER}∣ steel production, electric, low-alloyed ∣ Cut-off, S	5.78E+01	5.67E+01	5.67E+01	kg	Structural Steel
Processes					
Energy, from diesel burned in machinery/RER Energy	2.80E-02	2.70E-02	2.70E-02	kWh	
Transport, freight, sea, transoceanic ship {GLO}∣ market for ∣ Cut-off, S	1.11E+01	1.09E+01	1.09E+01	tkm	
Transport, lorry >32t, EURO5/RER S	1.92E+01	1.89E+01	1.89E+01	tkm	
Transport, lorry 16-32t, EURO5/RER S	3.18E+00	3.12E+00	3.12E+00	tkm	
Rainwater Harvesting System					
Material					
Cast iron {GLO}∣ market for ∣ Cut-off, S	2.90E-01	2.70E-01	2.60E-01	kg	Pumps
Glass fibre reinforced plastic, polyamide, injection molded {GLO}∣ market for ∣ Cut-off, S	1.78E+01	1.64E+01	1.59E+01	kg	Under Ground Water Tank
Polyethylene, HDPE, granulate, at plant/RER S	1.34E+00	1.23E+00	1.20E+00	kg	Pipes
Steel, chromium steel 18/8 {GLO}∣ market for ∣ Cut-off, S	3.00E-02	3.00E-02	3.00E-02	kg	Steel Pump
Processes					
Excavation, hydraulic digger {GLO}∣ market for ∣ Cut-off, S	4.40E-01	4.00E-01	5.70E-01	m3	Excavation
Injection molding/RER S	1.92E+01	1.76E+01	1.71E+01	kg	
Metal working, average for copper product manufacturing {RoW}∣ processing ∣ Cut-off, S	3.20E-01	3.00E-01	2.90E-01	kg	
Transport, lorry 3.5-7.5t, EURO5/RER S	1.17E+00	1.07E+00	1.52E+00	tkm	
Transport, lorry 7.5-16t, EURO3/RER S	2.14E+00	1.96E+00	2.78E+00	tkm	
Transport, van <3.5t/RER S	2.00E-01	1.80E-01	2.60E-01	tkm	

Pesticides					
Material					
Copper oxide {RER}∣ production ∣ Cut-off, S	1.70E-02	0.00E+00	0.00E+00	kg	Copper oxide
Pesticide, unspecified {GLO}∣ market for ∣ Cut-off, S	0.00E+00	2.35E-01	2.35E-01	kg	NeemAzal
Potassium sulphate, as K2O {GLO}∣ market for ∣ Cut-off, S	2.36E-01	7.57E-01	7.57E-01	kg	Potassium Soap
Sulfur {GLO}∣ market for ∣ Cut-off, S	3.43E-01	6.66E-01	6.66E-01	kg	Wettable Sulphur
Water, deionised, from tap water, at user {Europe without Switzerland}∣ market for water, deionised, from tap water, at user ∣ Cut-off, S	9.46E-01	3.03E+00	3.03E+00	kg	Water
Processes					
Transport, van <3.5t/RER S	1.08E-01	3.28E-01	3.28E-01	tkm	
Substrate					
Material					
Perlite {GLO}∣ market for ∣ Cut-off, S	3.76E+01	3.69E+01	3.69E+01	kg	Perlite
Polyethylene, high density, granulate {GLO}∣ market for ∣ Cut-off, S	9.90E-01	9.66E-01	9.66E-01	kg	Bag
Processes					
Transport, lorry 16-32t, EURO5/RER S	6.57E+01	6.44E+01	6.44E+01	tkm	
Nursery Plants					
Material					
Diesel {RoW}∣ market for ∣ Cut-off, S	2.91E-02	2.91E-02	2.91E-02	kg	
Processes					
Electricity, high voltage {ES}∣ market for ∣ Cut-off, S	1.95E-01	1.95E-01	1.95E-01	kWh	
Transport, passenger car, medium size, diesel, EURO 5 {GLO}∣ market for ∣ Cut-off, S	1.40E+01	1.40E+01	1.40E+01	km	

Appendix 9.3-D Life Cycle Inventory of Operation, and process used in Ecoinvent.

Item	**OP**	**RC**	**RR**	**Unit**	**Comment**
Operation					
Composting					
Material					
Compost {RoW}| treatment of biowaste, industrial composting | Cut-off, S	6.63E+02	4.06E+02	2.94E+02	kg	Compost biomass
Energy					
Processes					
Electricity, high voltage, production ES, at grid/ES S	2.72E+02	2.20E+02	1.97E+02	kWh	
Fertilizers					
Material					
Calcium chloride {RER}| market for calcium chloride | Cut-off, S	1.20E+01	7.78E+00	7.00E+00	kg	Calcium chloride
Calcium nitrate {GLO}| market for | Cut-off, S	2.42E+01	3.12E+01	2.81E+01	kg	Calcium nitrate
Copper oxide {GLO}| market for | Cut-off, S	3.76E-02	1.24E-01	1.12E-01	kg	Hortilon
Iron sulphate {RER}| market for iron sulphate | Cut-off, S	1.10E+00	9.92E-01	8.92E-01	kg	Hortilon, Sequestrene
Magnesium oxide {GLO}| market for | Cut-off, S	1.82E+01	1.06E+01	9.50E+00	kg	Magnesium oxide, Hortilon
Molybdenite {GLO}| market for | Cut-off, S	1.60E-02	1.32E-02	1.18E-02	kg	Hortilon
Phosphate fertiliser, as P2O5 {GLO}| market for | Cut-off, S	6.57E+00	9.98E+00	8.98E+00	kg	Potassium Phosphate
Potassium fertiliser, as K2O {GLO}| market for | Cut-off, S	4.32E+00	6.57E+00	5.91E+00	kg	Potassium Phosphate
Potassium nitrate {GLO}| market for | Cut-off, S	1.09E+01	8.07E+00	7.27E+00	kg	Potassium nitrate
Potassium sulphate, as K2O {GLO}| market for | Cut-off, S	1.99E+01	2.15E+01	1.93E+01	kg	Potassium sulphate
Zinc monosulfate {RER}| market for zinc monosulfate | Cut-off, S	1.89E-01	3.09E-02	2.78E-02	kg	Hortilon
Processes					
Transport, van <3.5t/RER S	6.81E+00	6.78E+00	6.15E+00	tkm	

Appendix 9.3-E Internal and external meteorological conditions, an average of these variables, into the crop season.

		Temperature [Cº]		Relative Humidity [%]		Vapor Pressure Deficit [kPa]		Radiation [MJ m^{-2} day^{-1}]	
		Internal	External	Internal	External	Internal	External	Internal	External
2019	Mean	20.7	15.1	52.0	68.1	1.3	0.7	9.0	20.8
	Max	25.7	25.4	67.3	72.5	1.5	1.3	11.1	27.0
	Min	16.4	7.1	41.6	59.6	1.1	0.3	6.1	13.7
2018	Mean	19.6	15.8	59.8	70.3	1.0	0.7	7.5	17.2
	Max	25.7	25.6	67.4	74.4	1.2	1.3	10.0	26.2
	Min	15.2	7.2	50.5	65.4	0.8	0.3	4.4	7.9

The mean was calculated as the mean of the monthly day mean. The maximum and minimum value is the monthly mean. The VPD was calculated following the methodology proposed by FAO (Allen et al., 2006), considering temperature means, and relative humidity means per each time interval recording by the data logger. The radiation in a monthly average of the total add value per day.

Appendix 9.3-F Yield variation as a function of radiation conditions.

Radiation is one of the most important variable to produce photosynthesis, affect directly at potential yield of a crop. For our work, determine to what degree yield varies due to radiation, it is important due to affect directly at the functional unit. We perform an analysis to show how radiation variability can affect the tomato crop yield based on an empirical equation proposed by Montero et al. (2017). The calculation is based on several factors: 1) The total external radiation during the growth period (TRGP) [MJ] which was obtained from a weather station (by data measured hourly) located 8 km from the study site (Ruralcat, 2019), The time period chosen was the Julian day 15 to 210 (corresponding approximately to the duration of the crop cycles analysed) of eleven consecutive years 2009 until 2019. During this period maximum and minimum radiation values obtained were 3,541 and 3,904 MJ respectively. Both values are applied to follow equation, so that we obtain a minimum and maximum yield range.; 2) Radiation Use Efficiency (RUE) is calculate as the relationship on the yield produced and the which for tomatoes is 8.77 g MJ^{-1} ;(Montero et al., 2017) and 3) Basal Radiation (BR), the minimum radiation requirement that the crop needs to produce tomatoes (defined as the intercept in the X-axis of the regression of RUE measured in different seasons). We use 1,600 MJ as BR (Montero et al., 2017) Equation 9.3.

$$Yield\ [kg\ m^{-2}] = \frac{(\mathbf{TRGP} - \mathbf{BR}) * \mathbf{RUE}}{\mathbf{1000}} \qquad \text{(Eq. 9.3)}$$

The result of the radiation model gave a maximum and minimum yield of 20.2 and 17.0 kg m^{-2}, respectively

Appendix 9.3-G Summary of information used to the model and water consumption estimations.

Scenario/ management	Radiation [MJ]	Yield estimated [Kg m^{-2}]	Water consumption estimated [m^3]	Yield Differential with RC	Water Differential with RC
Min	3541	17.0	71.3	-5%	20%
Max	3904	20.2	84.7	13%	42%
OP	3689				
RC	3888				

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