Air, food and soilless substrate quality assessment in rooftop agriculture

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Doctoral thesis

Supervisors: Dr. Pere Muñoz
Dr. J. Ignacio Montero (31/10/2017)
Dr. Joan Rieradevall i Pons (01/10/2017)

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Mireia Ercilla Montserrat

under the supervision of Dr. Joan Rieradevall until 1/10/2017, from the ICTA and the Department of Chemical Engineering at the UAB, Dr. J. Ignacio Montero until 31/10/2017, from the Environmental Horticulture Unit at the Institute of Agriculture and Food Research and Technology (IRTA), and Dr. P. Muñoz, from Department of Chemical, Biological and Environmental Engineering of the UAB

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En la vida ni se gana ni se pierde, ni se fracasa ni se triunfa. En la vida se aprende, se crece, se descubre; se escribe, borra y reescribe; se hila, se deshila y se vuelve a hilar.

Ana C Blum

Contents

Abbreviations

AOT40 – Accumulated Ozone exposure over a Threshold of 40 ppb

As – Arsenic

Cd – Cadmium

CO_2 – Carbon dioxide

FAO - Food and Agriculture Organization

ICP – Catalan Institute of Paleontology

ICP-MS – Inductively Coupled Plasma Mass Spectrometry

ICTA – Environmental Science and Technology Institute

i-RTG – Integrated Rooftop Greenhouse

i-RTG-Lab – Integrated Rooftop Greenhouse Laboratory

LCA – (Environmental) Life Cycle Assessment

Ni – Nickel

NO_2 – Nitrous Oxide

OFMSW – organic fraction of the municipal solid waste

Pb – Lead

RA – Rooftop Agriculture

RTG – Rooftop Greenhouse

SCS – Soilless Culture System

SO_2 – Sulfur Dioxide

UA – Urban Agriculture

List of figures

List of tables

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Summary

Urban agriculture (UA), particularly rooftop urban agriculture (RA), has increased in the last few years to satisfy the growing demand for local food production in cities. Previous research has demonstrated the technical viability and quantified the environmental impacts of producing food on rooftops, both in and outside greenhouses. However, no in-depth research has been carried out yet on the key aspect of food quality, which cuts right across the environment, the system and the final product, in this case the food. Moreover, perception of quality is also one of the main elements taken into account by customers in guiding their purchasing decisions and determines the viability of commercial UA projects

Air quality in urban areas is one of the issues generating most doubts when it comes to growing food in cities. In general, heavy metal pollution is one of the most pressing concerns in the deliberation about food security and food safety in Europe. Additionally, in the case of UA, crops are often very close to roads with heavy traffic and with a high atmospheric pollution risk. Another relevant concern about air quality specific to protected crops is the biological air quality inside greenhouses. The concentration levels of pollen and fungus spores suspended in the air can affect people who regularly work in the greenhouse and it is not known how this plays in an urban context. It is also unknown what happens in greenhouses integrated into buildings, both because of the potential impact on agricultural workers and also due to the impact on the users of the building - if a recirculation of air from the greenhouse was carried out for energy use. High water consumption of gardens in Mediterranean cities, where water is a scarce resource especially in the current climate change context, is also controversy among the different UA stakeholders. Therefore, innovative strategies are needed to reduce water consumption and provide resilience to the system in case of drought. At the same time, there is a demand to promote UA in the context of circular cities, using materials near the place of consumption, which helps reduce the environmental impacts of food production. The use of perlite as a substrate is one of the most criticized elements detected, as possible consumers perceive it as not very sustainable. That is why it is of great interest to study the use of vegetal waste from the city as alternative substrates that could promote the resilience to hydric stress.

The three aspects mentioned above (biological air quality, potential heavy metal contamination and high demand of water in a climate change context) lead possible promoters of UA to have doubts about customers' perception and acceptance of this type of agriculture and the food it produces. In addition, it should be taken into account that any kind of innovation in its early stage of implementation has a potential rejection by general public (Specht et al., 2016a). For these reasons, it was also considered essential to do a systematic study of possible consumers' perceptions of RA and the products obtained from it.

This doctoral thesis aims to fill these gaps by addressing the following research questions:

> Question 1: Does atmospheric heavy metal pollution in cities contaminate soilless crops from RA and RTGs?
>
> Question 2: Are the biological air conditions in RTGs adequate to provide safe working environments? And in the case of i-RTGS, can its air be recirculated while ensuring safe environment for building users?
>
> Question 3: Are we using adequate substrates for urban agriculture to mitigate the effects of climate change and increase resilience to drought?
>
> Question 4: What is the consumer's perception of RA and products grown in these systems?

With the aim of answering these questions, different approaches were used that come from different fields – biology, agronomy, chemistry and social studies. In addition, in all cases the studies have been based on experimental fieldwork and in those cases where the sampling point was relevant for the study, the experimental work was carried out in different types of AR (urban vs peri-urban, open-air vs greenhouse, courtyard (low altitude) vs building rooftop (high altitude).

High-volume sensors were used to assess heavy metal air contamination to sample air quality in the different points. At the same time, heavy metal content (Ni, As, Cd and Pb) of these samples and heavy metal concentrations in lettuce leaves were analyzed by inductively coupled plasma mass spectrometry (ICP-MS). Main results demonstrate that the air quality in Barcelona and its surroundings is not a limiting factor for the development of UA, although the chosen sampling locations were close to high-density roads. Heavy metal concentration in lettuce leaves was also below the EU-legislated limit in all studied cases and most of the heavy metals analyzed were below the detectable analytic values. Moreover, soilless systems (as an alternative to soil agriculture and where soil could be a polluting vector) can avoid introducing heavy metals into crops because it is possible to guarantee non-contaminated substrates and other system inputs.

The second research question about aerobiological air quality inside and outside rooftop greenhouses has been studied in collaboration with the aerobiology center AEROBIOTA. The research group has contributed to the identification of allergenic particles following the standard method in Spanish Aerobiology Network (Galán et al., 2014). Samples were obtained using volumetric suction pollen-spore traps based on the impact principle. The results evidence high levels of pollen grains and fungal spores inside the RTG with significant seasonal variations (4,924 pollen grains/m^3 were observed during 47 days and 295,038 fungal spores/m^3 during 5 months). The most important source of these particles was the outdoor environment and fungal spores have a much higher penetration efficiency compared with pollen grains. Solanaceae pollen and several allergenic fungal spore taxa largely originated inside the greenhouses or were able to colonize the indoor environment. Information on the qualitative and quantitative prevalence of airborne pollen grains and fungal spores is an important tool in the management of occupational allergic disorders in workers employed in the i-RTG and users of the building. Agricultural management tasks, such as pollination by hand, fungal treatments and sweeps (cleaning of space), increased the exposure to these particles. This highlights the need to establish internationally accepted occupational exposure limits for airborne fungi concentrations in greenhouses and in buildings to protect workers. Finally, it is possible to recirculate the air of the i-RTG to the building without posing health risks due to allergies to the building users if the biological air quality is monitored and the corresponding preventive measures are taken - interrupting recirculation during critical moments such as management tasks and removing the crop at the end of the season.

For the third research question the substrates used were: perlite, a standard commercial substrate; coir, an organic commercial substrate; vegetable compost from urban organic waste as local and sustainable material; and a mixture of this vegetable compost and perlite (1:1). The experiment involved 3 short crop cycles during the spring and summer periods of 2018 to observe all substrates during different meteorological conditions during the warmer periods of the year. With the aim of studying water stress resilience, during each crop cycle the substrates were tested under well irrigated and water stress conditions. Stress was applied by completely stopping irrigation until perlite bags reached -20 cbar. This situation simulated the water restrictions that could be applied during summer drought in Mediterranean cities as, UA is considered a green space and therefore, not a priority activity.

The results demonstrate that yields obtained with organic substrates well irrigated were almost equivalent to those obtained from perlite and greater than those obtained in open fields in the same area. Therefore, organic substrates are a recommended option from both an environmental and agronomic perspective. Moreover, compared to perlite, organic substrates increased resilience of crops to water stress. In the case of using coir, water stress effects were low until water tension reached -10. If water tension is higher, (until -20 cbar), compost and mixture presented higher yields.

Finally, perception of consumers was determined after the analysis of 238 surveys to potential consumers of a RTG that were distributed with the tomato samples from these facilities. Results show that perception is generally positive on both the product quality and the agronomic system. Indeed, consumers with more knowledge and interaction with UA projects had a more positive perception. Results suggest that some of the consumers' concerns could be overcame if they were better informed and could know by themselves the projects where RA food come from, as well as the characteristics, advantages and disadvantages of conventional production systems.

This dissertation contributes to a better understanding of the quality of RA and the products grown in different facilities. The social perception study made it possible to detect that most of the consumers' concerns have been addressed in this thesis. In a single document, useful tools are provided for UA promoters where the quality of the AR, quantifiable in different parameters and perceived by the consumer, are collected and evaluated together.

Future research might focus on assessing other pollutants that are in the atmosphere and whose behavior has not yet been detailed (AOT_{40}, SO_2, NO_2, and acid rain). Also, deepening the effects of heavy metal contamination on long cycle crops. In addition, this thesis provides different strategies to adapt rooftop agronomic production in the context climate change in cities. It is interesting to continue with the study of compost use as a substrate, improving its characteristics. This study could be complemented with research of other materials to replace perlite, applying circular economy strategies in cities. Finally, the results of this thesis along with other studies on food quality could be grouped to define a quality identifier that distinguishes those high quality products focusing on good practices of RA and quality health care.

Resum

L'agricultura urbana (AU), especialment en les cobertes (RA), és una pràctica cada vegada més implementada per a complementar la creixent demanda de producció local d'aliments a les ciutats. Diversos treballs de recerca han demostrat la viabilitat tècnica d'aquest tipus d'agricultura i han quantificat els seus impactes ambientals, tant si es desenvolupa en cobertes d'edificis a l'aire lliure com a l'interior d'hivernacles (RTG). No obstant això, encara no s'ha dut a terme una recerca profunda sobre la qualitat dels sistema productiu en cobertes que afecta tant, a l'entorn, al propi sistema on es cultiva, com al producte final obtingut, en aquest cas, l'aliment. A més, la percepció de la qualitat és un dels principals elements que els consumidors tenen en compte per orientar les seves decisions de compra i determina la viabilitat comercial dels projectes d'AU.

La qualitat de l'aire en les zones urbanes és un dels aspectes que generen més dubtes respecte cultivar aliments a les ciutats. En general, la contaminació per metalls pesats és un dels temes centrals en el debat sobre la seguretat alimentària. A més, en el cas de la AU, els cultius solen estar pròxims a zones d'alta densitat de trànsit amb un elevat potencial de contaminació atmosfèrica. Una altra preocupació rellevant sobre la qualitat de l'aire específica dels cultius protegits, és la qualitat aerobiológica dins dels hivernacles. El nivell de concentració de pol·len i espores de fongs suspesos en l'aire pot afectar les persones que treballen regularment en un hivernacle i es desconeix quina és la situació dels hivernacles situats en el context urbà. A més es desconeix què succeeix en els hivernacles integrats en edificis tant pel potencial impacte en els treballadors agrícoles com per l'impacte en els usuaris de l'edifici –si es realitzés una recirculació d'aire de l'hivernacle per objectius d'aprofitament energètic-. L'alt consum d'aigua dels horts de les ciutats mediterrànies, on l'aigua és un recurs escàs especialment en el context actual de canvi climàtic, també és motiu de controvèrsia entre els diferents actors relacionats amb la AU. Per això es necessita d'estratègies que permetin disminuir el seu consum i aportar resiliència al sistema en cas de sequera. Al mateix temps, existeix una demanda per a promoure la AU en el context de les ciutats circulars aprofitant residus verds pròxims al lloc del cultiu, la qual cosa ajuda a reduir els impactes ambientals de la producció d'aliments. L'ús de perlita com a substrat és un dels elements més criticats, ja que els consumidors la perceben com a poc sostenible. Per això, és de gran interès estudiar l'ús de residus vegetals de la ciutat com a substrats alternatius a la perlita que poden promoure la resiliència a l'estrès hídric.

Els aspectes esmentats anteriorment (potencial contaminació per metalls pesats, qualitat biològica de l'aire i alta demanda d'aigua en un context de canvi climàtic) porten als possibles promotors de la AU a tenir dubtes sobre la percepció i acceptació dels consumidors d'aquest tipus d'agricultura i els aliments produïts. A més, s'ha de tenir en compte que qualsevol tipus d'innovació en l'etapa inicial d'implementació té un potencial rebuig per part del públic.. Per aquestes raons, cal realitzar un estudi sistemàtic de les possibles percepcions dels consumidors sobre la RA i els productes que s'obtenen d'ella.

La present tesi doctoral aborda aquest àmbit d'estudi intentant donar resposta a les següents preguntes:

- Quina és la potencial contaminació de metalls pesants en els cultius sense sòl de l'agricultura urbana en coberta a l'aire lliure o en hivernacles deguda a la contaminació atmosfèrica de les ciutats?

- Les condicions biològiques de l'aire en els hivernacles en coberta són adequades per a proporcionar entorns de treball segurs? I en el cas dels hivernacles integrats, es pot recircular el seu aire residual amb finalitats d'aprofitament energètic al mateix temps que es garanteix un entorn segur de qualitat biològica per als usuaris de l'edifici?

- Estem utilitzant substrats ambientalment adequats per a l'agricultura urbana sense sòl i capaces de mitigar els efectes del canvi climàtic fent-los resilients a la sequera?

- Quina és la percepció del consumidor de l'agricultura en coberta i els productes conreats en elles?

Per a respondre a aquestes qüestions es van utilitzar diferents aproximacions que provenen de diverses disciplines com biologia, química, ciències socials i agronomia. A més, en tots els casos els estudis s'han basat en treball de camp experimental i en aquells casos on el punt de mostreig era rellevant per a l'estudi, el treball experimental es va realitzar en diferents tipologies de RA (urbà-periurbà, aire lliure-interior d'un hivernacle, pati (poca altitud)-coberta edifici (elevada altitud).

Per a l'estudi de la potencial contaminació atmosfèrica per metalls pesats (Ni, As, Cd i Pb) es van utilitzar captadors d'alt volum per a mostrejar la qualitat de l'aire en els diferents punts d'estudi. Alhora, el contingut de metalls pesats en aquestes mostres i en els cultius es va realitzar mitjançant Espectrometria de Masses amb Plasma Acoblat Inductivament (ICP-MS). Els resultats obtinguts permeten afirmar que la qualitat de l'aire a Barcelona i els seus voltants no és un factor limitant per al desenvolupament de la AU, malgrat que els punts de mostreig estaven prop de vies d'alta densitat de trànsit. Les concentracions de metalls pesats en l'enciam analitzat es van trobar per sota dels límits legislats per la UE en tots els casos i per a la majoria dels metalls estudiats les concentracions analitzades estaven fins i tot per sota del límit de detecció. A més, els sistemes sense sòl (com a alternativa a l'agricultura en sòl, on la terra és un dels vectors de contaminació) poden evitar la introducció de metalls pesats en els cultius perquè és possible garantir substrats no contaminats.

La segona qüestió sobre la qualitat aerobiològica en hivernacles en coberta ha estat estudiada en col·laboració amb el centre de aerobiologia AEROBIOTA research group que van contribuir en la identificació de les partícules al·lergògenes. En concret es va seguir el mètode estàndard de la Xarxa Espanyola de aerobiologia (Galán et al., 2014). Les mostres es van obtenir utilitzant mostrejadors basats en el principi de l'impacte per succió. Els resultats obtinguts van mostrar alts nivells de grans de pol·len i espores de fongs en l'aire de l'RTG amb variacions estacionals significatives (4,924 grans de pol·len en 47 dies i 295038 espores de fongs en 5 mesos). La font més important d'aquestes partícules és l'ambient exterior i la taxa de penetració a l'interior de l'hivernacle és superior en el cas de les espores de fongs que en el cas del pol·len. El pol·len de les solanáceas i diversos tàxons d'espores de fongs al·lergògenes probablement es van originar dins del RTG o van ser capaços de colonitzar l'ambient interior. Conèixer la prevalença qualitativa i quantitativa d'aquestes partícules en l'aire és una eina important en el maneig dels trastorns al·lèrgics ocupacionals en els treballadors i usuaris del RTG en el cas de recircular l'aire calent. Les tasques de maneig agrícola, com la pol·linització manual, els tractaments fúngics i els escombratges (neteja de l'espai), van augmentar l'exposició. Destaca la necessitat d'establir uns límits d'exposició acceptats internacionalment per la contaminació aerobiològica a l'interior d'hivernacles i edificis per protegir als treballadors. D'altra banda, si es prenen les mesures preventives corresponents –interrompre la recirculació en certs moments crítics com les tasques de maneig agrícola i la retirada del cultiu al final de la temporada- és adequat recircular l'aire calent residual de l'hivernacle en altres parts de l'edifici sense presentar riscos per a la salut dels usuaris.

En relació a la tercera pregunta els substrats utilitzats van ser: perlita, com a substrat comercial estàndard; fibra de coco, com a substrat comercial orgànic; compost vegetal a partir de residus orgànics urbans com a material sostenible de proximitat; i una mescla d'aquest compost vegetal i perlita (1: 1). L'experiment va involucrar 3 cicles de cultius curts durant els períodes de primavera i estiu de 2018 amb l'objectiu d'avaluar els substrats durant diferents condicions meteorològiques en l'època més càlida de l'any. Per a estudiar la seva resiliència a l'estrès hídric en cada cicle de cultiu els substrats es van provar en condicions de reg òptim i estrès hídric. Aquest estrès hídric va ser induït mitjançant un tall de l'aigua de reg que es va mantenir fins que la tensió hídrica de la perlita va assolir -20cb. Aquesta situació simulava els talls de reg que podrien donar-se en el context de sequera d'estiu que assolen les ciutats mediterrànies i on la AU es considera una activitat de jardineria (i per tant una activitat no prioritària). Els resultats indiquen que els rendiments obtinguts amb substrats orgànics són equivalents als obtinguts en perlita i majors que els obtinguts en camps de la mateixa àrea (aproximadament 420 g planta^{-1}). Per tant, els substrats orgànics són una opció recomanada des d'una perspectiva ambiental i agronòmica. A més, en comparació amb la perlita, els substrats orgànics van augmentar la resiliència dels cultius a l'estrès hídric. En el cas de la fibra de coco els efectes de l'estrès hídric van ser molt lleus fins que assolir els -10cbar. Quan la tensió va ser superior (fins -20 cbar) el compost i la mescla van presentar majors produccions.

Finalment, la percepció dels consumidors es va determinar després de l'anàlisi de 238 enquestes realitzades a potencials consumidors d'un RTG que es van lliurar al mateix temps que una mostra de tomàquets provinents d'aquest sistema. En general la percepció dels consumidors sobre la RA és positiva, tant per a la qualitat del producte, com per al sistema de producció. A més, es va detectar que els consumidors amb més coneixement i interacció amb els projectes de RA tenen una millor percepció. Els resultats suggereixen que algunes de les reticències detectades entre els consumidors podrien sobreposar-se si s'informés millor i es coneguessin de primera mà els projectes d'on prové l'aliment, així com quines són les característiques, avantatges i desavantatges dels sistemes de producció majoritaris actuals.

Aquesta tesi contribueix a una millor comprensió sobre la qualitat de la AR i els productes cultivats en les diferents instal·lacions. L'estudi de percepció social va permetre detectar que la majoria de les preocupacions detectades en els consumidors han estat tractades en la present tesi. En un únic document s'aporten eines útils per a promotors de la UA on la qualitat de la RA, quantificable en diferents paràmetres i la percebuda pel consumidor, es recullen i s'avaluen en conjunt.

Es proposa per a futures recerques, ampliar els estudis de recerca sobre l'impacte de la contaminació de les ciutats en els cultius en coberta estudiant altres tipus de contaminants que es troben en la atmosfera i dels quals encara no s'ha detallat el seu comportament (AOT40, SO_2, NO_2, i pluja àcida) alhora que aprofundir en els efectes de la contaminació per metalls pesats en aliments amb un cicle de cultiu molt més llarg. A més, aquesta tesi proporciona diferents estratègies per a adaptar la producció agronòmica en el context de la RA a les ciutats. És interessant prosseguir amb l'estudi d'ús de compost com a substrat millorant les seves característiques. Aquest estudi podria ser complementat amb la cerca d'altres materials per a substituir la perlita aplicant estratègies de l'economia circular a les ciutats. Finalment, els resultats d'aquesta tesi juntament amb altres estudis en matèria de qualitat alimentària podrien agrupar-se per a definir un identificador de qualitat alimentària que posés en relleu aquells productes d'alta qualitat, intrínseca, però també associada al sistema de producció i atenent a criteris de sostenibilitat.

Resumen

La agricultura urbana (AU), especialmente en las cubiertas (AR), es una práctica cada vez más implementada para complementar la creciente demanda de producción local de alimentos en las ciudades. Diversos trabajos de investigación han demostrado la viabilidad técnica de este tipo de agricultura y han cuantificado sus impactos ambientales, tanto si se desarrolla en cubiertas de edificios al aire libre como en el interior de invernaderos (RTG). Sin embargo, aún no se ha llevado a cabo una investigación profunda sobre la calidad del sistema productivo en cubiertas que afecta tanto, al entorno, al propio sistema en donde se cultiva, como al producto final obtenido, en este caso, el alimento. Además, la percepción de la calidad es uno de los principales elementos que los consumidores tienen en cuenta para orientar sus decisiones de compra y determina la viabilidad de los proyectos comerciales de AU.

La calidad del aire en las zonas urbanas es uno de los aspectos que generan más dudas cuando se trata de cultivar alimentos en las ciudades. En general, la contaminación por metales pesados es uno de los temas principales en el debate sobre la seguridad alimentaria. Además, en el caso de la AU, los cultivos suelen estar próximos a zonas de alta densidad de tráfico con un alto potencial de contaminación atmosférica. Otra preocupación relevante sobre la calidad del aire específica de los cultivos protegidos es la calidad aerobiológica dentro de los invernaderos. El nivel de concentración de polen y esporas de hongos suspendidos en el aire puede afectar a las personas que trabajan regularmente en un invernadero y se desconoce cuál es la situación de los invernaderos situados en el contexto urbano. Además se desconoce qué ocurre en los invernaderos integrados en edificios tanto por el potencial impacto en los trabajadores agrícolas como por el impacto en los usuarios del edificio –si se realizara una recirculación de aire del invernadero por objetivos de aprovechamiento energético-. El alto consumo de agua de los huertos de las ciudades mediterráneas, donde el agua es un recurso escaso, también es motivo de controversia entre los distintos actores relacionados con la AU. Por ello se necesita de estrategias que permitan disminuir su consumo y aportar resiliencia al sistema en caso de sequía. Al mismo tiempo, existe una demanda para promover la AU en el contexto de las ciudades circulares aprovechando residuos cercanos al lugar del cultivo, lo que ayuda a reducir los impactos ambientales de la producción de alimentos. El uso de perlita como sustrato es uno de los elementos más criticados, ya que los consumidores lo perciben como poco sostenible. Por ello, es de gran interés estudiar el uso de residuos vegetales de la ciudad como sustratos alternativos a la perlita que podrían promover la resiliencia al estrés hídrico.

Los tres aspectos mencionados anteriormente (potencial contaminación por metales pesados, calidad biológica del aire y alta demanda de agua en un contexto de cambio climático) llevan a los posibles promotores de la AU a tener dudas sobre la percepción y aceptación entre los consumidores de este tipo de agricultura y los alimentos producidos. Además, se debe tener en cuenta que cualquier tipo de innovación en su etapa inicial de implementación tiene un potencial rechazo por parte del público en general. Por estas razones, debe realizarse un estudio sistemático de las posibles percepciones de los consumidores sobre la AR y los productos que se obtienen de ella.

La presente tesis doctoral aborda este ámbito de estudio intentando dar respuesta a las siguientes preguntas:

- ¿Cuál es la potencial contaminación de metales pesados en los cultivos sin suelo de la agricultura urbana en cubierta al aire libre o en invernaderos debida a la contaminación atmosférica de las ciudades?

- ¿Las condiciones biológicas del aire en los invernaderos en cubierta son adecuadas para proporcionar entornos de trabajo seguros? Y en el caso de los invernaderos integrados, ¿se puede recircular su aire residual con finalidades

aprovechamiento energético y al mismo tiempo garantizar un entorno seguro de calidad biológica para los usuarios del edificio?

- ¿Estamos utilizando sustratos ambientalmente adecuados para la agricultura urbana sin suelo y capaces de mitigar los efectos del cambio climático haciéndolos resilientes a la sequía?

- ¿Cuál es la percepción del consumidor de la agricultura en cubierta y los productos cultivados en ellas?

Para responder a estas cuestiones se utilizaron distintas aproximaciones que provienen de diversas disciplinas como biología, química, ciencias sociales y agronomía. Además, en todos los casos los estudios se han basado en trabajo de campo experimental y en aquellos casos donde el punto de muestreo era relevante para el estudio, el trabajo experimental se realizó en diferentes tipologías de AR (urbano-periurbano, aire libre-interior de un invernadero, patio (poca altitud)-cubierta edificio (elevada altitud).

Para el estudio de la potencial contaminación atmosférica por metales pesados (Ni, As, Cd y Pb) se utilizaron captadores de alto volumen para muestrear la calidad del aire en los distintos puntos de estudio. A la vez, el contenido de metales pesados en dichas muestras y en los cultivos se realizó mediante Espectrometría de Masas con Plasma Acoplado Inductivamente (ICP-MS). Los resultados obtenidos permiten afirmar que la calidad del aire en Barcelona y sus alrededores no es un factor limitante para el desarrollo de la AU, a pesar de que los puntos de muestreo estaban cerca de vías de alta densidad de tráfico. Las concentraciones de metales pesados en la lechuga analizada se encontraron por debajo de los límites legislados por la UE en todos los casos y para la mayoría de los metales estudiados las concentraciones analizadas estaban incluso por debajo del límite de detección. Además, los sistemas sin suelo (como alternativa a la agricultura en suelo, en donde la tierra es uno de los vectores de contaminación) pueden evitar la introducción de metales pesados en los cultivos porque es posible garantizar sustratos no contaminados.

La segunda cuestión sobre la calidad aerobiológica en invernaderos en cubierta ha sido estudiada en colaboración con el centro de aerobiología *AEROBIOTA research group* que contribuyeron en la identificación de las partículas alergénicas. En concreto se siguió el método estándar de la Red Española de aerobiología (Galán et al., 2014). Las muestras se obtuvieron utilizando muestreadores basados en el principio del impacto por succión. Los resultados obtenidos mostraron altos niveles de granos de polen y esporas de hongos en el aire del RTG con variaciones estacionales significativas (4,924 granos de polen en 47 días y 295038 esporas de hongos en 5 meses. La fuente más importante de estas partículas es el ambiente exterior y la tasa de penetración al interior del invernadero es superior en el caso de las esporas de hongos que en el caso del polen. El polen de las solanáceas y varios taxones de esporas de hongos alergénicas probablemente se originaron dentro del RTG o fueron capaces de colonizar el ambiente interior. Conocer la prevalencia cualitativa y cuantitativa de estas partículas en el aire es una herramienta importante en el manejo de los trastornos alérgicos ocupacionales en los trabajadores y usuarios del RTG en caso de recircular el aire caliente. Las tareas de manejo agrícola, como la polinización manual, los tratamientos fúngicos y los barridos (limpieza del espacio), aumentaron la exposición. Destaca la necesidad de establecer unos límites de exposición aceptados internacionalmente para la contaminación aerobiológica en el interior de invernaderos y edificios para proteger a los trabajadores. Por otra parte, si se toman las medidas preventivas correspondientes –interrumpir la recirculación en los momentos de tareas agrícolas o la retirada del cultivo al final de la temporada- es adecuado recircular el aire caliente residual del invernadero en otras partes del edificio sin presentar riesgos para la salud de los usuarios.

En relación a la tercera pregunta los sustratos utilizados fueron: perlita, como sustrato comercial estándar; fibra de coco, como sustrato comercial orgánico; compost vegetal a partir de residuos orgánicos urbanos como material sostenible de proximidad; y una mezcla de este compost vegetal y perlita (1: 1). El experimento involucró 3 ciclos de cultivos cortos durante los períodos de primavera y verano de 2018 con el objetivo de evaluar los sustratos durante diferentes condiciones meteorológicas en la época más cálida del año. Para estudiar su resiliencia al estrés hídrico en cada ciclo de cultivo los sustratos se probaron en condiciones de riego óptimo y estrés hídrico. Este estrés hídrico fue inducido mediante un corte del agua de riego que se mantuvo hasta que la tensión hídrica de la perlita alcanzó los -20cb. Esta situación simulaba los cortes de riego que podrían darse en contexto de sequía de verano que asolan las ciudades mediterráneas y en donde la AU se considera una actividad de jardinería (y por lo tanto una actividad no prioritaria). Los resultados indican que los rendimientos obtenidos con sustratos orgánicos son equivalentes a los obtenidos en perlita y mayores que los obtenidos en campos de la misma área (aproximadamente 420 g planta^{-1}). Por lo tanto, los sustratos orgánicos son una opción recomendada desde una perspectiva ambiental y agronómica. Además, en comparación con la perlita, los sustratos orgánicos aumentaron la resiliencia de los cultivos al estrés hídrico. En el caso de la fibra de coco los efectos del estrés hídrico son muy leves hasta que alcanzaron los -10cbar. Si la tensión es superior (hasta -20 cbar) el compost y la mezcla presentaron mayores producciones.

Finalmente, la percepción de los consumidores se determinó tras el análisis de 238 encuestas realizadas a potenciales consumidores de un RTG que se entregaron al mismo tiempo que una muestra de tomates provenientes de este sistema. En general la percepción de los consumidores sobre la RA es positiva, tanto para la calidad del producto, como para el sistema de producción. Además, se detectó que los consumidores con más conocimiento e interacción con los proyectos de RA tienen una mejor percepción. Los resultados sugieren que algunas de las reticencias detectadas entre los consumidores podrían sobreponerse si se informara mejor y pudieran conocer de primera mano los proyectos de donde proviene el alimento, así como cuáles son las características, ventajas y desventajas de los sistemas de producción mayoritarios actualmente.

Esta tesis contribuye a una mejor comprensión sobre la calidad de la AR y los productos cultivados en las diferentes instalaciones. El estudio de percepción social permitió detectar que la mayoría de las preocupaciones detectadas en los consumidores han sido tratadas en la presente tesis. En un único documento se aportan herramientas útiles para promotores de la UA en donde la calidad de la AR, cuantificable en distintos parámetros y la percibida por el consumidor, se recogen y se evalúan en conjunto.

Se propone para futuras investigaciones, ampliar los estudios de investigación sobre el impacto de la contaminación de las ciudades en los cultivos en cubierta estudiando otros tipos de contaminantes que se encuentran en la atmosfera y de los cuales aún no se ha detallado su comportamiento (AOT40, SO_2, NO_2, y lluvia ácida) a la vez que profundizar en los efectos de la contaminación por metales pesados en alimentos con un ciclo de cultivo mucho más largo. Además, esta tesis proporciona diferentes estrategias para adaptar la producción agronómica en el contexto de la AR en las ciudades. Es interesante proseguir con el estudio de uso de compost como sustrato mejorando sus características. Este estudio podría ser complementado con la búsqueda de otros materiales para sustituir la perlita aplicando estrategias de la economía circular en las ciudades. Por último, los resultados de esta tesis junto con otros estudios en materia de calidad alimentaria podrían agruparse para definir un identificador de calidad que pusiera de relieve aquellos productos de alta calidad, intrínseca, pero también asociada al sistema de producción y atendiendo a criterios de sostenibilidad

Preface

The present doctoral thesis was elaborated from March 2016 to February 2019 in compliance with the PhD program of Environmental Science and Technology of the Universitat Autònoma de Barcelona. Its development took place within the research group of Sustainability and Environmental Prevention (Sostenipra; 3.0 2017SGR 1683) at the Institute of Environmental Science and Technology of the Universitat Autònoma de Barcelona, which was awarded with María de Maeztu program for Units of Excellence in R&D (MDM-2015-0552). The thesis was supported by the pre-doctoral fellowship awarded by the Secretaria d'Universitats i Recerca del Departament d'Economia i Coneixement de la Generalitat de Catalunya (FI-DGR 2016) from March 2016 to February 2019.

This dissertation analyzes the quality of rooftop urban agriculture in a multidisciplinary approach. The quality is assessed studding both, the growing system during its operation phase taking into account the whole crop cycle and the environment of the crop, and also the aliments obtained. Previous studies in the Sostenipra Research group studied the technical, environmental and economic feasibility of implementing urban agriculture in the city's roofs in the framework of the Fertilecity I project (MINECO: CTM2013-47067-C2-1-R) "*Agrourban sustainability through rooftop greenhouses. Eco innovation on residual flows of energy, water and CO_2 for food production*". This project is coordinated by the Institute of Environmental Science and Technology (ICTA)-Universitat Autònoma de Barcelona .The results of this research were the background of this thesis where the main important quality issues were revealed and needed to be answered. The research on the quality parameters was conducted in the framework of Fertilecity II project (MINECO/FEDER, UE: CTM2016-75772-C3-1-R; CTM2016-75772-C3-3-R) "*Integrated rooftop greenhouses: energy, waste and CO_2 symbiosis with the building. Towards foods security in a circular economy*". This project is also coordinated by the Institute of Environmental Science and Technology (ICTA) - Universitat Autònoma de Barcelona and the Universitat Politècnica de Catalunya (UPC)

The potential food contamination is a key issue to be resolved to guarantee the health of consumers, and it affects both urban agriculture promoters and consumers. Moreover, with the aim to encourage the integration of urban agriculture in building in future smart cities, the quality of the facilities is a crucial issue for workers and building user's health. The novelty of the dissertation relies on the interdisciplinary approach adopted for the quality assessment and the scenario under study. This approach integrated multiple dimensions as agronomy, environmental science, chemistry and social science and allowed obtaining comprehensive results about the factors influencing the quality of UA products. The scenario of this dissertation is the urban agriculture developed in rooftops a solution to increases the space available to grow crops inside cities, with an especial focus in a research oriented integrated rooftop greenhouse (i-RTG)

Specifically, this dissertation is based on the following 4 articles either published or submitted in peer-reviewed index journals from the first quartile.

- Ercilla-Montserrat, M., Muñoz, P., Montero, J. I., Gabarrell, X., & Rieradevall, J. (2018). A study on air quality and heavy metals content of urban food produced in a Mediterranean city (Barcelona). Journal of Cleaner Production. http://doi.org/10.1016/j.jclepro.2018.05.183

- Ercilla-Montserrat, M., Izquierdo, R., Belmonte, J., Montero, J. I., Muñoz, P., De Linares, C., & Rieradevall, J. (2017). Building-integrated agriculture: A first assessment of aerobiological air quality in rooftop greenhouses (i-RTGs). Science of the Total Environment, 598, 109–120. http://doi.org/10.1016/j.scitotenv.2017.04.099

- Ercilla-Montserrat, M., Sanjuan-Delmás, D., Sanyé-Mengual, E., Calvet-Mir, L., Banderas, K., Rieradevall, J., Gabarrell, X. Ercilla-Montserrat, M., Sanjuan-Delmás, D., Sanyé-Mengual, E., Calvet-Mir, L., Banderas, K., Rieradevall, J., Gabarrell, X., 2019. Analysis of the consumer's perception of urban food products from a soilless system in rooftop greenhouses: a case study from the Mediterranean area of Barcelona (Spain). Agric. Human Values 1–19. http://doi:10.1007/s10460-019-09920-7

- Ercilla-Montserrat, M., Parada F., Arcas V., Lopez-Capel E., Carazo N., Montero J.I., Gabarrell, X., Rieradevall, J., Muñoz, P. Comparison of organic substrates in urban rooftop agriculture, a measure to improve crop production resilience to water stress in Mediterranean cities. Submitted to the journal Scientia Horticulturae.

Moreover, the following five poster and oral communications were presents in international congress and conferences of interest as part of the doctoral thesis:

- Ercilla-Montserrat, M., Llorach-Massana,P., Sanjuan-Delmás, D., Nadal, A., Rovira, M.R., Josa, A., Montero, J.I., Muñoz, P. Gabarrell, X., Rieradevall, J., (2016). Potential environmental and economic benefits from local food production in Mediterranean rooftop greenhouses. Oral presentation. 10th International Conference on Life Cycle Assessment of Food. October 2016. Dublin (Ireland).

- Ercilla-Montserrat, M., Barrell, X., Llorach-Massana,P., Nadal, A., Petit,A., Alabert, A., Casanovas, E., Cuerva, E., Planas,C., Pons, O., Josa, A., Montero, J.I., Muñoz, P., Villalba, G., Rovira, M.R., Puig, I., Cortés, F., Giampetro, M., Gassó, S., Zambrano, P., Rufí, M., Manríquez, A.M., Pomt, I., Rieradevall, J. (2017) Fertilecity II. Integrated rooftop greenhouses: symbiosis of energy, water and CO_2 emissions with the building – Towards urban food security in a circular economy. Poster. VI Jornada Ambiental [Universitat de Barcelona]. June 2017. Barcelona (Spain)

- Ercilla-Montserrat M., Izquierdo R., Belmonte J., De Linares, C., Montero, J., Muñoz P., Rieradevall J. Pollen dynamics in building-integrated rooftop greenhouse in urban areas. (2017). Oral presentation. International Symposium on greener cities. September 2017. Bologna (Italy)

- Ercilla-Montserrat M., Izquierdo R., Belmonte J., De Linares, C., Montero, J., Muñoz P., Rieradevall J. A first assessment of aerobiological air quality in rooftop greenhouses. (2017). Oral presentation. Mediterranean Palynology Symposium 2017. September 2017. Barcelona (Spain)

- Ercilla-Monserrat M., Parada F., Arcas V., Rufí M., Villalba G., Gabarrell X., Muñoz P. Substrate selection in urban agriculture, water holding capacity and resilience to water stress. (2019). Oral presentation. Greensys 2019 - International Symposium on Advanced Technologies and Management for Innovative Greenhouses. Angers (France)

Furthermore, additional training and knowledge was obtained through collaborations in other studies related with the goals of the dissertation.

Participation as a coauthor in five articles and one book chapters, either published or under review in peer-reviewed index journals

- Montero, J. I., Baeza, E., Heuvelink, E., Rieradevall, J., Muñoz, P., Ercilla, M., & Stanghellini, C. (2017). Productivity of a building-integrated roof top greenhouse in a

Mediterranean climate. Agricultural Systems, 158, 14–22. http://doi.org/10.1016/J.AGSY.2017.08.002

- Sanjuan-Delmás, D., Llorach-Massana, P., Nadal, A., Ercilla-Montserrat, M., Muñoz, P.,Montero, J. I.,… Rieradevall, J. (2018). Environmental assessment of an integrated rooftop greenhouse for food production in cities. Journal of Cleaner Production, 177, 326–337. http://doi.org/10.1016/J.JCLEPRO.2017.12.147

- Sanjuan-Delmás, D., Llorach-Massana, P., Nadal, A., Sanyé-Mengual, E., Petit-Boix, A., Ercilla- Montserrat, M., Cuerva, E., Rovira, M.R., Josa, A., Muñoz, P., Montero, J.I., Gabarrell, X., Rieradevall, J., Pons, O. (2018). Improving the Metabolism and Sustainability of Buildings and Cities Through Integrated Rooftop Greenhouses (i-RTG) (pp. 53–72). http://doi.org/10.1007/978-3-319-67017-1_3

- Sanjuan-Delmás, D., Llorach-Massana, P., Nadal, Ercilla- Montserrat, M., Muñoz, P., Montero, J.I., Josa, A., Gabarrell, X., Rieradevall, J. (2017). Water, energy, CO_2 and food symbiosis between crops and buildings. Environmental assessment of an integrated rooftop Green house. Journal of Cleaner Production (under review)

- Boneta, A., Rufí-Salís, M., Ercilla-Montserrat, M., Gabarrell, X., Rieradevall, J. (2018). Agronomic and environmental assessment of a polyculture rooftop soilless urban home garden in a Mediterranean city. - Plant Science, section Crop and Product Physiology (under review)

Participation as a coauthor in six congress and conferences

- Nadal, A., Ercilla-Montserrat, M., Cuerva, E., Cerón, I., Josa, A., Rieradevall, J. (2016) Improving energy efficiency of buildings metabolism and promoting local food production through integrated rooftop grenhouses (i-RTG). V Jornada ambiental, La solución al cambio global no es nomas una cuestión de tecnología. Universidad de Barcelona. May 2016. Barcelona, (Spain).

- Sanjuan-Delmás., Llorach-Masa, P., Sanyé-Mengual, E., Josa, A., Montero, j.I., Rieradevall, J., Gabarrell, X., Ercilla-Montserrat, M., Nadal,A., Muñoz,P., Rovira M.R,, Cuerva, E., Pons, O. (2016). The Fertilecity Project: Improving local food production in cities from an industrial ecology approach. Oral presentation. ISIE America's 2016.May 2016, Bogotá.

- Sanjuan-Delmás, D., Ercilla-Montserrat, M., Llorach-Massana, P., Nadal, A., Muñoz, P., Montero, J.I., Villalba, G., Rovira, M.R., Josa, A., Gabarrell, X., Rieradevall, J. (2017). Environmental assessment of hydroponic tomato crops in an urban Building integrated rooftop greenhouse using LCA. Poster. Agriculture and Climate Change. March 2017. Sitges (Spain).

- Sanjuan-Delmás, D., Ercilla-Montserrat, M., Muñoz, P., Rieradevall, J., Josa, A., Gabarrell, X. (2017) Phosphorous balance in hydroponic crops to enhance resource efficiency. Case study: tomato crops in a rooftop greenhouse. Poster. Agriculture and Climate Change. March 2017. Sitges (Spain).

- Rufí-Salís, M; Ercilla-Montserrat, M; Sanjuan-Delmás, D; Petit-Boix, A; Arcas, V; Parada, F; Toboso, S; Muñoz, J; Rovira, MR; Rieradevall, J; Villalba, G; Gabarrell, X. Intercropping, urban agriculture and circular economy. A first approach using Life Cycle Assessment to determine best annual crop combination. Oral presentation.

CILCA 2019 - Conferencia Internacional Análisis de Ciclo de Vida 2019 ACV para la Competitividad Global. Cartago (Costa Rica)

- Rufí-Salís, M; Sanjuan-Delmás, D; Ercilla-Montserrat, M; Josa, A; Montero, JI; Muñoz, P; Gabarrel, X; Rieradevall, J. Vertical Farming reduces environmental impacts of food in cities. Case Study of common bean crop. Oral presentation. CILCA 2017 - VII International Conference on Life Cycle Assessment in Latin America. Medellín (Colombia).

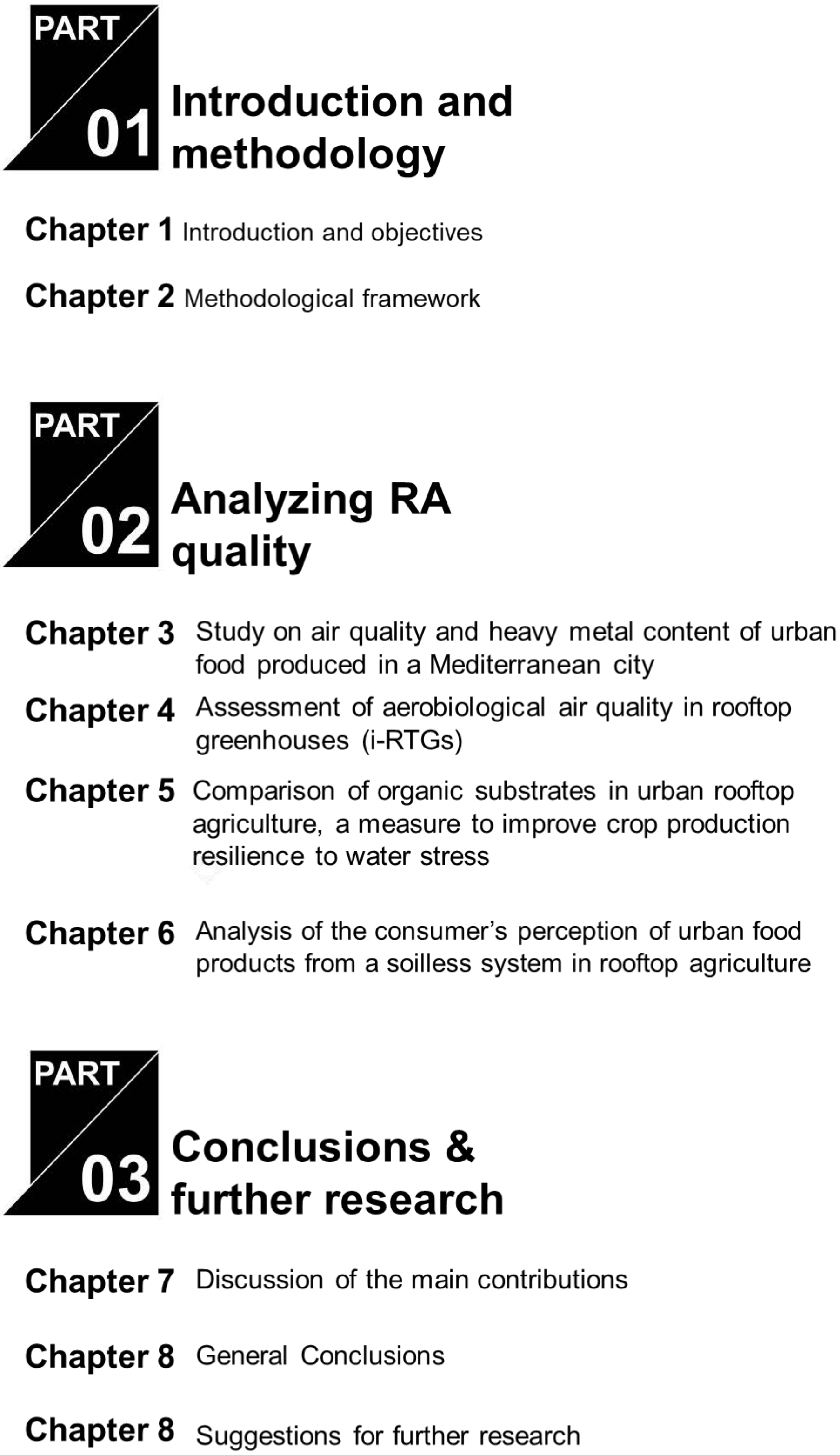
Finally, during the PhD training there has been the possibility to teach the Simapro life cycle assessment software in the official master's degree in Interdisciplinary Studies in Environmental and Social Sustainability from the Institute for Environmental Science and Technology (ICTA). Two master thesis have been supervised:

- Adapting urban farming to the winter season. Bean production in an integrated rooftop greenhouse (i-RTG). Student: Martí Rufí Salís. Cotutor: David Sanjuan, Mireia Ercilla, Xavier Gabarrell, Pere Muñoz, Joan Rieradevall. (2016-2017)

- Agronomic and environmental assessment of a polyculture rooftop soilless urban home garden in a Mediterranean city. Student: Anna Boneta. Cotutors: Martí Rufí Salís; Mireia Ercilla Montserrat i Joan Rieradevall. (2017-2018)

Structure of the dissertation

This thesis is composed of three main parts and 8 chapters as illustrated in the following figure:



PART 01 **Introduction and methodology**

Chapter 1 Introduction and objectives

Chapter 2 Methodological framework

PART 02 **Analyzing RA quality**

Chapter 3 Study on air quality and heavy metal content of urban food produced in a Mediterranean city

Chapter 4 Assessment of aerobiological air quality in rooftop greenhouses (i-RTGs)

Chapter 5 Comparison of organic substrates in urban rooftop agriculture, a measure to improve crop production resilience to water stress

Chapter 6 Analysis of the consumer's perception of urban food products from a soilless system in rooftop agriculture

PART 03 **Conclusions & further research**

Chapter 7 Discussion of the main contributions

Chapter 8 General Conclusions

Chapter 8 Suggestions for further research

PART 01

Introduction
and methodology

Chapter

01

Introduction and objectives

CHAPTER 1 - Introduction and objectives

This section presents the general framework of the Thesis which focuses on urban agriculture (UA) with a special emphasis on crops developed on roofs (RA) and grown in soilless culture system (SCS). Concretely, it addresses different aspects related to the quality of RA and the food it produces (Figure 1-1). Finally, this chapter highlights the motivations and objectives of the dissertation.

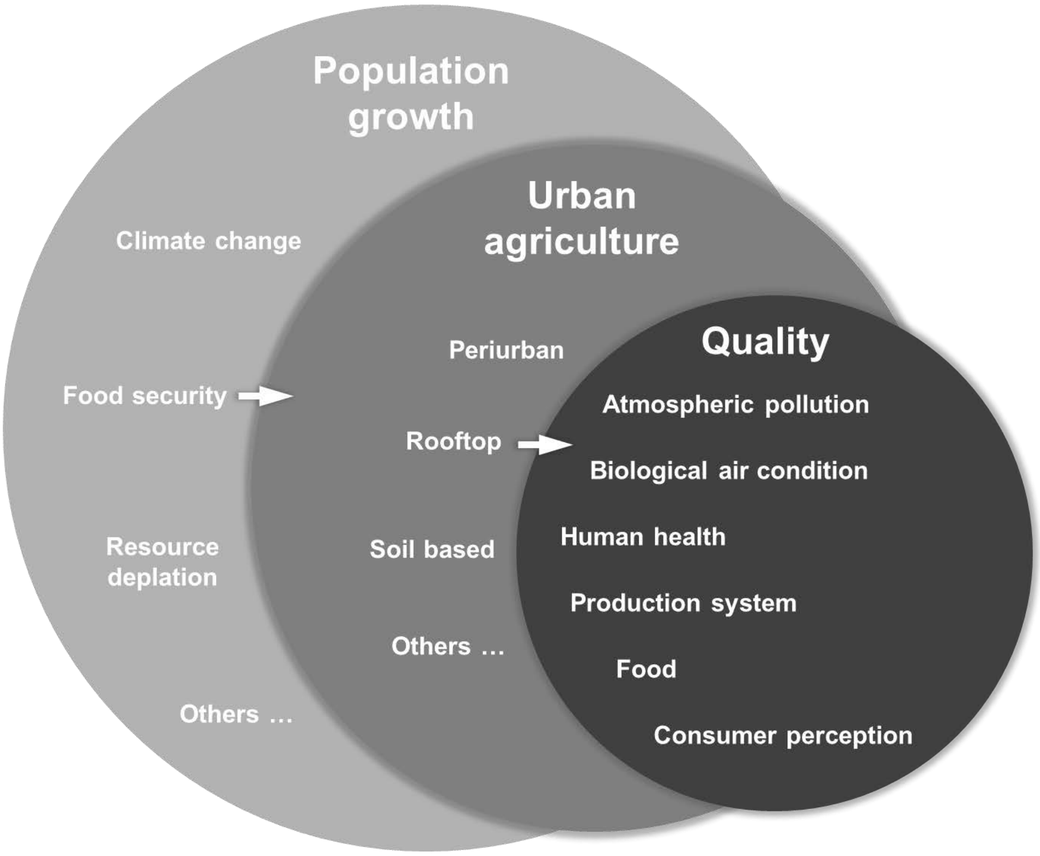


Figure 1-1 General overview of the framework of the dissertation

1.1. Urban Agriculture

The first experiences of UA begin at the same time as urban development with the aim of increasing the food security of cities. Remarkable experiences are detected in the Egyptian societies, in pre-industrial cities (citizens bred domestic animals and managed small farms and garden plots), in the Industrial Revolution when garden cities and allotment gardens emerged providing opportunities to produce food and during the European 20th century war and post-war periods (Calvet-Mir and March, 2017; Lohrberg et al., 2016).

Today, Urban Agriculture takes place in numerous cities, in all regions of the world, in various styles and involves several kinds of stakeholders. Now, UA face two global challenges: increasing urbanization, and food security (FAO, 2017). For this reason, periurban and urban agricultural activities are increasing worldwide, thereby providing citizens with local and fresh produce from vacant spaces in urban areas. Nevertheless, UA not only provide food to citizens but also provided other valuables services as social services, healthier spaces, and environmental friendly cities. Citizen desire more sustainable, self-sufficient and greener cities.

1.1.1. Urban Agriculture as strategy for food security in cities

Today, one of the main issues that UA faces is the increment in the world's population. In the last 50 years, the world population has more than doubled and it is foreseen to reach 9.7 billion by 2050. By then, it is estimated that 66% of the global population will be living in urban areas. This challenge, is amplified by climate change and environmental degradation through decreased arable land availability and increased extreme weather events (Godfray et al., 2010).

The United Nations Food and Agriculture Organization (FAO) coined the term "food security" in 1945 as 'a situation that exists when all people, at all times have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life' with the aim of highlighting the disparities of food access between world regions (Burton et al., 2013).

In the European Union (EU), 72% of the total population lives in urban areas. Compared to other regions, the EU is highly urbanized (Eurostat, 2015). Some implications of this situation include greenhouse gas emissions, water consumption, natural habit appropriation (Foley, 2011) and food availability. Moreover, conversion of farmland to urbanized land is considered an irreversible process (Haygarth and Ritz, 2009; Lal et al., 2008; Slätmo, 2017). In this context is necessary to find ways to increase food supply in cities. This has promote the development of innovative technologies focused on increasing food production in a sustainable way on a scanty surface (Godfray et al., 2010; The Royal Society, 2009). Also numerous local governments have developed and implemented policies and plans in order to guarantee urban food security, nutrition and urban agriculture (L. Baker and Zeeuw, 2015).

1.1.2. Urban agriculture not only a feeding system

Nowadays, in Europe, UA tackles a myriad of motivations that not only search food production but also to waving socio-cultural relations (Calvet-Mir et al., 2016). UA is being promoted for its contribution to sustainable, resilient urban development and the creation and maintenance of multifunctional urban landscapes (Specht et al., 2016b). In addition to enhancing food security, main functions are: providing environmentally-friendly food, educating and promoting health habits, building and empowering communities (e.g., Altieri et al. 1999; Lee 2001; Saldivar-tanaka and Krasny 2004; Kortright and Wakefield 2010; Bendt et al. 2013; Hu et al. 2013; Orsini et al. 2014). Moreover, urban agriculture placed in rooftops can offer new landscape opportunities while decrease the pressure to agricultural land and achieving more sustainable and resilient cities (Thomaier et al., 2015). This is one of the main the reasons because urban planners in the global north are already including UA in their agendas and policy planning (Morgan, K., 2009). To summarize this information in the (COST Action, 2013) was defined 6 key dimension that characterize UA from conventional agriculture in rural areas Figure 1-2.

At family level, UA contribute to the household's income, decreases the family's food expenditure (Anthopoulou et al., 2013; Ghosh et al., 2008) and as an educational tool, UA promotes the intake of fruit and vegetables among participants (Alaimo 2008, D'Abundo and Carden 2008). This implies an improvement in nutrition and an increase of physical activity and improvement of mental health (Kingsley et al., 2009; Kortright and Wakefield, 2010).

At social level, studies in this issue show that social benefits are also a relevant reason for engaging UA, often enhancing the common social and cultural identity for city residents. In larger urban farms, people also participate in community enrichment through job training and other educational programs (Ackerman et al., 2014; Veenhuizen, 2006).

In terms of environmental impacts, UA has a great potential. Most of conventional production is normally intensive in the use of chemicals and pesticides and long distances of food transport. In contrast, UA tends to obtain product in the optimal harvesting point with more nutrient using organic production techniques or minimizing environmental impacts in intensive systems. Moreover, as UA is developed inside or near the cities, it is reduced the need for transport and shortens the agri-food chain (Sanyé-Mengual et al., 2013) and reduces food losses due to transport damaging . For this reason UA can reduce the environmental impact of food production, especially in terms of transport, cutting the need for transportation and packaging (Sanyé-Mengual et al., 2015; Specht et al., 2014). Moreover, community gardens can reduce the urban heat island effects and mitigate urban storm water impacts (Ackerman et al., 2014).

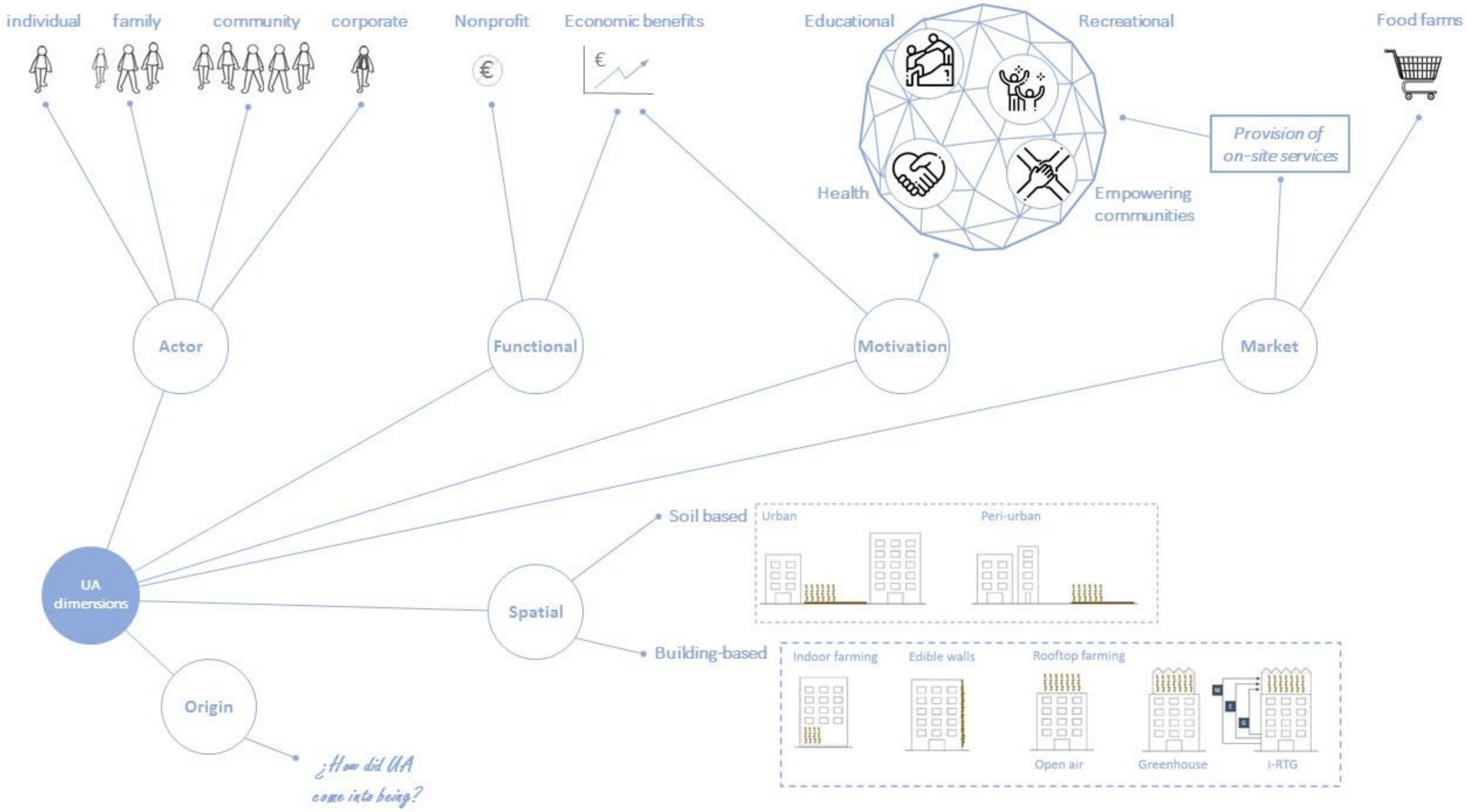


Figure 1-2 Scheme of the multiple dimensions of UA. Source: Own elaboration from (COST Action, 2013)

1.1.3. Urban Agriculture, the concept and their typologies

This dissertation focuses on UA in the Global North, and uses the following definition, which summarizes the discussion around UA conceptualizations of the Working group 1 of the COST Action "Urban Agriculture Europe" (Lohrberg and Timpe, 2012)

> *"farming operations taking place in and around the city that beyond food production provides ecosystem services (soil, water and climate protection; resource efficiency; biodiversity), social services (social inclusion, education, health, leisure, cultural heritage) and supports local economies by a significant direct urban market orientation"*

Currently, within this concept, different types of UA have been developed in European cities (Figure 1-3). UA is divided into two main groups: urban and periurban crops depending on its location in the city. Moreover, due to urban pressure in many European cities, UA has led to the use of the roofs and courtyards of buildings, where professionals and growers have found normally unoccupied spaces for producing food (Weatherell et al., 2003). This is described in the literature as building-based agriculture (Sanyé-Mengual et al., 2015a), and rooftop agriculture (RA) is the most common type (64.4%) (Thomaier et al., 2015). This subcategory includes all crop plants that are grown on the tops of buildings (Sanyé-Mengual, 2015a), in this case, it means that food is grown in soilless systems. In RA most of the crops are grown in open air so its development and final quality are conditioned by the environmental conditions. The present dissertation focuses on RA developed on the open air and inside greenhouse (Figure 1-3). For this reason, next paragraph provide specific information about this system.

Rooftop Greenhouses (RTG) are built by installing greenhouses on the top of buildings to produce food with high yields using soilless growing systems, increasing the efficiency of resources and using constructed spaces that are currently unoccupied (Cerón-Palma et al., 2012). The first commercial RTGs were built in North America, and include Gotham Green (2011) in Brooklyn, USA, with an area of 1400 m^2, and Lufa Farm (2011) with 2,900 m^2 dedicated to the production of traditional crops (e.g., tomato, cucumber, pepper). These existing RTGs are constructed on roofs that are isolated from buildings. However, this typology of RTG can also be integrated (i-RTG) into a building. One key aspect of i-RTGs is their capacity to make use of the hot and cold air supplied by the building to provide an optimum range of temperatures for the crops, without the need for extra energy. This is true because, first, due to their particular features, i-RTGs provide thermal insulation on the roof of the building. Second, they offer the possibility of supplying air from heated/air conditioned areas to the crops using a pumping system (Nadal et al., 2017b).

Greenhouses used for intensive cultivation of horticultural crops also use the carbon enrichment technique known as carbon fertilization to improve yield. In an i-RTG, this technique consists of increasing the environmental level of CO_2 by injecting waste CO_2 from some places of the building inside the greenhouse via an air current (Montero et al., 2017). Exposure to environments with a high concentration of carbon dioxide generally stimulate crop growth and photosynthetic fixation (i.e., in the case of tomatoes exposed to a CO_2 concentration of 900 $\mu mol \cdot m^{-3}$, the rate of growth increased by 30%) (Yelle et al., 1990).

Meanwhile, they also offer the possibility of using greywater or rainwater collected in or on the building for irrigating the crop (Sanjuan-Delmás et al., 2018b)

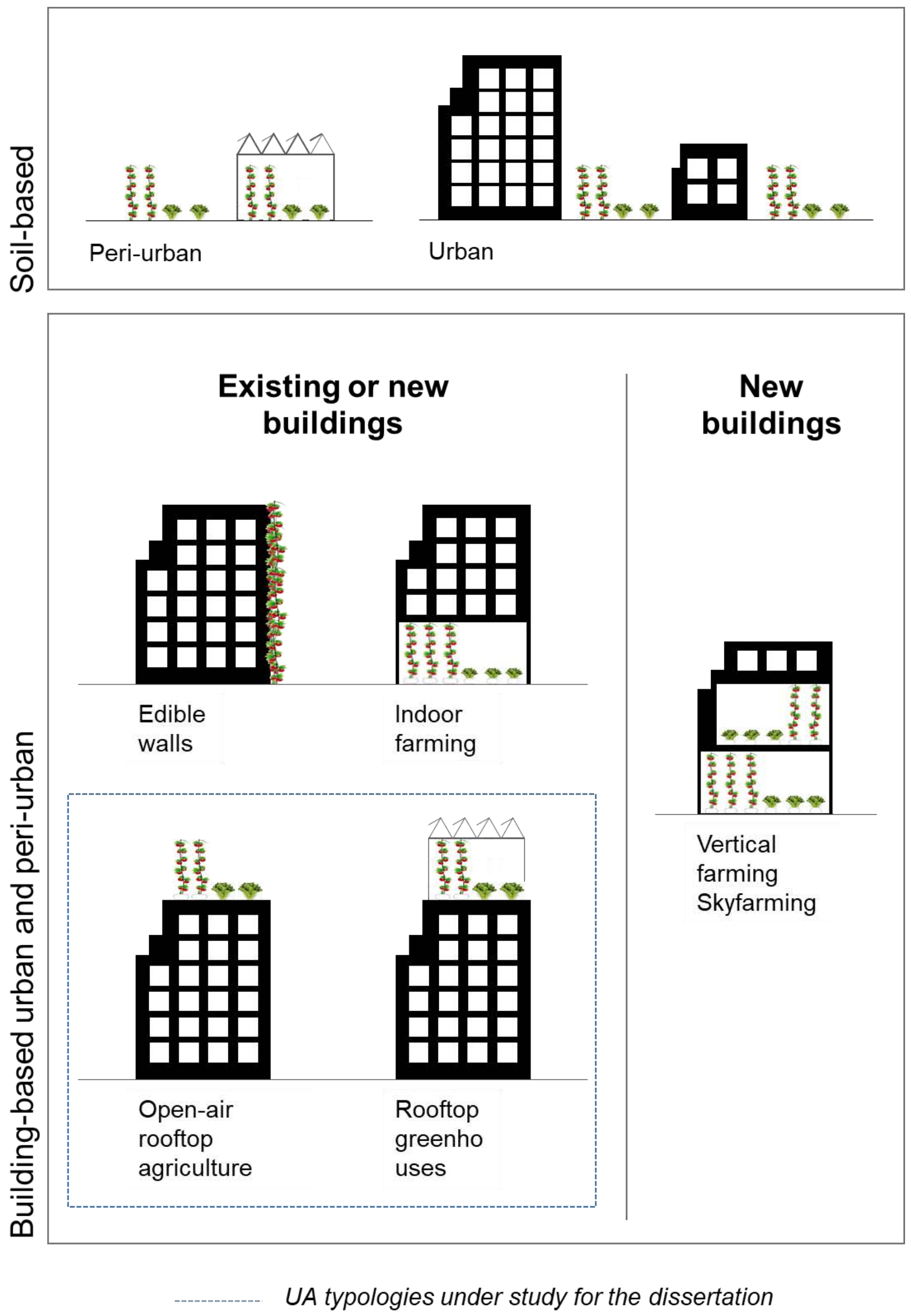


Figure 1-3 Urban Agriculture classification and typologies under study in the dissertation. Adaptation from (Sanyé-Mengual, 2015b)

1.2. Soilless system

Soilless culture system (SCS) is defined as “any method of growing plants without the use of soil as a rooting medium, in which the inorganic nutrients absorbed by the roots are supplied via the irrigation water”. The fertilizers containing the nutrients to be supplied to the crop are dissolved in the appropriate concentration in the irrigation water and the resultant solution is referred to as “nutrient solution” (Savvas, D. et al., 2013). According to the media where the roots grow, it is defined: aquaponic culture, aeroponic culture and media culture (Figure 1-4). In the first case the roots are suspending in the nutrient solution that is oxygenated. In the aeroponic systems plants grow in an air medium without any substrate. The nutrient solution is provided to the roots using a mist system. The media culture use a substrate that drains well yet retains some nutrients and water.

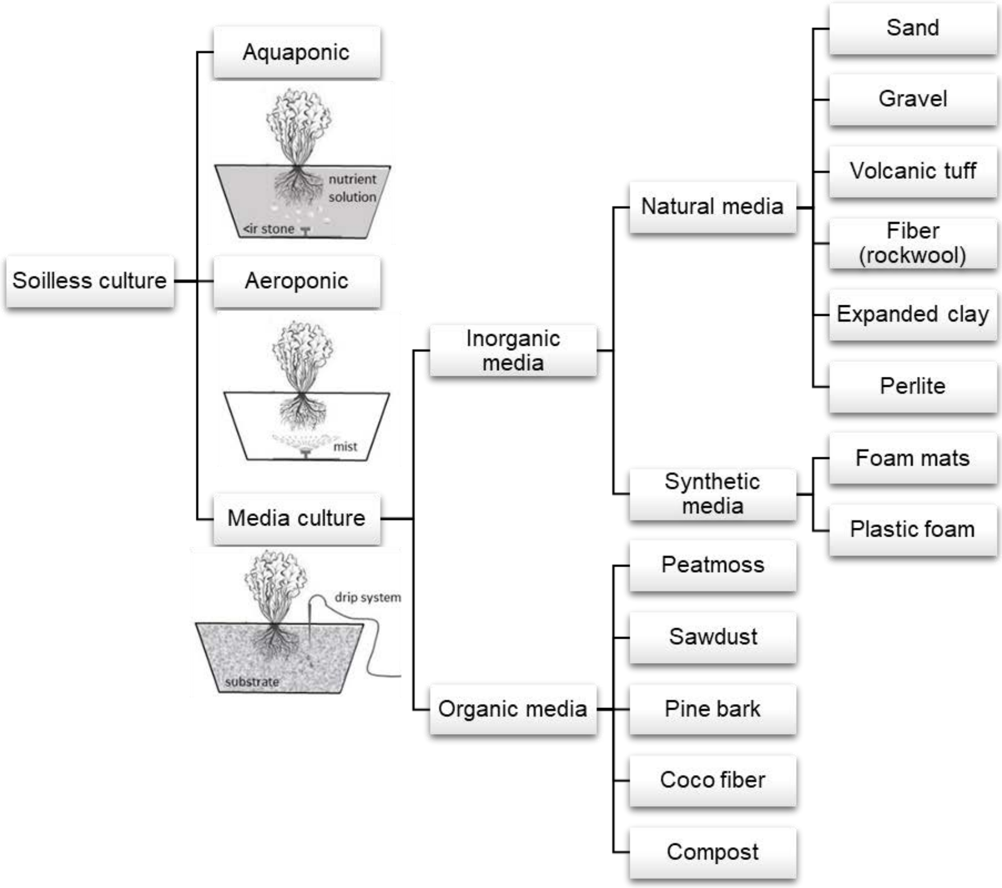


Figure 1-4 Main soilless culture systems

As it has been described in the previous section, soilless culture is the most common system used in RA. Specifically, mostly it is used media culture as growing system, thus substrate placed in small containers is used to house the crops A substrate is defined in (RD 865/2010, 2010) as a solid material different from the soil << in situ >> where plants grow. In these cases, the containers have a small water storage capacity between irrigations (Bunt, 1998). It is vital that the growing media provide a balance of air and water storage to prevent root asphyxia and drought in the crop. If this containers are filled with common soil these objective is not able to accomplish (Fonteno, 1993; Caron & Nkongolo, 1999). In response, soil-less growing media have been developed to allow for growing in small containers, as is ideal for urban areas (Barrett et al., 2016). At the same time this system allows to reduce the structural load of the building (Nadal et al., 2017b).

In addition to the structural lightness, studies in the issue show other advantages of this system most of theme related with the independence of the crop from the soil. Soil, as a natural medium is heterogeneous, there: there are soil-borne pathogens, may be infertile or saline (Savvas et al., 2013). On one hand, the independence from the soil enables to provide the exact necessary quantity of water and nutrients and the yields could highly increase. FAO estimates that garden plots can be up to 15 times more productive than rural holdings (FAO, 2018). Moreover if it is used a closed hydroponic systems the environmental impacts related with fertigation could be decreased (Antón, 2004; FAO, 2013). On the other hand, this independence allows an effective control of pathogens without applying phytosanitary products in the soil. This implies higher yields at a reasonable cost with minimal pesticides application and high quality can be attained (Savvas and Gruda, 2018).

Despite the advantages mentioned, some features that limit its widespread implementation were detected (Savvas et al., 2013; Sonneveld and Voogt, 2009) such as: high installation costs and technical skills requirements. Different materials can be used as growing media offering numerous advantages (Table 1-1)

Table 1-1 Advantages and disadvantages of using media culture as a soilless system

Advantages	Compared with water culture and aeroponics:	Reservoir for water and plant nutrients
		Adequate oxygen exchange
		Anchorage or support for plant
		Lower rhizosphere temperature excursion
	Compared with natural soil culture:	Standardization
		Light weight
		Virtual absence of pests in the root environment
		Cultivation without soil
Disadvantages	Compared with on-soil cultivation	Volume limitation
		Balanced fertilizer ratios requirement
		Potential expense
		Rapid development of deficiency symptoms
		Skilled manpower
		Greater number of analytics

1.3. Social Perception of UA and soilless systems

In the Global North, most people appreciate UA for its benefits to the community and it is usually associated with crops at the ground level in the vacant and non-built spaces of the cities. UA is mainly perceived as a socially-oriented activity, including recreational and leisure projects that are highly valued by citizens (Sanyé-Mengual et al., 2016; Specht et al., 2016a) and the commercial UA projects are less known. Usually, UA is also associated as a green urban element in the city infrastructure. In the case of profit UA initiatives, It has been detected a lower acceptance by consumers for two main reasons. Firstly, guarantee the food security between citizens is not perceived as challenge to solve. Secondly, the UA origins relays on a recreational goal that, nowadays, is still prioritized in front to commercial UA (Specht et al., 2016b). Nevertheless, FAO consider that profit UA can contribute to household food security, especially in times of crisis and/or in low-income residents. First, because UA food requires less transportation and refrigeration and can supply close markets with fresher and more nutritious at competitive prices. This implies that urban vegetable growers can sell directly through street food stands and market and more income goes to them instead of middlemen. Secondly as it has been described previously because are highly productive systems. Garden plots can be than rural holdings and one square meter can provide 20 kg of food a year. Thirdly, UA provides employment and incomes for disadvantaged groups (FAO, 2018). Some studies assessed the social perception in UA profit projects. Consumers linked UA with local food production and consumers appreciate it for this reason. Some people prefer local products because they perceive them as more environmentally friendly (Specht et al. 2016a). Other consumers, view local food as fresher, safer and healthier than imported products (Feldmann and Hamm, 2015) because they consider that the harvesting is produced just before consumption. That is also the reason for valuing the fresh quality but also other sensorial characteristics. Specifically, consumers prefer UA products to conventional rural products because they show benefits such as high quality, regionality, organic production or the inclusion of additional social benefits (Specht et al., 2016b). In the economic perspective this high valuation is translated to a higher willing to pay for local and organic products (Feldmann and Hamm, 2015).

As roofs are commonly unused in cities while there is a high competition for soil availability, RA is perceived as an opportunity towards a productive urban use, even for private initiatives (Specht et al., 2016b). As in soil-based UA, the main perceived benefits in RA are increased consumer awareness, education and creation of experimental spaces (Specht et al., 2016a). Nevertheless consumers and other stakeholders perceive other benefits due to its location and the techniques used. The production of fresh and/or organic food towards saving resources and promoting local economy is considered a good commercial opportunity (Sellers, 2016).

As noted above, RA is usually related with SCSs and to assure its competiveness requires using innovative and high technology systems (i.e. closed system for water efficiency) (Putra and Yuliando, 2015; Sanjuan-Delmás et al., 2018a). In general these innovations have a low social acceptance. Specht and Sanyé-Mengual (2017) detected that stakeholders from Barcelona and Berlin involved in UA projects think that producing in soilless or hydroponic systems is “too artificial” and “unnatural” method of growing food. In general there is high acceptance to buy UA products but an important rejection is detected when food comes from an intensive production (Specht et al., 2016b). Nevertheless, a low acceptance was also detected in the early stages of implementation of other agriculture innovations such as the case of organic farming (Padel, 2001) or the precision farming (Kutter et al., 2011). As discussed, there are indications that commercial RA may lead to rejection due to its motivation and technology used between potential consumers. Nevertheless there are not specific studies that focus on consumer perception of RA and the food produced. A key element to contribute to the viability of commercial UA projects is to supply food which is perceived by consumers as high quality product.

1.4. Food quality

Food quality is a complex term because it can be perceive and evaluate differently by farmers, food manufacturer, food scientist, consumers among others.

Legal

The definition of food quality in the Spanish legislation is:

> *"set of properties and characteristics of a food product relative to the raw materials or ingredients used in its preparation, to its nature, composition, purity, identification, origin, and traceability, as well as to the elaboration process, storage, packaging and marketing used and the presentation of the final product, including its effective content and information to the final consumer, especially the labeling".* (BOE-A-2015-8563, 2015).

This definition shows that the legislative enumeration of these qualities of the food product responds to a need to measure from a technical point of view the quality of a product and thus be able to compare it with others. It could be understood as an objective way to quantify food quality. Public administration recommends a set of requirements and food standards to ensure public health and safety.

Consumer's perception

However, there is another concept of quality, the quality perceived by the consumer, as for example, the opinion of the consumers on the superiority or excellence of a product (Zeithaml, 1988). It involves the subjective response of consumers and is consequently a relativistic characterization that differs between perceptions. According to the results of the survey "Global Consumer Food Safety and Quality" conducted to consumers in nine countries (Brazil, Denmark, Finland, France, Germany, Sweden, United States, United Kingdom and Spain), most consumers do not trust in the safety and quality of the food that they usually consume (TRACEONE, 2015). In this case, the quality is determined by:

> *The appearance of the product (color, size, shape, and the no presence of physiological disorders), texture, and organoleptic (flavor) and nutritive properties (health benefits).*

This characteristics are commonly associated to an intrinsic characteristic of the product and strongly influences consumer preference and demand (Moser et al., 2011). Nevertheless, consumers and farmers also consider other aspects that are not immediately detected in the shop, such as the nutritional value, taste and environmental production characteristics (Torjusen et al., 2001). So, for food producers and farmers quality is an important factor to incentive the consumer purchasing because they expressed a highest willing to pay for theme (Hussein et al., 2015). Food marketers base their concept of quality through consumer ratings. They use different approaches to evaluate a specific product by conducting interviews, questionnaires, sensory evaluations, etc. (Leong and Oey, 2017).

1.5. Motivations of the dissertation

Based on the background information presented previously, this section exposes the main reasons that inspired the studies conducted in this dissertation.

As explained in the introduction to this dissertation, UA is a strategy to be considered for achieving secure food supplies in cities. It has been developed in different social contexts in many places in the world and in various forms.

In modern Europe, it is a common issue on the public agenda. More than 100 cities from all over the world have signed up for the Milan Urban Food Policy Pact, emphasizing the promotion of local food systems through urban and periurban agriculture and their integration into cities' resilience plans (Milan_Expo, 2015). At the same time, the European Union has promoted research into UA through two Cost Actions to create a specific European approach taking into account the specific features of the context, the urban landscape model, as well as the particular features and important regulatory role of the Common Agricultural Policy (CAP) (COST Action, 2013, 2012). Inventories on UA business models were also complied in the Erasmus+ projects (BUGI, 2018; Urban Green Train, 2018)

Various pieces of previous research have demonstrated the technical viability (Cerón-Palma et al., 2012; Nadal et al., 2017a; Orsini et al., 2014; Sanyé-Mengual et al., 2015c) and quantified the environmental impacts (Sanjuan-Delmás et al., 2018a; Sanyé-Mengual et al., 2015b) (of producing food on the roofs of buildings, both in and outside greenhouses. This previous research focused on improving the design of the system, optimizing the resources used and finding new uses for waste (LLorach Massana, 2017; Sanjuan Delmás, 2017). However, no in-depth research has yet been carried out on the key aspect of food quality, which cuts right across all the issues already mentioned previously.

As far as we know there are no studies that focus on the quality of RA with an interdisciplinary approach.

The perception of quality is also one of the main elements taken into account by customers in guiding their purchasing decisions (Hussein et al., 2015). It is therefore a key factor contributing to the viability of commercial UA projects and encouraging the improvement of current designs. For this reason, this thesis groups different quality-related studies in a single document. It begins with the uncertainties detected in previous publications, like possible metal pollution (Sanyé-Mengual et al., 2016) or high water consumption (Sanyé-Mengual et al., 2016). But it also answers the questions and uncertainties detected as they arose in the Fertilecity project in visits by the public and experts to the i-RTG ICTA-ICP building; at Spanish and international conferences; and in work done in cooperation with public administrations. This formal and informal knowledge has made it possible to detect that the greatest concerns of stakeholders – consumers, owners of urban market gardens and users of buildings with integrated UA – are: aerobiological pollution, heavy metal pollution, water consumption and the use of non-renewable materials.

Air quality in urban areas is one of the issues generating most doubts when it comes to grow food in cities. In general, the heavy metal pollution is one of the most pressing concerns in the deliberation about food security and food safety in Europe (CEC, 2006). Additionally, in the case of UA, crops are often very close to roads with heavy traffic with a high atmospheric pollution risk (Gherardi et al., 2009; Säumel et al., 2012; Vittori Antisari et al., 2015). There is a very common concern detected among future consumers and promoters of UA about the possible adverse effects of heavy metals on horticultural production and quality (Sanyé-Mengual et al., 2016; Specht et al., 2016a). For example, users of the ICTA-ICP building, which is very close to an 11-lane motorway (AP7-E90), are afraid whether heavy metals suspended in the air leads to contamination of food. Despite the importance of this contamination there has been no enough data to dimension the real extent of the problem and most of the studies have been focus in soil contamination (Tóth et al., 2016). In the case of UA, and there are few studies focus on heavy metal contamination and most of theme analyze the end product for consumption (Kumar Sharma et al., 2007; Pennisi et al., 2016; Säumel et al., 2012; Vittori Antisari et al., 2015). As far as we know, the air-crop interaction and the benefits of use soilless systems has not been studied.

Another relevant concern about air quality specific of protected crops is the biological air quality inside greenhouses. The people who work in the ICTA-ICP building wonder about the effect of aerobiological pollution caused by crops in the greenhouse. The level of concentration of pollen and fungus spores suspended in the air can affect people who regularly work in the greenhouse (Illing, 1997; T. Lee et al., 2006b; Malling et al., 1986). The greenhouse is also integrated into the building in such a way that the air accumulated inside it can, in future, be used in other, colder areas. That means possible biological contamination of that air is an issue that concerns and worries all users of the building. The scarce bibliography about bioaerosols in conventional greenhouse is a first step to evaluate the air quality in RTG. Nevertheless, to our knowledge, indoor bioaerosols have not previously been measured in building-integrated agriculture facilities, and even less in urban rooftop greenhouses. Moreover the European Union legislation does not regulate the concentrations of pollen and spores in a building because they are not considered a consequence of human activity (EAACI, 2015). For this reason, it is necessary to conduct a field study in an RTG to shed light on which is the biological air quality and which are the key factors affecting it.

Another objection among stakeholders (administration, consumers, growers, architects, researchers, users of the building, etc.) detected during the Fertilecity project was linked to the high water consumption of market gardens in Mediterranean cities, where water is a scarce resource. At the same time, there is a demand to promote UA in the context of circular cities, using materials from near the place of consumption, which helps reduce the environmental impacts of food production. The use of perlite as a substrate is one of the most criticized elements detected, as possible consumers perceive it as not very sustainable. In the Sostenipra group's previous doctoral thesis, a need to seek renewable and sustainable local resources and to reduce the current water consumption of hydroponic systems was detected (Sanjuan Delmás, 2017; Sanyé-Mengual, 2015a). For these two reasons it is of great interest to study the use of vegetal waste from the city as alternative substrates that could promote the resilience to hydric stress

The three aspects above mentioned (biological air quality, potential heavy metal contamination and high demand of water in a clime change context) lead possible promoters of UA to have doubts about customers' perception and acceptance of this type of agriculture and the food it produces. In addition, it should be taken into account that any kind of innovation in its early stage of implementation has a potential rejection by general public (Specht et al., 2016a). For these reasons, it was also considered essential to do a systematic study of possible consumers' perceptions of RA and the products obtained from it.

1.6. Objectives of the dissertation

The main objective of the present dissertation is to assess the quality of the RA and the food produced in this systems though the analysis of the different factors that can decrease or improve its conditions and characteristics and determine the perceived quality of this products by the potential consumers. To do so, the following main research questions were addressed:

Question 1: Does atmospheric heavy metal pollution in cities contaminate soilless crops in RA and RTGs?

Question 2: Are the biological air conditions in RTGs adequate to provide safe working environments? And in the case of i-RTGS, can its air be recirculated while ensuring safe environment for building's users?

Question 3: Are we using adequate substrates for urban agriculture to mitigate the effects of climate change and increase the drought resilience?

Question 4: Which is the consumer perception of RA and products grown in these systems?

To address these questions, the following specific objectives were studied in detail:

Objective 1: To determine the potential contamination of heavy metals in hydroponic lettuce crops due to atmospheric pollution in high-traffic areas. Chapter 3

Objective 2: To study the pollen and fungal spores' concentration in i-RTG air in order to evaluate the greenhouse workers' exposure to prevent allergy problems associated with occupational tasks. Chapter 4

Objective 3: To study whether the quality of the hot air accumulated in the i-RTG is adequate for recirculation to heat the building. Chapter 4

Objective 4: To evaluate the agronomic behavior of different environmental friendly organic substrates that can be currently used instead of the perlite in the circular city context. Chapter 5

Objective 5: To study the response of different organic substrates under hydric stress conditions and the consequences involved for crops, in order to find a more water stress resilience media in UA. Chapter 5

Objective 6: To evaluate RA consumers' acceptance, focusing on the perceived quality of the product and its production system. Chapter 6

To specify and analyze these aspects related to the quality of RA, the present dissertation focused on 4 specific studies which impinge in different aspects of RA quality (Figure 1-5)

① Study on air quality and heavy metal content of urban food produced in a Mediterranean city Chapter 3

② Assessment of aerobiological air quality in rooftop greenhouses (i-RTGs) Chapter 4

③ Comparison of organic substrates in urban rooftop agriculture, a measure to improve crop production resilience to water stress Chapter 5

④ Analysis of the consumer's perception of urban food products from a soilless system in rooftop agriculture Chapter 6

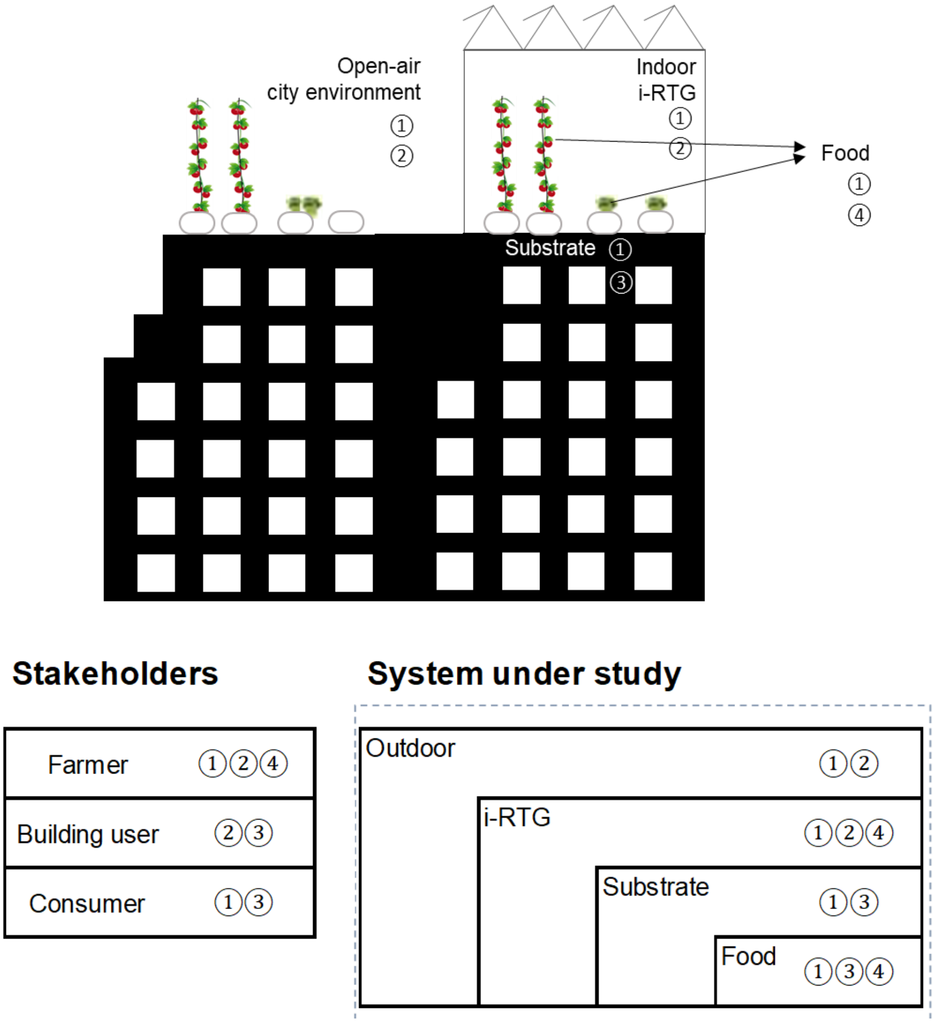


Figure 1-5 Scheme of the systems analyzed in each chapter of the present dissertation

These four studies analyze the different aspects of quality in RA. The different systems making up RA are considered all together: the atmosphere outside on the flat roof, the atmosphere inside the greenhouses, the production media and the end product obtained. Quality must be studied from different fields – biology, agronomy, chemistry and social studies. At the same time the different actors affected by the quality of RA, such as growers, users of the buildings where RA is implemented and the consumers of the food produced, must be taken into account (Figure 1-5).

Chapter

02

Methodological frameworks

CHAPTER 2 - Methodological framework

This chapter describes the methods applied in the present dissertation, lists the main materials used in each specific study and describe the case studies.

2.1.Materials and methods

A number of methods were used to deal with the quantification of the quality of RA system and the products grown in it. As it has been presented in the previously chapter, some of these methods comes from biology, chemical, social and agronomic disciplines. Table 2-1 shows the different approaches done in each chapter.

Table 2-1. Overview of the methods applied in the dissertation

	Chapter 3	Chapter 4	Chapter 5	Chapter 6
Biological	☐	☑	☐	☑
Physico-chemical	☑	☑	☐	☐
Social	☐	☐	☑	☐
Agronomic	☑	☐	☑	☑
Experimental field work	☑	☑	☑	☑

In the different studies a number of specific methods are used (Table 2.2.) and in all cases the studies have been based on experimental field work specific for each chapter.

Table 2-2. Methods and analysis applied in each chapter of the dissertation. CM: continuous monitoring; PM: Punctual measures

		Chapter 3	Chapter 4	Chapter 5	Chapter 6
Meteorological	Indoor Humidity sensor (CM)	☑	☑	☑	☐
	Indoor Temperature sensor (CM)	☑	☑	☑	☐
	Outdoor Humidity sensor (CM)	☑	☑	☑	☐
	Outdoor Temperature sensor (CM)	☑	☑	☑	☐
Biological	Pollen-spore traps (CM)	☐	☑	☐	☐
	Fungal spore identification (PM)	☐	☑	☐	☐
Physic-chemical	Air metal content analysis (PM)	☑	☐	☐	☐
	Crop metal content analysis (PM)	☑	☐	☐	☐
	% dry mass (PM)	☐	☐	☑	☐
Social	Consumer's surveys (PM)	☐	☐	☐	☑
Agronomic	Total production (PM)	☑	☐	☑	☐
	Water consumption (CM)	☐	☐	☑	☐
	Plant growth (PM)	☐	☐	☑	☐
	chlorophyll content (PM)	☐	☐	☑	☐
Data analysis	Spearman's non-parametric correlation	☐	☑	☐	☐
	One-way analysis of variance	☑	☐	☑	☐
	Multivariate analysis	☐	☐	☐	☑
	Cluster analysis	☐	☐	☐	☑

For this reason, experimental and analytical methods are deeper detailed in each chapter of the dissertation.

Meteorological sensors were used in the first three chapters of Part II (Chapter 3 - Chapter 5) and are deeper described in the next section *2.2.1. The ICTA-ICP building.*

The metal content in air has been analyzed in Chapter 3 following the methodology (UNE-EN 12341:2015; UNE-EN 14907:2006) (described in the same chapter) and using high-volume sensors to assess air contamination. Chapter 3 also includes the complete methodology used to determine heavy metal contents in crops. After a microwave digestion of the lettuce, heavy metals were determined by inductively coupled plasma mass spectrometry (ICP-MS).

In Chapter 4 it was described the materials and methods used to quantify the biological air quality inside and outside the i-RTG in the ICTA-ICP building following the standard method in Spanish Aerobiology Network (Galán et al., 2014). Samples were obtained using volumetric suction pollen-spore traps based on the impact principle. Pollen and fungal spore identification were performed by technicians specializing in palynology using a light microscope at 600X magnification.

The agronomic measures to evaluate the behavior of different substrates and the crops grown in them are detailed in Chapter 5. The bulk density test for each growth medium was performed by the ring method (USDA, 1999). The crop response was determined using: final yield, water content, dimeter and height of the lettuces.

The social perception of RA quality is described in Chapter 6, following the perception aspects proposed by (Boizot-Szantai et al., 2005) and using in most of the ranking attributes a likert-type scale (Wadgave and Khairnar, 2016). Finally, in each chapter the statistical methods and the software used are described in depth.

2.2.Systems under study

This doctoral thesis was developed in four different scenarios: a periurban rooftop, a periurban i-RTG, an urban rooftop and an urban courtyard (Table 2-3). The periurban-rooftop and the periurban i-RTG were located in the same building: the ICTA-ICP building in the Universitat Autònoma de Barcelona (UAB) campus. The i-RTG was used for the four study chapters and the periurban rooftop in the chapter 3 and 4. In chapter 3 -focused on the potential contamination of heavy metals in soilless crops due to atmospheric pollution- the 4 points were chosen to evaluate if there are differences between the different locations of UA. Chapter 6 was conducted as well in the facilities of the periurban i-RTG.

Table 2-3. Scenarios for each chapter of the dissertation

		Chapter 3	Chapter 4	Chapter 5	Chapter 6
Periurban area	UAB i-RTG	☑	☑	☑	☑
	UAB rooftop	☑	☑	☐	☐
Urban area	Barcelona Rooftop	☑	☐	☐	☐
	Barcelona courtyard	☑	☐	☐	☐

The four ZONES under study were selected from urban and metropolitan areas of Barcelona (Figure 2-1). The selected places are all located close a high-density road (more than 50,000 cars/(work day)

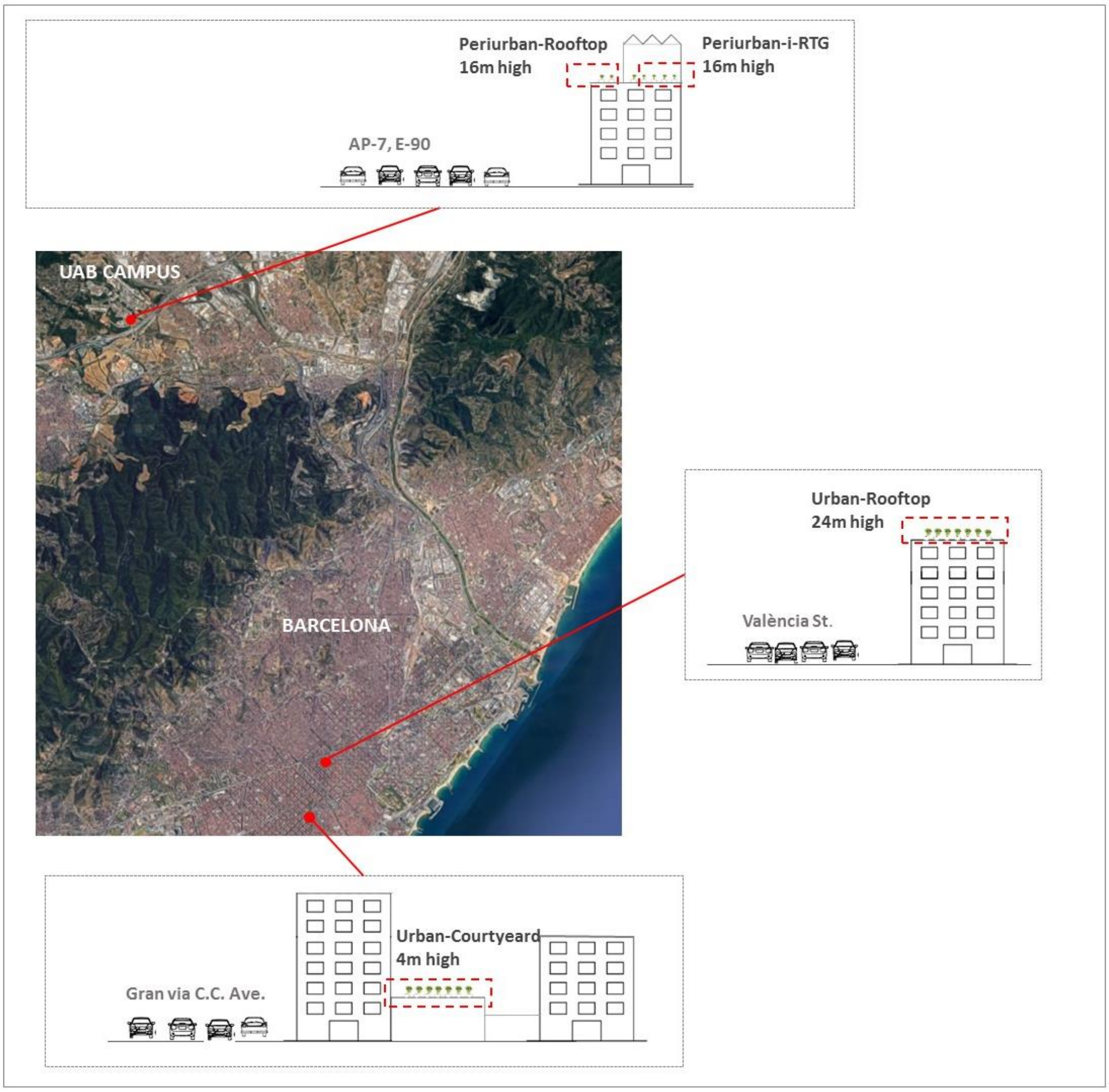


Figure 2-1. Conceptual characteristics and location of the scenarios used in the dissertation (Adaptation from *(Ercilla-Montserrat et al., 2018)*)

2.2.1. The ICTA-ICP building

The ICTA-ICP building is the building that hosts the Environmental Science and Technology Institute (ICTA) and the Catalan Institute of Paleontology (ICP). It is located in the Universitat Autònoma de Barcelona (UAB) campus, 20 km from the Barcelona city center, (41.497681N, 2.108834E). Although the campus is located in a highly populated area between two highways with high volumes of traffic, the university's facilities are surrounded by a forested landscape. It consists of 5 floors of 40 x 40m^2 designed following the most sustainable criteria. For example, the consumption of energy is one of the most important characteristics. It use a Bioclimatic Outer Skin which regulates the solar radiation and ventilation through a series of automatic opening window system, it means that it reduces energy demands and improves temperatures inside in a natural way like in conventional greenhouses is done. Also the building was constructed reducing the amount of materials used as well as, it was selected as much as possible organic or recycled materials that could be reversible and reusable. Moreover it the cycle of water was optimized and a 90% reduction in the water consumption needed for a conventional building was get. For all this reason it is awarded with the LEED-Gold® certification.

Periurban i-RTG

On the roof of the building there are four i-RTGs to increase the efficiency of both the building and the greenhouses. The symbiosis between the building and the i-RTGs includes: heating the greenhouse with the thermal inertia of the building, in winter to use the residual hot air from the RTG to heat the building, use the exceeded CO_2 in the building as a fertilizer in the RTG, and to collect the rainwater from the rooftop for the irrigation system (Sanjuan 2017). Nowadays two of them are prepare to hold a different research-oriented crops: i-RTG-Lab1 and i-RTGLab2. The symbiosis between the building and the greenhouse makes it possible to produce all year round, as the temperature conditions are right for the plants to develop properly without the need to provide energy for heating (Nadal et al., 2017).

- The i-RTGLab1 covers a total area of 122.8 m^2, of which 84.34 m^2 supports a crop including 171 plants grown in 57 40L perlite bags. The specie implemented was beef tomato (Solanum lycopersicum Arawak) and five crops were grown since the Fertilecity project started. This variety is considered a product with added value, representative of gastronomic closure. The water and the nutrient solution needed by the plants were provided through a drip fertigation system (Figure 2-2).

- The i-RTGLab2 covers a total area of 125 m^2, which 70 m^2 supports a leafy crop. As the space and light requirements needed are lower, 416 plants could be planted using 40L perlite bags. In this dissertations Oakleaf lettuces (Lactuca sativa var. Capitata) were used as a crop under study but other leafy crops have been tasted in the Fertilecity project (Figure 2-3).

Two independent monitoring system are placed in the i-RTG Labs to control the meteorological conditions inside it:

a) Siemens control system

The meteorological conditions inside the i-RTG was passive controlled by five schedules that control a mechanism to open and close the ventilation system depending on internal and external temperatures (Nadal et al., 2017b). The Siemens control (© Siemens AG, 2008) was the operation software that allowed to manage the meteorological conditions schedules opening and closing the wall-cortains and the continuous double roof ventilation on each span (which makes a total of four roof ventilators 19.55 m long) as well as four flap ventilators on the exterior side wall. The Siemens software measured and register data of different sensors: temperature, humidity, air quality, solar radiation.

b) Campbell system

It was used 12 temperature sensors (Campbell 107; accuracy: ±0.18 °C), 3 combined temperature and humidity sensors (Campbell CS215; accuracies: ±0.3 °C and ±2%), 2 pyranometers (Campbell LP02; accuracy: ±10%) and 2 surface-temperature probes (Campbell 110PV; accuracy: ±0.2 °C) to measure the conditions inside the i-RTG. A CR3000 data-logger was used to collect data from the Campbell devices and takes measurements every 5 s and records the averages at 10 min intervals. Data were collected through the support software package of the Campell that allowed to communicate of PC to visualize the values at real time and save the historical data (Short Cut and PC200W software's).

i-RTG Lab 1

Typology: i-RTG
Location: Periurban
Building: ICTA-ICP (UAB)
Crop area: 84.34^2
Nº plants: 171
Crops developed: tomato

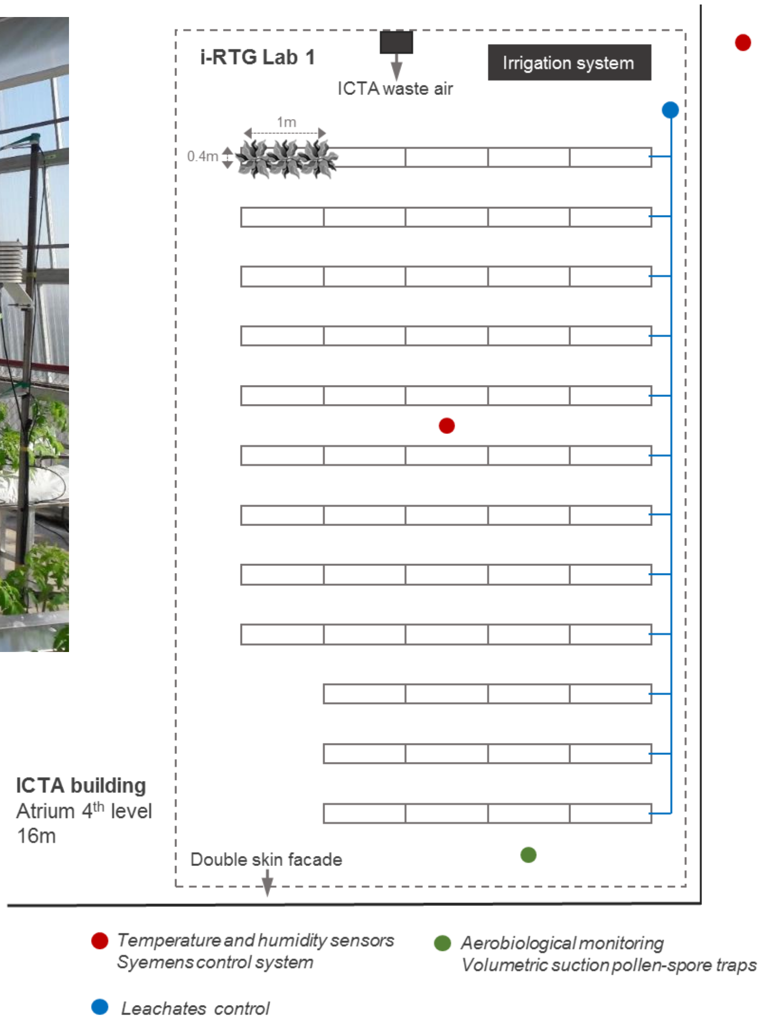
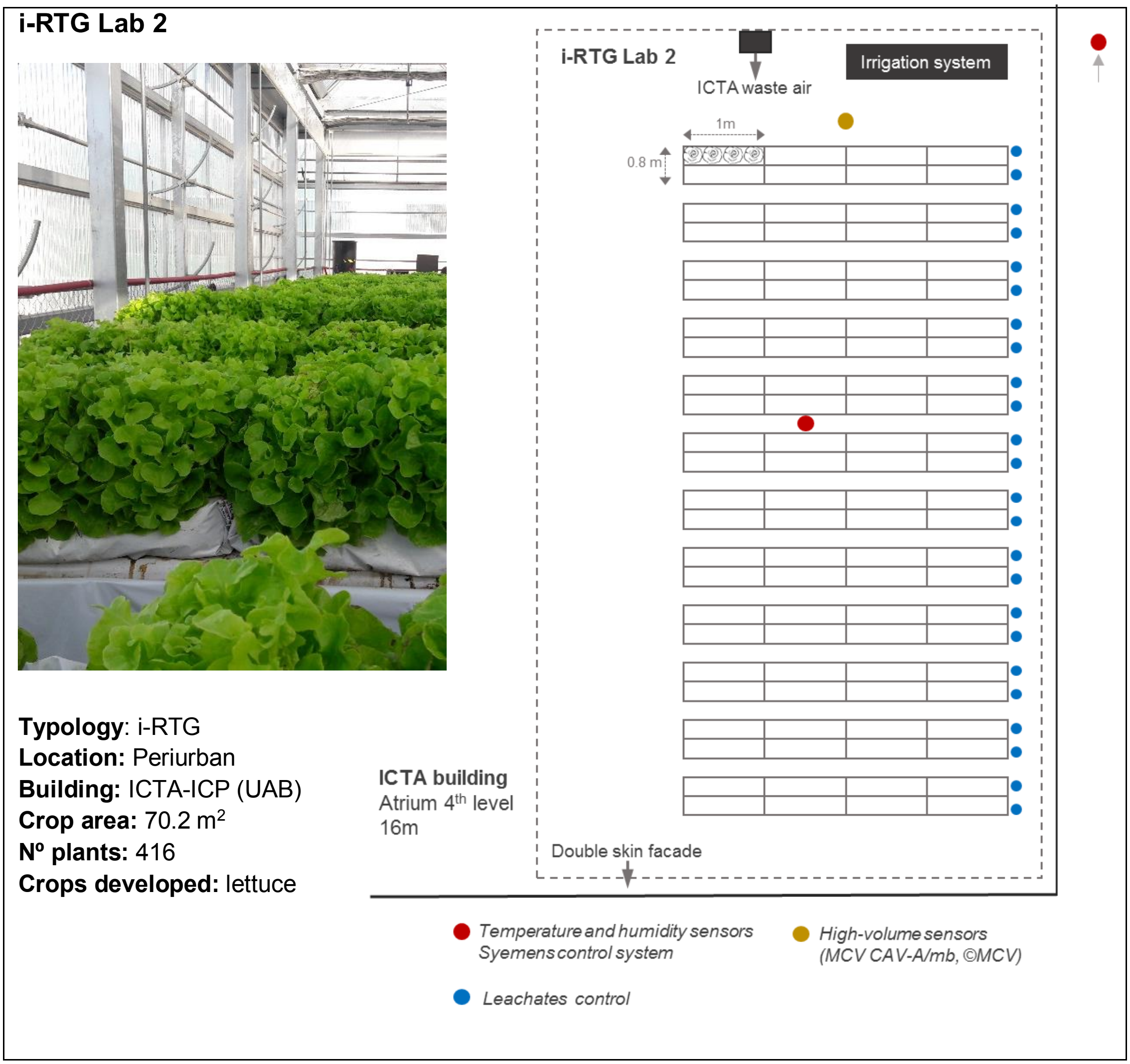


Figure 2-2 i-RTG used for the experimental study on chapter 4



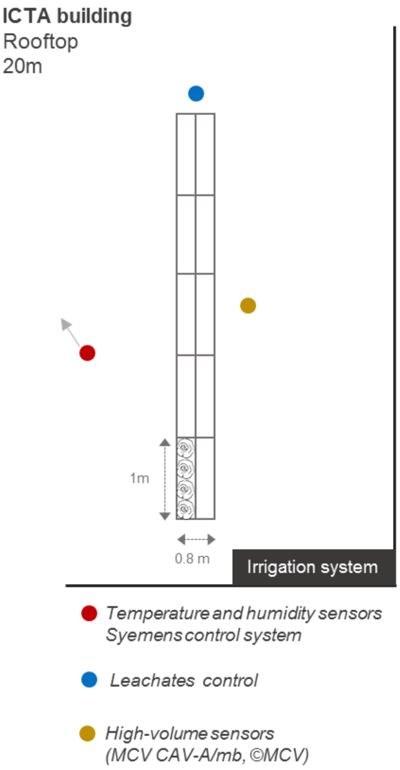
Typology: i-RTG
Location: Periurban
Building: ICTA-ICP (UAB)
Crop area: 70.2 m^2
Nº plants: 416
Crops developed: lettuce

Figure 2-3 i-RTG used for the experimental study on chapter 3 and 5

Periurban Rooftop

The research developed in the periurban rooftop is placed on the vacant spaces between the 4 greenhouses in the same ICTA-ICP building. They consist on 35 m^2, that allow to implement 10 perlite bags connected to the i-RTG fertigation system. A total of 40 leafy plants could be grown if the i-RTGLab2 crop design is followed: 40L perlite bags with 4 plants each one (Figure 2-4).

ICTA-building rooftop

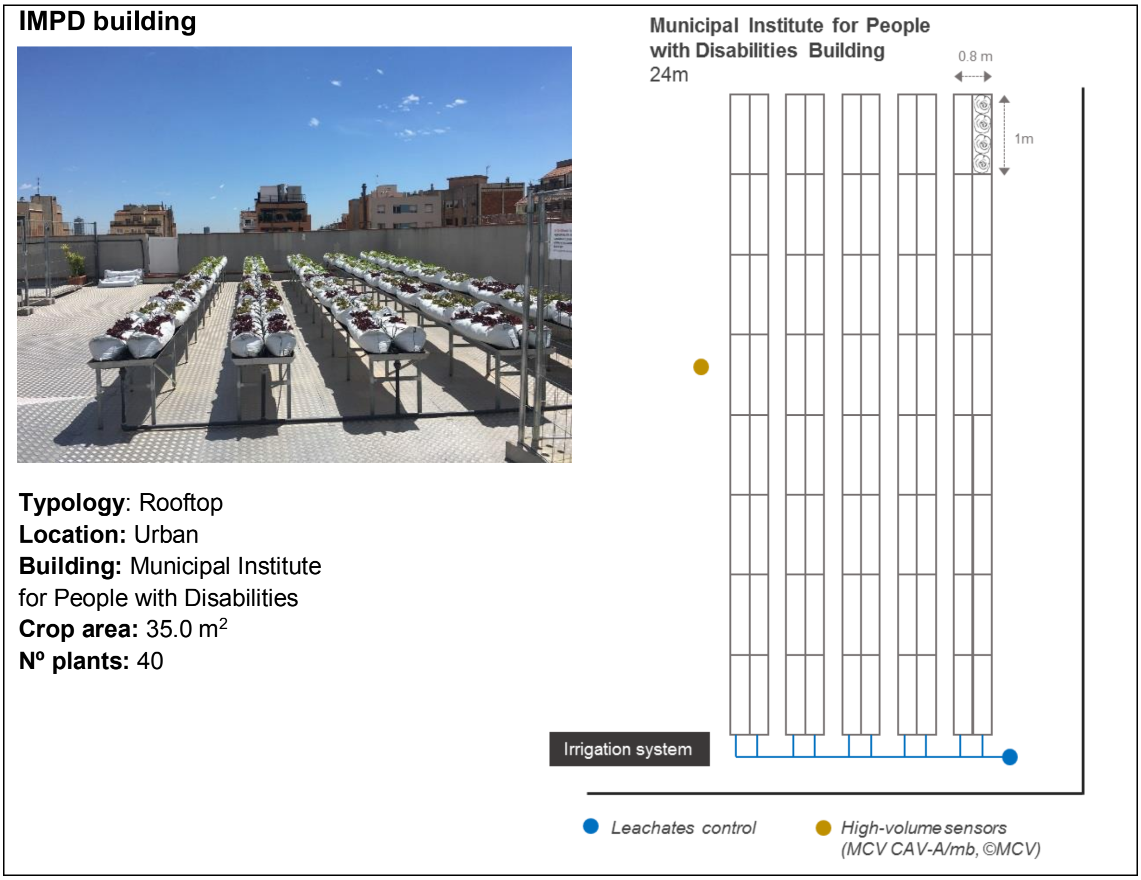


Typology: Rooftop
Location: Periurban
Building: ICTA-ICP (UAB)
Crop area: 35.0 m^2
Nº plants: 40
Crops developed: lettuce

Figure 2-4 Periurban rooftop used for the experimental study on chapter 3

2.2.2. Urban rooftop

A social orchard on the roof of the Municipal Institute for People with Disabilities (IMPD) in València Street from Barcelona (41.396970N, 2.169318E) was used in Chapter 3 (Figure 2-5). This facility consists in 260m^2 divided in three different spaces: aromatic area, fruit area and leafy area. In this dissertation the study was conducted in the leafy area which consist in 8 lines of 10 perlite bags (40L, 1x0.3 m^2), each bag with 4 plants.



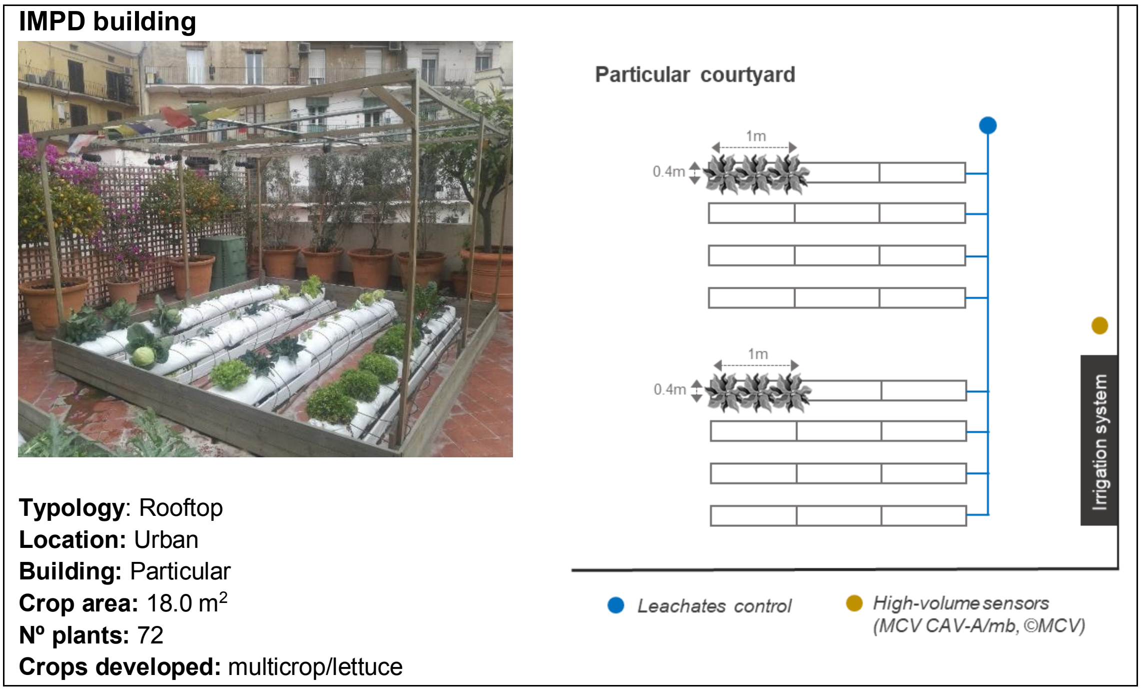
IMPD building

Typology: Rooftop
Location: Urban
Building: Municipal Institute for People with Disabilities
Crop area: 35.0 m^2
Nº plants: 40

Figure 2-5 Urban rooftop used for the experimental study on chapter 3

2.2.3. Urban-Courtyard

A particular courtyard within the center of Barcelona, in Gran Via Street (41.38481N, 2.163125E) is used for the 4 chapters. It is on the first floor above street level and accounts for 18 m^2 in a particular flat. Also a soilless operation system was used in which plants grow in perlite bags and nutrients and water are supplied through fertigation system. Specifically, 24 perlite bags of 40L (1x0.3 m^2) were installed, and each bag contains 3 plants. The distance between crops is 45 cm (Figure 2-6).



IMPD building

Typology: Rooftop
Location: Urban
Building: Particular
Crop area: 18.0 m^2
Nº plants: 72
Crops developed: multicrop/lettuce

Figure 2-6. Urban courtyard used for the experimental study on chapter 3

2.3. Agronomic management of the crops

2.3.1. Crop selection

Beef tomato Lycopersicon esculentum var. Arawak (*Cor de bou*) and Oakleaf lettuces (Lactuca sativa var. Capitata) were the crops under assessment in this research study (Table 2-4). The lettuce crop was selected because in the edible parts leaf crops generally have more metal absorption and/or accumulation than inflorescence crops (Peris et al., 2007). At the same time, as lettuce is a fast-growing crop, it is possible to detect a rapid response to the effect of different stress or pollution situations without other types of interference, as is possible in crops with slower development. Beef tomato was selected due to the highest added value comparing with other tomatoes types and also due to the available previous information about its agronomic behavior and the available previous environmental dates. For example, their production in available rooftops of a logistic park in Barcelona could produce 2000 tons of tomato per year, that could cover the 150000 people's demand (Sanyé-Mengual et al., 2015a).

Table 2-4. Crops under assessment in each chapter of the dissertation

	Lettuce	Tomato
Chapter 3	☑	☐
Chapter 4	☐	☑
Chapter 5	☑	☐
Chapter 6	☐	☑

2.3.2. Fertigation management

As has already been mentioned, crops were managed in the same way in order to reduce the uncertainty factors in the different studies. In all cases, the control treatment was growth in 40 l perlite sacks (1x0.3 m^2) fertilized with a nutrient solution consisting of salts suited to the needs of he crop at each stage. The nutrient disorders are more risky in high technical greenhouse than in soil based crops and the damage could imply important economic costs (Savvas et al., 2013) . Perlite is an inert substrate and the nutrient available for plants at any moment is restricted and cover few percentages of the total crop requirements on minerals. Therefore, usually all plant nutrients are added to nutrient solution. The quantity of nutrients present in the irrigation water or possibly released from the substrate should be taken into account in advance or will be controlled during the cropping period (Sonneveld and Voogt, 2009). In this study, nutrient analysis of irrigation water were made weekly and nutrient content in leachates 3 times every week (Monday, Wednesday and Friday). With this information some adjustments of the nutrient solution were made weekly. Elements being essential, but in most cases deliberately not added are Cl and Ni. Cl and Na are usually abundantly available in the irrigation water used to cover the essential requirements. An exception is the addition of Cl in nutrient solutions for tomato to promote the uptake of Ca (Sonneveld and Voogt, 2009). Guarantee the absortion of Ca is the most difficult challenge due to the type of water that supplies the irrigation system in the tests conducted in the ICTA-ICP building. Irrigation water can come from the rainwater harvesting system (it does not contain either Ca or Cl) or from the network. Tap water contains a small amount of Cl (between 1 and 3 meq Cl/L).Most annual plants are moderately or highly tolerant to chlorides; for this reason the concentration detected was not a constraint to ensure a good development of the crops under assessment. Moreover, the tap water does not contain Ca because the water is decalcified in the building for all possible uses (Sanjuan Delmás, 2017). Due to the importance of the absorption of Ca for many crops that can lead to the occurrence of Ca disorders (tip burn in leafy crops and blossom-end-root in tomato and pepper crops). Especially for the case of tomato, the nutritive solution was adjusted to fit this singularity. Some examples of nutrient solutions for different crops are presented in Table 2-5 and Table 2-6

Table 2-5 Example of nutrient solution used along the tomato crop cycle irrigated with rainwater.

Patron solution for tomato fertigation						
(meq/L)	11/01/2017 to 19/01/2017	19/01/2017 to 17/02/2017	17/02/2017 to 28/02/2017	28/02/2017 to 24/03/2017	24/03/2017 to 03/05/2017	03/05/2017 to 25/07/2017
NO_3^-	5	7,5	8	8,5	10,0	9
P^{+5}	1	1	1	1	1	1
SO_4^{2-}	2	6	6	6	6	6
Cl^-	2	2	2	1	1	1
Na^+	0	0	0	0	0	0
K^+	5	5	5	5	6	5
Ca^{2+}	3	3	4	5	5	5
Mg^{2+}	1	1	1	1	1	1
NH_4^+	0	0	0	0	0	0

Table 2-6 Example of nutrient solution used in two lettuce crops (spring and summer crops) irrigated with rainwater

Patron solution for lettuce fertigation		
(meq/L)	Spring crop 28/04/2016 to 10/06/2016	Summer crop 20/06/2018 to 16/07/2018
NO_3^-	9	8
P^{+5}	1	1
SO_4^{2-}	2	3
Cl^-	2	3
Na^+	0	0
K^+	6	8
Ca^{2+}	4	4
Mg^{2+}	1	1
NH_4^+	0	0

The nutrient solution was in two different tanks to prevent salt precipitation (Figure 2-7). as it is recommended in the standard fertigation to separate calcium from sulphate and phosphate fertilizers, thereby avoiding precipitation due to low solubility of calcium sulphates and phosphates (Sonneveld and Voogt, 2009).

Tank 1	**Tank 2**
K_2SO_4	$Ca(NO_3)_2$
K_3PO_4	$CaCl_2$
KNO_3	$Mg(NO_3)_2$
	Sequetrene ® 138Fe
	Tradercorp ® AZ

The water system was open (or linear) and allowed daily monitoring using an experimental device making it possible to quantify and characterize the nutrient solutions supplied and the leachates obtained. The water and fertilizers applied and lost were measured daily, together with the pH and the electric conductivity of the nutrient solutions applied and the volume applied and drainage for each treatment. Every week, macro- and micro-nutrient analyses are carried out both of the nutrient solution and the leachates obtained for each treatment.

All irrigation systems in the 4 study scenarios consisted of an irrigation head, where clean water (rain water or tap water) was accumulated in two 300L black polyethylene tanks. An irrigation digital timer (Hunter ® X-CORE) with a solenoid valve (RainPro 8410B) was used to activate the irrigation. Firstly, the incoming water from the tanks goes through a flow meter to measure the amount of water irrigated. Secondly in the clean water flow was injected the nutrient solution using two injectors (Dosatron ®, dosing pumps) connected with the nutrient tanks. The nutrient solution was diluted at a ratio of 1: 100. This system was protected by a 50-mesh filter. After the irrigation head, the irrigation water was transported in a primary pipe to each crop row. The secondary pipes distributed the irrigation to each plant using drippers placed with pegs in the substrate.

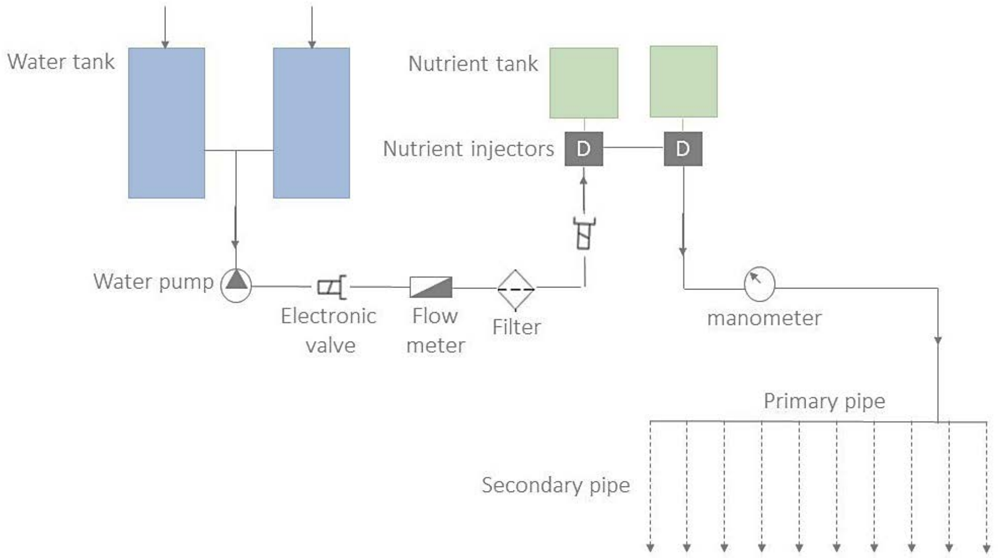


Figure 2-7. Scheme of the common elements of the irrigation system of the crops

2.3.3. Cultural practices

In the case of crops in the i-RTG, checks were also made every day that the temperature was between 15º and 28ºC and the humidity between 40% and 80%. If these conditions were not found, the deviation was recorded and measures were taken to prevent the plants suffering stress.

The stipulated monitoring of the proper development of the crops consisted of checking the state of the plants every day to detect and record the number of dead plants, if any, plants affected by worms and plants with burned leaves, growth irregularities and other unexpected physiopathies.

In the case of the tomato crop, as well as the daily monitoring mentioned, the following tasks were carried out to keep the crop in the best possible condition for production:

1. Staking the tomato plants every week.
2. Pruning the secondary branches every week.
3. Pulling off the leaves and stems from the lower parts of the tomato plant where the fruits have already been picked.
4. Harvesting the ripe tomatoes twice a week.
5. Weighing the residual organic matter produced during and at the end of cropping.
6. When cropping is over, weighing all the organic waste (roots, leaves, stems, etc.).

The procedure for evaluating the quality of the tomatoes consisted of periodically picking ten tomatoes from three rows chosen at random from the production area, avoiding the edges of the crop area. Physical data from these samples were recorded every week, such as: fresh weight, dry weight, length and brix degrees °Bx (dissolved solids – saccharose), using spectrometry methods. At the end of cropping, analyses were made of the macronutrients in the stems, leaves and fruits for each treatment.

Lettuce crops are less demanding on a daily basis. However, the following actions were carried out every week:

1. Pulling off leaves in poor condition.
2. Harvesting the lettuces: pulling the whole plant up from the perlite sack with the roots, trying to reduce perlite loss as much as possible.
3. Cutting off the roots of the lettuces.
4. Weighing the roots, the surface parts of the plant and the part produced for sale.
5. At the end of cropping, weighing all the organic waste (roots, leaves).

The quality of the lettuce crop was determined with at least 20 lettuces, for which the following factors were measured: individual, commercial fresh weight; average diameter; and length of the longest leaf. Of these samples, at least ten lettuces were selected to have their dry weight determined and to analyze the samples in a similar way to the tomatoes (macro- and micro-nutrients and heavy metals, if any).

PART 02

Analysing RA quality

Chapter

03

A study on air quality and heavy metals content of urban food

CHAPTER 3 - A study on air quality and heavy metals content of urban food

This chapter is based on the journal paper:

Ercilla-Montserrat, M., Muñoz, P., Montero, J. I., Gabarrell, X., & Rieradevall, J. (2018). A study on air quality and heavy metals content of urban food produced in a Mediterranean city (Barcelona). Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2018.05.183

Abstract

Urban agriculture is growing in cities and is rising to the roofs of buildings. The potential food contamination is a key issue to be resolved to guarantee the health of consumers, and it affects both urban agriculture promoters and consumers. Crop contamination from the soil can be overcome by adopting a soilless cultivation system that, with good management practices, can also avoid contamination from the fertigation system and pest treatments. It has recently increased the number of soilless cultivation systems in cities due to the good features it offers. This study focuses on the potential contamination of heavy metals in hydroponic lettuce crops due to atmospheric pollution in high-traffic areas. The contents of heavy metal in the air and the lettuce leaves were measured at 4 sites: a periurban-integrated rooftop greenhouse, a periurban rooftop, an urban courtyard and an urban rooftop. High-volume sensors were used to assess air contamination. Lettuce leaves were analyzed to evaluate the heavy metal concentrations.

The results show that the heavy metal concentration in lettuce leaves is also below the EU-legislated limit in all studied cases. Specifically, the concentrations below the detectable analytic values were <0.02 mgNi/kg, <0.008 mgHg/kg, 0.005mgAs/kg and <0.005 mgCd/kg. The Pb concentration ranged from 0.0060 mg/kg to 0.0244 mg/kg. Although the chosen sampling locations were close to high-density roads and they are more vulnerable to a high concentration of metals, in the 4 sampling points heavy metal concentration in the air were less than 50% of the limits established in the legislation as the lower assessment threshold. This study concludes that the heavy metal content in the air of Barcelona is low and is not a source of contamination for urban crops including high traffic areas.

Keywords: soilless system, contamination, cities, food security, food quality, toxicity, atmospheric particulate, vertical farming

Chapter

04

Assessment of aerobiological air quality in i-RTGs

CHAPTER 4 - Assessment of aerobiological air quality in i-RTGs

This chapter is based on the journal paper:

Ercilla-Montserrat, M., Izquierdo, R., Belmonte, J., Montero, J. I., Muñoz, P., De Linares, C., & Rieradevall, J. (2017). Building-integrated agriculture: A first assessment of aerobiological air quality in rooftop greenhouses (i-RTGs). Science of The Total Environment, 598, 109–120. https://doi.org/10.1016/j.scitotenv.2017.04.099

Abstract

Building-integrated rooftop greenhouse (i-RTG) agriculture has intensified in recent years, due to the growing interest in the development of new agricultural spaces and in the promotion of food self-sufficiency in urban areas. This paper provides a first assessment of the indoor dynamics of bioaerosols in an i-RTG, with the aim of evaluating biological air quality in a tomato greenhouse near Barcelona. It evaluates the greenhouse workers' exposure to airborne pollen and fungal spores in order to prevent allergy problems associated with occupational tasks. Moreover, it evaluates whether the quality of the hot air accumulated in the i-RTG is adequate for recirculation to heat the building.

Daily airborne pollen and fungal spore concentrations were measured simultaneously in the indoor and outdoor environments during the warm season. A total of 4,924 pollen grains/m^3 were observed in the i-RTG, with a peak of 334 pollen grains/m^{3}day, and a total of 295,038 fungal spores were observed, reaching a maximum concentration of 26,185 spores/m^{3}day. In general, the results showed that the most important source of pollen grains and fungal spores observed indoors was the outdoor environment. However, Solanaceae pollen and several fungal spore taxa, such as the allergenic Aspergillus/Penicillium, largely originated inside the greenhouses or were able to colonize the indoor environment under favourable growing conditions. Specific meteorological conditions and agricultural management tasks are related to the highest observed indoor concentrations of pollen grains and fungal spores. Therefore, preventive measures have been suggested in order to reduce or control the levels of bioaerosols indoors (to install a system to interrupt the recirculation of air to the building during critical periods or to implement appropriate air filters in ventilation air ducts). This first evaluation could help in making decisions to prevent the development of fungal diseases, specifically those due to Oidium and Torula.

Key words: urban agriculture, greenhouse, tomato crop, pollen grains, fungal spores, indoor and outdoor bioaerosols, air recirculation, symbiosis

Chapter

05

Organic substrates, a measure to improve crop production resilience to water stress

CHAPTER 5 - Organic substrates, a measure to improve crop production resilience to water stress

This chapter is based on the journal paper:

Ercilla-Montserrat, M., Parada F., Arcas V., Lopez-Capel E., Carazo N., Montero J.I., Gabarrell, X., Rieradevall, J., Muñoz, P. Comparison of organic substrates in urban rooftop agriculture, a measure to improve crop production resilience to water stress in Mediterranean cities. Submitted to the journal Scientia Horticulturae

Abstract

Urban agriculture, especially on rooftops, is an increasingly popular practice to complement the growing demand for local food production in cities. However, less attention has been paid to the growing media of crops in soilless systems. A deeper understanding of the agronomic response to the substrate used can contribute to the use of more environmentally friendly substrates with more resilience to water stress. The present study was conducted in an integrated rooftop greenhouse near Barcelona. The substrates used were: perlite, a standard commercial substrate; coir, an organic commercial substrate; vegetable compost from urban organic waste; and a mixture of this vegetable compost and perlite (1:1). The experiment involved 3 short crop cycles during the spring and summer periods of 2018 to observe all the substrates during different meteorological conditions during the warmer periods of the year. During each crop cycle, the substrates were tested under well irrigated and water stress conditions (irrigation stopped until perlite reached -20 cbar). All the parameters were measured in all the substrates under well irrigation and hydric stress conditions: substrate behavior, crop yield, crop growth and health.

The results demonstrate that there were not significant difference ($p<0.05$) between yields obtained in organic substrates than those obtained from perlite. Moreover yields were greater than those obtained in open fields in the same area. Nevertheless, tipburn was detected in organic substrates rather than perlite, especially in spring crops due to meteorological conditions. Compared to perlite, organic substrates increased the resilience of the crops to water stress. Coir tended to take some time to lose water (-10 cbar); however, when dryness began, it occurred very quickly, and the yield decreased. In general, when water stress reached -20 cbar, vegetable compost and substrate mixture presented more agronomic resilience and highest yields than perlite (in July 16% and 20% respectively)

Keywords

Circular economy perspective, sustainable cities, soilless system, water stress resilience, vegetable compost, coir, lettuces

5.1.Introduction

5.1.1. UA and water: a challenge for the future of cities

In past decades, population growth and its concentration in cities has created great concern due to a greater demand for resources such as energy, water and food in urban areas. Urban agriculture (UA) is an alternative for meeting those food demands and an option that contributes to the sustainability of the agri-industrial sector: cutting the distribution chain, reducing the packaging used and promoting the local economy (Sanyé et al., 2012).

UA can be carried out at different levels: on the ground and on building rooftops, which is known as rooftop agriculture (RA) (Thomaier et al., 2015). Agriculture on roofs takes advantage of spaces that are not normally used (Nadal et al., 2017a), increasing current local food production and reducing the environmental load associated with food production and the buildings that sustain it (Nadal et al., 2017b). Moreover, the implementation of RA is perceived as an opportunity for productive urban use, even for private RA initiatives, as roofs are commonly unused urban spaces (Specht et al., 2016b).

On a global scale, one of the biggest problems to be addressed in agriculture is the high demand for water for food production. This situation is aggravated by the advance of climate change, which is causing drought situations in many places. UA requires water for its maintenance, which might make it compete with other activities and water uses in cities (Lupia and Pulighe, 2015). One example in the Mediterranean area is the city of Barcelona, where droughts have been repeated cyclically for the past two decades. This situation has led to the creation of a management plan that aims to prioritize water uses in cities, especially during emergency situations. UA is currently not considered an agricultural activity in Spain but rather as a green space, being hampered by the legal restrictions applied on these areas. For example, in 2008, it was forbidden to irrigate private gardens with water tap, and therefore, gardens within the city could not be irrigated either. For this reason, it is important to develop strategies to alleviate drought situations in urban crops.

In conventional forms of agriculture, innovative solutions for water management have been implemented for some time to achieve greater water efficiency for crops and thereby reduce their consumption and, as a result, their water footprint. Different alternatives have been promoted (Seif-Ennasr et al., 2016): irrigation optimization, soil cover, the development of soilless culture systems (SCSs), develop climate change resilient crops or the reuse of leachates and the wastewater.

5.1.2. Soilless culture systems

A soilless culture system (SCS) is defined as any method of growing plants without the use of soil as a rooting medium in which the inorganic nutrients absorbed by the roots are supplied via irrigation water (Savvas et al., 2013). In the case of RA, as these are crops planted in an artificial medium, SCSs are widely used (Barrett et al., 2016).

Specifically, the use of substrates as a growing medium is very widespread in RA. SCSs can offer a more cost-effective alternative to soil cultivation systems, making it possible to obtain greater yields. SCSs are usually also more efficient in water and nutrient consumption than soil crops (Putra and Yuliando, 2015). At the same time, as these are imported substrates, contamination from materials in the soil, which are common in urban contexts in Europe, can be avoided (Peris et al., 2007).

The Spanish Royal Decree (RD 865/2010, 2010) defines a substrate as a solid material different from the in situ soil where plants grow. The National Organic Program of the United States

Department of Agriculture (NOP, (2016)) defines substrate as a material that provides sufficient support for plant root systems and enables plants to extract water and nutrients.

In this study, we used the definition of (Fonteno and Harden, 2000), who defines substrate as any material or combination of materials used to provide support, an adequate capacity for cation exchange, a correct retention of humidity, but maintaining a porosity that guarantees a good aeration in order to achieve optimal root development

A wide variety of substrates can be suitable for crop production under different growing conditions. The selection of a growing medium has been predominantly based on yield and financial cost without considering environmental or health factors.

Perlite is a natural material of volcanic origin that has been heated up to 1,000 ºC. This substrate is characterized by its capacity for aeration and drainage and optimum water retention and has an easily available water content of up to 45%. In the Mediterranean region and specifically Spain, there has been a rapid expansion of perlite soilless culture systems in growbags mainly for vegetable production in the Almería and Murcia regions (Grillas et al., 2001).

Coir (coconut fiber) is an alternative substrate. It 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 very limited geographical areas far from areas of maximum horticultural use, and thus, it generates a high impact on transportation (Barrett et al., 2016).

Compost is an alternative to peat and coir, making it possible to work with organic waste, which is highly available locally. It is more fertile than the other substrates (which is why it has an added value for saving nutrients). If compost is well-stabilized, it acts as a slow-releasing fertilizer. At the same time, it has progressive mineralization, providing phosphorus and other micronutrients, making it possible to reduce the dose of fertilizer given in nutrient solutions (Savvas et al., 2013). Its use as a substrate makes it possible to recover organic waste as a resource and reduces the dependence on other substrates, cutting the cost of horticultural production. One of the greatest disadvantages of using compost is the low level of uniformity of its physical, chemical and biological characteristics.

Vegetable compost, i.e., material from plant waste, such as gardening waste, forestry pruning and agricultural waste, has a lower conductivity, nutrient content, organic matter stability and C/N ratio than that of organic fraction of municipal solid waste (OFMSW) or livestock waste (Barrett et al., 2016).

5.1.3. Selecting new substrates in Mediterranean cities

Currently, there is a need for progress in researching substrates that are easy to manage, have a low environmental impact, show high moisture retention and have nutrients that are easily available for crops. Previous studies have detected that peat retains water better than perlite, having a high water-holding capacity and readily available water (Ampim et al., 2010). Nevertheless, in selecting alternative substrates to perlite, environmental considerations have become more important, and for this reason, an emphasis has been placed on organic materials derived from agricultural, industrial and municipal waste flows instead of the use of peat (Savvas and Gruda, 2018).

Barcelona seeks to become a self-sufficient city by 2050, and circular economy strategies play a facilitative role in achieving this goal. This economic approach focuses on the greater sustainability and resilience of a system: maximizing the reuse of resources and products and minimizing their downgrading (Prendeville et al., 2018). The mayor of the city has proclaimed that becoming a circular city is one of the four key targets for 2020. Most of the strategies of European cities related to the circular economy focus on urban infrastructure (Petit-Boix and Leipold, 2018). RA is one of the most important strategies for achieving this objective because different fluxes are connected (Sanjuan-Delmás et al., 2018b). In circular economy for food organic resources are free from contaminants and can safely be returned to the soil in the form of organic fertilizer. Some of these by-products can provide additional value before this happens by using them of other purposes (Ellen MacArthur Foundation, 2019), such as new food products, fabrics for the fashion industry, as sources of bioenergy or like in this case, a substrate for soilless system production. Barcelona signed the Milan urban food policy pact, which states that sustainable UA incentives should be promoted. For this reason, it is expected that commercial RA will increase in the next decade in European cities, and new environmentally friendly strategies will be implemented. However, the current cases of RA are usually noncommercial operations for self-consumption, educational purposes or social projects (Specht et al., 2016b).

Organic substrates have been widely studied for their use in the horticultural industry. In the UA context and from a circular economy approach, there has been an urge to study organic materials derived from agricultural, industrial and municipal waste streams. The disposal of such materials is already an environmental problem, and their reuse as substrates might provide a suitable solution. Nevertheless, few of the materials studied in the research community have been widely adopted by the horticultural industry, and even less in RA, mainly for three reasons (Barrett et al., 2016): first, alternative materials have predominantly been selected with environmental factors in mind, with less consideration given to yields and financial costs. Second, these materials are characterized with a wide variety of approaches; this leads to results that are difficult to compare and interpret between different potential substrates. Finally, few researchers have considered the commercial realities of the increased manufacturing of the growing media.

However, as it has been presented in the UA context, not only the origin of the substrate is important for improving the sustainability of agricultural production: water consumption is an important factor. It must be highlighted that protected RA, i.e., greenhouses on roofs, RTGs, can undergo high levels of hydric stress. RTGs are usually small and well-ventilated and have a very low relative humidity. This leads to conditions generating high water consumption by plants and, therefore, a propensity to suffer hydric stress (Montero et al., 2017). On the other hand, SCS operators need specialized knowledge to produce high yields of crops (Lee and Lee, 2015). For this reason, there is a probability of irrigation management mistakes when the operators are amateurs. As these are less-automated systems than conventional agriculture systems1 and have fewer alerts if the system stops, i.e., when the electricity is turned off or during water system leaks, there can be periods of several days when crops receive no water.

In general, there is a gap in the literature concerning the optimization of substrates in the specific context of UA in terms of both irrigation optimization and agricultural production. As far as we know, there has been no in-depth study of the response of different substrates in the case of hydric stress or the consequences involved for crops in the context of SCSs in RA. It is necessary to develop more lines of research that create new ways for increasing resilience, become more aware of the sustainability of food production systems and the quality of the products and to make it possible for any entity, government, company and social aggrupation to use these improvements. For this reason, this study attempts to, first, contribute to the existing literature on the use of urban and agricultural residues as substrates for crop production as an approach to a circular economy. To achieve this, this study focuses on the comparison of the different substrates currently used in SCSs: a commercial organic substrate (coir) and a locally produced and highly available alternative organic substrate (compost). The second aim of the study is to find viable

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[1] The production method resulting from the green revolution that dominates the current food market and entails the use of chemical products (i.e., fertilizers and pesticides) and specific cultivars (e.g. hybrid and transgenic varieties) to boost productivity and reduce production costs.

alternatives to perlite that might be less vulnerable to possible disturbances in the water supply as an adaptation strategy for UA in the face of climate change in Mediterranean cities.

Hereby, this paper presents four specific objectives:

- The study of the agronomic viability of the use of coir, vegetable compost and a mixture (1:1) of compost and perlite as alternative substrates for perlite in an RTG for the production of leafy greens.
- The study of the behavior of the four previously mentioned substrates under water stress caused by a halt in irrigation for a certain number of days during the warmer seasons in the Mediterranean area.
- The quantification of production losses due to hydric stress in each substrate.
- The study of the effects of hydric stress on plant growth and development in all four substrates.

5.2.Materials and methods

5.2.1. Study site

The experiments were conducted in the integrated rooftop greenhouse laboratory (i-RTG Lab) of the Fertilecity project2. It is located in the Environmental Science and Technology (ICTA-UAB) building (UTM: 425624 m E, 4594364 N, elevation 146 m) on the campus of the Universitat Autònoma de Barcelona (Autonomous University of Barcelona) in Bellaterra, which is 14 km northwest of Barcelona (Catalonia, Spain). The cropping system is representative of other RA projects developed in Barcelona and other Mediterranean cities (Ercilla-Montserrat et al., 2018). This is especially relevant because the implementation of SCSs at the ground level in cities will rise due to the rapidly declining soil fertility, land degradation, drought increase, and elevated CO_2 levels in cities.

The i-RTG Lab is a greenhouse connected to the building, and this connection allows an exchange of different flows between them (rain water, residual heat energy and CO_2 emissions) (Nadal et al., 2017b; Sanjuan-Delmás et al., 2018b). Protected cultivation is performed under a steel and polycarbonate greenhouse structure. The symbiosis between the building and the greenhouse enables year-round production (Nadal et al., 2017b) and reduces water consumption (Sanjuan-Delmás et al., 2018a). Specifically, the meteorological conditions in the i-RTG Lab were passively controlled by five schedules that order heating, cooling and window openings to optimize energy use. Each control schedule adjusts the greenhouse control system to adapt it to seasonal temperature requirements (Nadal et al., 2017b). There are two different ventilation modes that were applied in the i-RTG Lab during this study: (1) the spring mode was employed from 4 April to 31 May 2018, and (2) the summer mode was employed from 1 June to 20 July 2018. The highest temperatures and the highest ventilation rate occurred during the summer mode, as the summer mode includes a cooling system.

5.2.2. Substrate characteristics

The present study focused on 4 substrates, with perlite selected as the control. The other three substrates used in the study were coir, compost from vegetal wastes and a mixture of the same vegetable compost and perlite (1:1).

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[2] www.fertilecity.com/en

Commercial inorganic substrate: Commercial perlite was the control growing media used in this study. One of the advantages of using perlite is that it is an inorganic chemically inert substrate and is free of potential diseases, pests and weed seeds. The manufacturer of the perlite bags (OTAVI S&B ®) specifies the values for the most important characteristics of the substrate. The granulometry present in the perlite ranged from 0 to 6 mm, the electrical conductivity (EC) was 0.09 dS/m, the pH was 7 and the total effective porosity was > 90%. Perlite was used within bags with a 40 L capacity, and this initial volume was used to achieve uniformity between the substrates.

Commercial organic substrate: Coir was selected as a commercial substrate (Cocoplant-Sicosa®) and packed into 40 L bags to make the dimensions uniform with the control bags. The main components were coir and coco dust. The commercial company facilitates the ranges of the physical-chemical characteristics of the substrate, with 85% organic matter, 0.45 mS cm-1, and a pH of 6.25.

Alternative organic substrate: The vegetable compost used was derived from municipal pruning waste, and the composting process takes up to 3 months to finish on open-air piles. The compost is chipped and mixed for 3-4 weeks and irrigated 4 times per month with rain water. When the composting process is finished, the material is sieved to 10 mm and packed. The municipality makes periodic controls of the compost, which in our case presented 59.8% organic matter, an EC of 2.77 mS cm-1 and a pH of 7.79 at the beginning of the study.

Previous studies have suggested that composted materials such as green waste must be a component of a growing medium (up to 50%), but not exclusively (Prasad and Maher, 2001). For this reason, in this study, the compost was used in two different ratios: one substrate was entirely compost (100%), and the other was a mixed substrate (1:1) with perlite, containing the highest ratio recommended for compost (50%) (Prasad and Maher, 2001).

5.2.3. Experimental design

The experiment consisted of 3 short crop cycles during the spring and summer period of 2018, when drought conditions are usually reported (Agència catalana de l’aigua, 2009). The aim was to be able to monitor all the substrates during different meteorological conditions that can take place during normal cultivation cycles, especially during warmer periods. The internal and external meteorological conditions recorded (Campbell Datalogger model CR3000; Campbell Scientific Inc., USA) can be found in Table 1. The 3 crop cycles are considered independent tests: 1) March-April; 2) May; and 3) June-July (Table 1). During each crop cycle, the 3 substrates selected were tested under well irrigation and water stress conditions, as explained later, and treatments were carried out in triplicates. In the case of the control substrate, there were four replications: two under well irrigated conditions and the other under water stress conditions.

Cultivation system: The i-RTG Lab has a total area of 125 m^2; for this study, the effective area used was 70 m^2. The substrate bags were placed on eleven rows along the i-RTG Lab area, and each row contained two lines of bags. Each line consisted of four substrate bags, and four plants were grown in each bag. The dimensions of the bags were 0.4 m x1 m, and they had a volume of 40 L. Each plant was planted at distances of 0.2 x 0.4 m from each other in bags with the same growth media. The rows were disposed at 0.5 meters from each (Figure 5-1).

Oak leaf lettuces (Lactuca sativa var. Intybacea) were planted in the 4 substrates. The crops were monitored and controlled following conventional agronomic guidelines for lettuce production, and no phytosanitary products were used to avoid their possible influences. During the growing periods, diseases and deficiencies detected in the crops were monitored.

Irrigation management: Water and nutrition solutions for the plants were provided via a drip fertigation system. The nutrition solution was the same for all, and the irrigation volumes were adapted to the needs of the crop grown in the control media (perlite substrate). This means that the dosage was optimized according to the demands of the lettuce planted in the perlite substrate. Specifically, the irrigation quantity ranged between 0.3-0.45 L/(day·plant). (The nutrient solution contained the following : HNO3 63 mg/L, KPO4H2 136 mg/L, KNO3 101 mg/L, K2SO4 174 mg/L, Ca(NO3)2 164 mg/L, CaCl2 111 mg/L, Mg(NO3)2 148,3 mg/L, and microelements 0,1 mg/L.)

The water stress took place 20 days after transplanting with the objective of making a late temporary drought when the plants were bigger and require a higher water and nutrient supply following the methodology proposed by (Kerbiriou et al., 2013). This stress was applied by completely stopping irrigation until the perlite bags reached -20 cbar. At this time, irrigation was reestablished for all the stressed rows. The water losses in the growing media were determined with an analog 12 cm tensiometer (irrometer® MLT) through the variation in the hydric potential, with a range of 0 to -40 cbar. In addition, in the third test, a second hydric stress was performed. This second stress consisted of the same irrigation stoppage, but it was only maintained until the tensiometers in the control substrate perlite reached -10 cbar. Substrates generally hold most of their water in a matric potential range from –1 to –10 cbar. The easily available water ranged between -1 to -5 cbar, and the water buffering capacity occurred between –5 and –10 cbar (Montesano et al., 2016). This knowledge of the water availability in the substrate was used to define the maximum stress applied to the crops, ensuring that the values were far from the recommendations. As will be shown in the results, during this experiment, a difference in the water losses was detected in the coir; therefore, the last test included a second hydric stress reaching -10 cbar (Table 1).

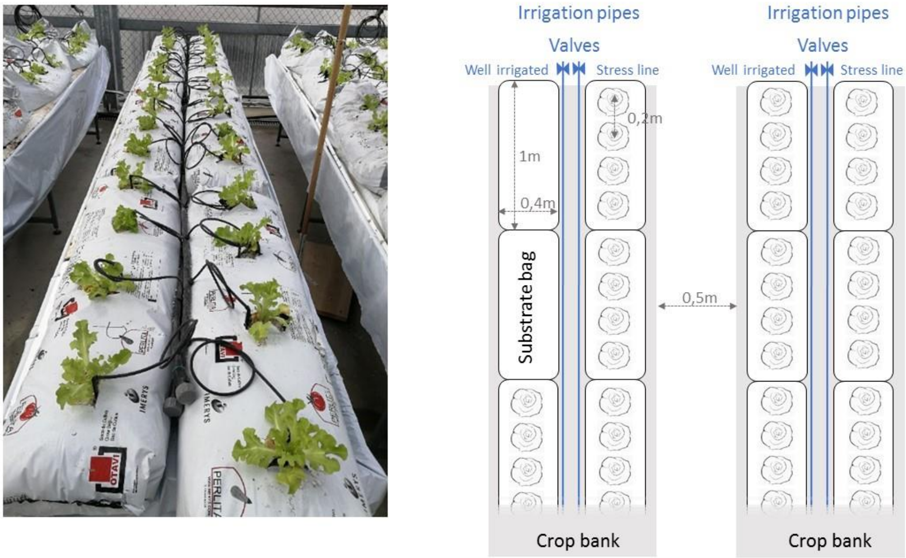


Figure 5-1 Schematic of the cultivation system design

Table 5-1 Schedule and meteorological conditions inside and outside the greenhouse during the three tests

		Test						
		1		2		3		
Transplanting		19/03/2018		03/05/2018		19/06/2018		
Harvest		26/04/2018		04/06/2018		18/07/2018		
Growing season		43 days		33 days		29 days		
Treatments		No stress	Stress -20 cbar	No stress	Stress -20 cbar	No stress	Stress -10 cbar	Stress -20 cbar
Hydric stress		06/04/18 to 20/04/18		22/05/18 to 31/05/18		10 cbar: 09/07/18 to 13/07/18		20 cbar: 09/07/18 to 16/07/18
Temperature inside	Max.	31.7		29.9		35.8		
	Min.	11.3		14.4		18.6		
	Avg.	19.57		20.52		26		
Relative humidity inside	Max.	68		86.2		83.2		
	Min.	9.2		25.2		19.2		
	Avg.	43.86		60.46		53.55		
Temperature outside	Max.	23		25.5		30,8		
	Min.	1.5		8.4		17,9		
	Avg.	13.21		18.3		24,49		
Relative humidity outside	Max.	100.1		100		100		
	Min.	17.3		30.4		30,3		
	Avg.	69.48		71.38		62,72		

5.2.4. Monitoring control; data collection and physicochemical analysis

Water flow characterization: Daily sampling was performed in each repetition of the tests, and the amount of irrigated water, the leachates drained and its conductivity and pH were measured. The volume of the leachates was measured using collection buckets (8 L) that were placed at the end of each line.

Characterization of the substrate: The bulk density test for each growth medium was performed by the ring method (USDA, 1999); the result is shown in Table 2, indicating the amount of water, the porosity and the bulk density. It was also shown the differential of the water content in each substrate between the well irrigation treatment and the stress irrigation treatment at the end of the study (θ %W-θ %S).

Crop sampling: Five crop samples were taken randomly from different repetitions of each treatment. The maximum diameter and height were measured weekly.

At the end of the test, when the crop was harvested, the final yield was determined (g of the commercial part of lettuce) as well as the water content (humidity %) with leaf samples that were oven-dried and weighed. For the commercial weight, 5 plants in each crop line were selected randomly, while for the water content determination, 3 plants were also selected randomly in each line.

5.2.5. 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 stress. All statistical tests were performed using “R” version 3.1.2 software (R Development Core Team 2014). The significance was tested using a one-way analysis of variance (ANOVA) (LSD test, $p<0.05$). Before the statistical analysis, the assumptions of ANOVA were checked by a Shapiro-Wilk test. A multiple comparison of the means was determined by a post hoc Duncan test. When the data were not normally distributed, a Kruskal-Wallis test was used followed by a post hoc Nemenyi test ($p<0.05$). This was the case for the characterization of the substrate, as the number of samples was smaller and there was no equality of variances for each group.

5.3.Results and discussion

The commercial production and the development of the crop was analyzed, and a difference was detected between the lettuces in the different substrates by comparing the first tests to the second test. Because one of the most important factors damaging the crop was water stress, the behavior of the substrates relative to their water content was previously explained.

5.3.1. Substrate characteristics

At the end of the three consecutive experiments, the bulk density (BD) for each growing medium was determined and is shown in Table 2. This information allows us to describe the porosity system behavior for each substrate under irrigation and water stress. The coir presented an 81% water content, the perlite showed a 14% water content, and the vegetable compost and substrate mixture showed 31% and 25% water contents, respectively. For the BD, the coir showed the lowest value, with 0,09 g cm-3, followed by perlite, mix and compost, the latter with 0,23 g cm-3 (Table 5-2).

Perlite: In this study, it was not possible to see a final compaction of this growing media, which was possible in all the other substrates. The conductivity of the leachates in the well irrigated perlite substrate ranged between 0.86 mS cm-1 and 1.90 mS cm-1 depending on the percent drainage or the water consumption of the plants.

Coir: The amount of water at the end of the assay for the well irrigated coir was 71.17%, as shown in Table 2. In comparison to the well irrigated perlite (57%), there was a 14% higher WC in the coir. Additionally, the coir showed the smallest BD of all the growing media used in this assay, with 0.1 g cm-3. This indicates the great potential of this growing media, having a very low weight and high water retention. The conductivity in the coir was constant throughout the study, ranging between 1.59 mS cm-1 and 1.70 mS cm-1.

Vegetable compost: The conductivity on the first day of the first test was 3.80 mS cm-1, which decreased over time, down to 3.40 mS cm-1 and 2.10 mS cm-1 at the beginning of the two other tests. At the end of the study, the compost leachates had a conductivity of 1.90 mS cm-1.

Mixture: The substrate mixture indicated values ranging between those of the compost and the perlite, as in the case of the EC of the leachates (2.27 mS cm-1) and the BD (0.17 g cm-3), indicated in Table 5-2. During the experiment, the EC of the leachate had the same decreasing tendency as that reported in the compost substrate.

In addition, to understand the behavior over time, the final water content (WC) □was evaluated together with the measures obtained daily with the tensiometers placed in each substrate.

Table 5-2 Physical characterization of the growth media

Growth media	Irrigation	Bulk density		WC		Differential at the end of the study	Leachates		
		Start	End	Start	End		Start	Max.	End
		g cm-3		□□ % [V/V]		(θ %W-θ %S)	EC		
Vegetable compost	S	0.23 ±0.02^{a}	0.29±0.04	31.62 ±0.99b	38.00±0.18cd	25.67	3.60	3.8	2.2
	W		0.29±0.03		63.67±0.05ab		4.03	4.9	1.9
Coir	S	0.09 ±0.00d	0.09±0.02	81.76 ±1.71a	38.50±0.07cd	32.67	1.59	1.7	1.9
	W		0.1±0.01		71.17±0.06a		1.67	2.2	1.6
Mixture	S	0.17 ±0.00b	0.18±0.03	25.29 ±8.46bc	31.17±0.05d	18.00	2.27	2.47	1.6
	W		0.17±0.03		49.17±0.05bc		2.77	3.5	1.7
Perlite	S	0.11 ±0.01c	0.13±0.01	14.43 ±15.96c	34.75±0.03cd	22.25	0.86	2.1	1.9
	W		0.12±0.03		57.00±0.05abc		0.83	3.45	1.5

S: stressed, W: well-irrigated, WC: water content, and EC: electrical conductivity in the leachates

Effect of water stress on the substrates

For the WC, it was possible to observe differences between irrigation management in only one case, that of the stressed coir and the well irrigated mixture. The coir showed a 32% higher water content (θ % well irrigation treatment - θ % stress irrigation treatment); in this sense, the mixture showed poor performance, at 18%. The vegetable compost and the perlite had a performance of approximately 25% and 22%, respectively.

Due to the different hydric curves of each growing media, the point of stress 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 test, when the perlite presented 19 cbar, the coir and compost presented -23 and 4, respectively. The period of stress was different throughout the three tests (Table 1) due to the temperature increase during the study, with each test showing higher temperatures than the previous test (Table 1). This induced the same water stress levels in less time.

Perlite: Focusing on the tensiometers, the perlite water holding capacity (WHC) remained constant through the 3 tests, with a progressive release of water content over time. When stress was induced, the variation in the percent drainage occurred in a matter of hours compared to the other substrates, which took approximately 2 days. This explained that after the stress period, the EC was very high at 3.45 mS cm-1, 2.95 mS cm-1 and 2.52 mS cm-1 for each consecutive test, indicating a higher concentration of salts in the bag. Moreover, it was detected that the major differences in the leachate conductivities of the well irrigated and stressed perlite bags were related to the duration of the stress periods and not just to the hydric tension of the substrate. As previously explained, the temperatures increased throughout the second and third tests, reaching the limiting - 20 cbar in shorter periods of time. This explains the lower EC values in the second test (9 days without irrigation) and the third test (7 days without irrigation) compared to the first test (14 days without irrigation) once irrigation was restored.

Coir: In tests 1 and 2, the coir showed a slow response to water stress, but when the matrix potential ranged between 5 and 8 cbar, it decreased rapidly. This agrees with the results obtained using the water retention curve, where the coir presented a high percent available water (27.60%), especially easily available water (23.06%). Compared with the perlite, its water loss was more progressive since perlite has 19.49% available water and 8.25% easily available water. Moreover, the measure of stress response decreased in the last test with the same hydric demand, and the growing media presented less tension in the pore system. It is possible that the coarse porosity collapsed with the different processes of irrigation and drought throughout the essay, creating a more complex porosity with a normalized pore distribution, which would explain its behavior during test number 3. The conductivity in the stressed coir was constant throughout the study, and no differences were detected in the well irrigated substrates.

Vegetable compost: Through monitoring with tensiometers, the compost showed a low response to hydric potential in tests 1 and 2 (4 and 17,5 kPa). In the last test, the compost had a similar behavior to perlite in both of the stress treatments (-10/- 20 kPa, with 15 and 25 kPa for compost and 11 and 20 kPa for perlite, Figure 2). Focusing on the retention curve, the compost presented a similar available water content (20.67%) as perlite, but the percent easily available water was higher (17.23%). The final water content of the stressed compost was similar to that of perlite and the water content when the compost was well irrigated. The increase of BD from 0.23 to 0.3 g cm^{-3} can be explained by the fact that the general irrigation management of the essay was adjusted to the perlite demands. This could have meant a higher irrigation input during tests 1 and 2, which could have favored the arrangement of particles, and for concomitance, the increment of the bulk density. Moreover, when irrigation was stopped, no leachates were detected, and after the stress period, the EC was the highest among the substrates.
Specifically, in the first test, the leachates were detected 6 days after irrigation was reestablished, and the conductivity was 4.70 mS cm-1. For the other two tests, the leachates were recovered after two days, and the conductivity was 3.70 mS cm-1 and 2.20 mS cm-1. Nevertheless, this finding highlights that at the end of each test, the conductivity of the leachates was the same in the stressed crops as in the well irrigated crops.

Mixture: For hydric potential, the mixture showed an intermediate performance between the compost and the perlite in the water stress treatment during the first test, while during the second and third tests, it showed a high response to hydric potential, with a lower value (27 cbar) compared to the control (perlite with 20 cbar) (Figure 5-2). This is consistent with results obtained in the water retention curve as the percent available water and the easily available water ranged between the values obtained in the compost and the perlite (19.20% and 11.79%, respectively). This could be explained by the mix having a poor water content performance. The well irrigated and stressed 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 g cm-3; the BDs of the compost and perlite at the start of the essay were 0.23 and 0.11 g cm-3, respectively. At the end, the compost showed a slight compaction (0.29 g cm-3), but this was not the case in the mixture. The EC was similar, but its behavior was closer to that of the perlite than that of the compost. In the case of the electric conductivity, the mixture had the same pattern as the compost, but the conductivity was approximately the average between the electric conductivity in the compost and the perlite. For example, at the beginning of the three tests, the EC was 2.50 mS cm-1 (test 1), 3.30 mS cm-1 (test 2) and 1.80 mS cm-1 (test 3). The highest values after the stress period were 2.87 mS cm-1 (test 1), 2.36 mS cm-1 (test 2) and 2.20 mS cm-1 (test 3). Nevertheless, as shown, the differences between the well irrigated treatment and the stressed treatment are smaller than those of the compost.

If we consider the difference in water content from the well irrigated and the stressed substrates as the available water for the crop, it is possible to determine and quantify the number of days before it has to be watered again. For a crop having an evapotranspiration (ETc) rate of 3 mmd-1, the compost would need to be watered after 8.5 days and the coir could last up to 10.9 days while the mixture and perlite would take 6 and 7 days, respectively.

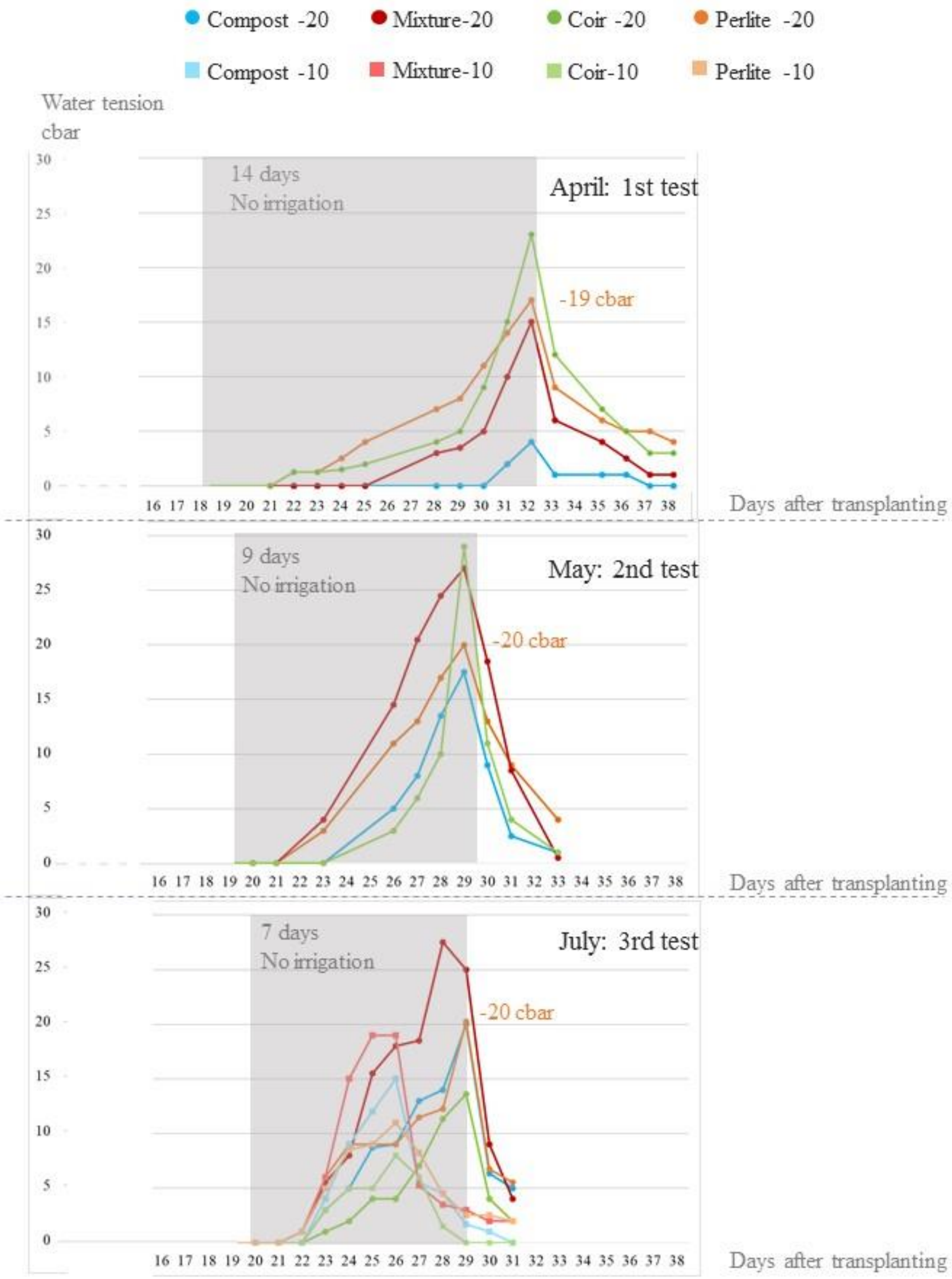


Figure 5-2 Water tension inside the bags of each substrate under study after inducing water stress up to -20 cbar (tests 1, 2 and 3) and -10 cbar (test 3). Tested substrates: vegetable compost, a mixture of compost and perlite in a 1:1 volume, coir and perlite (the control substrate)

5.3.2. Crop production

The crop yields ranged from 242.0 to 490.0 g plant-1, and some differences were detected due to the substrates, the effect of water stress and the meteorological conditions (Table 3). 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). 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 stress period, production decreased, but the magnitude of these losses were different among the substrates.

Conventional irrigation

During the first test (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. Comparing tests 1 and 2, different results were obtained. In test 2, when appropriated irrigation was applied, the 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 significantly lowest production (423.9 g plant-1, 14% less weight). In this test, the best results in the well-irrigated crops were obtained with compost alone (408.7 g plant-1) and compost mixed with perlite (418.4 g plant-1). Compared to the substrate with highest obtained weight, the coir presented the lowest production (370.1 g plant-1), -11.5% less. The behavior of the compost was especially different than those of the other substrates. The lettuce grown in the compost presented successive decreasing weights with the three consecutive tests (Table 5-3). This difference could be due to the fact that in the first test, the vegetable compost was new and could provide a large quantity of nutrients to the lettuce. However, in May, a nutrient depletion was detected by measuring the electric conductivity of the leachates, as noted in the previous section. The conductivity of the compost leachates ranged between 4.77 and 3.60 mS cm-1 in April, between 3.70 and 2.47 mS cm-1 in May and between 2.8 mS cm-1 and 2.2 mS cm-1 in July. Furthermore, a compaction of the substrate was detected, and this could be a further reason for the production decrease (Mastouri et al., 2005).

Water stress effect

Some differences were detected when the crops were under stress. In the first test, compared to the control, the mixture and the coir substrates, the plants grown in the compost reached higher weights (322.5 g plant-1). These results agree with (Mastouri et al., 2005), who detected that the growth of lettuce increased as the contribution of either type of compost in the growing media increased. Specifically, the production in the soil obtained in that study was 282.2 g plant-1, and the highest production using a mixture of tree bark compost was 308.9 g plant-1. These results demonstrate that the vegetable compost from green urban 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 (Annex I). Previous studies have suggested that the yield decrease could have been due to exaggerated 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 (not osmotic) potential (Wallach, 2008). As previously shown, the conductivity of the leachates did not change after the stress periods, which could cause a concentration of salts in the substrate.

In the second test, in all the treatments, compared to the well-irrigated crops, the production in the water-stressed crops 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 test were not detected here. Second, because the other three stressed substrates presented an increase in production compared to the first test (25-30%), the production obtained in compost was similar to that in the first test (320 g).

Compared to the previous tests, during the third test, the higher temperatures induced a more rapid appearance of water stress (Figure 5-2). Whether the stress reached -10 cbar or -20 cbar, the lowest production was obtained in the perlite bags. When the stress reached -20 cbar, the mixture and the compost substrates presented the best results (295.2 and 284.9 g plant-1, respectively). Nevertheless, when the stress did not exceed -10 cbar, the crops grown in the coir and the mixture reached the highest production values (358.9 and 350.3 g plant-1). These results could have been perceived when analyzing the water loss curves of the different substrates. As shown in the previous section, in the first test, the coir took a long time to lose water; however, when dryness begins, water loss occurs very quickly and can damage crop production.

Table 5-3 Evolution of the crops during the three tests: commercial production (g/plant), average diameter (cm) measured weekly and tipburn damage (% of the plants with tipburn symptoms). Different letters (in columns) represent significant differences ($p < 0.05$).

Commercial production (g/plant)

		Compost		Mixture		Coir		Perlite	
April	Well-irrigated	**445.67**	**a**	**427.14**	**a**	**422.67**	**a**	**445.01**	**a**
	Stressed -20	322.55	b	*242.05*	*c*	*277.46*	*c*	*259.25*	*c*
May	Well-irrigated	423.86	b	**477.18**	**ab**	**453.71**	**ab**	**490.03**	**a**
	Stressed -20	*320.19*	*c*	*323.50*	*c*	*348.53*	*c*	*340.70*	*c*
July	Well-irrigated	**408.67**	**ab**	**418.40**	**a**	370.31	c	381.82	bc
	Stressed -10	336.29	ed	350.27	cde	358.88	cd	322.43	f
	Stressed -20	284.98	g	295.16	fg	*276.13*	*gh*	*245.67*	*h*

Lettuce diameter week 2

		Compost		Mixture		Coir		Perlite	
April	Well-irrigated	**19.43**	**a**	**19.07**	**ab**	**18.53**	**ab**	*16.05*	*bc*
	Stressed -20	**19.30**	**a**	**19.22**	**ab**	**18.40**	**ab**	*16.50*	*c*
May	Well-irrigated	19.70	-	20.43	-	18.00	-	18.35	-
	Stressed -20	19.20	-	20.17	-	19.83	-	20.65	-
July	Well-irrigated	**26.00**	**ab**	**26.47**	**ab**	**27.23**	**a**	*23.40*	*c*
	Stressed -10	**26.91**	**a**	**27.29**	**a**	**27.38**	**a**	*25.25*	*bc*
	Stressed -20	**26.20**	**ab**	**26.43**	**ab**	**26.80**	**a**	*23.35*	*c*

Lettuce diameter week 3

		Compost		Mixture		Coir		Perlite	
April	Well-irrigated	**28.80**	**a**	26.47	bc	**28.40**	**abc**	*24.10*	*d*
	Stressed -20	**28.73**	**abc**	26.13	c	**27.93**	**abc**	*24.18*	*d*
May	Well-irrigated	26.40	ab	**27.63**	**a**	**27.73**	**a**	**27.70**	**a**
	Stressed -20	*25.07*	*b*	**28.20**	**a**	**28.47**	**a**	26.70	ab
July	Well-irrigated	**39.57**	**ab**	34.70	de	**38.10**	**abc**	*31.30*	*f*
	Stressed -10	**39.55**	**ab**	36.75	cd	**39.08**	**abc**	*31.56*	*ef*
	Stressed -20	**39.43**	**ab**	37.23	bc	**40.10**	**a**	*33.40*	*f*

Lettuce diameter week 4

		Compost		Mixture		Coir		Perlite	
April	Well-irrigated	**33.93**	**a**	31.67	abc	**33.60**	**ab**	*30.00*	*bc*
	Stressed -20	31.73	abc	*29.47*	*c*	**32.47**	**ab**	*29.00*	*c*
May	Well-irrigated	*36.40*	*cd*	**39.07**	**abc**	**38.53**	**abc**	36.80	bc
	Stressed -20	36.87	bc	**40.00**	**abc**	**40.47**	**a**	*34.70*	*d*
July	Well-irrigated	**54.87**	**a**	**52.07**	**abc**	**53.87**	**ab**	**54.40**	**a**
	Stressed -10	49.55	bc	*47.92*	*cd*	**50.83**	**abc**	*44.50*	*d*
	Stressed -20	**52.47**	**ab**	*47.73*	*cd*	**52.20**	**abc**	*44.50*	*d*

Lettuce diameter week 5

		Compost		Mixture		Coir		Perlite	
April	Well-irrigated	**39.73**	**a**	**37.80**	**ab**	**39.47**	**a**	36.70	bc
	Stressed -20	35.33	cd	*33.13*	*de*	35.27	cd	*32.00*	*e*
May	Well-irrigated	**47.13**	**ab**	**46.73**	**ab**	**49.00**	**a**	**46.90**	**ab**
	Stressed -20	*42.00*	*c*	45.33	b	**48.53**	**a**	*40.50*	*c*
July	Well-irrigated	**61.93**	**ab**	**60.60**	**abc**	**62.40**	**a**	57.70	de
	Stressed -10	**61.68**	**ab**	58.67	cde	59.67	bcd	54.75	f
	Stressed -20	56.93	e	54.53	f	54.33	f	*46.50*	*g*

Lettuce diameter week 6									
		Compost		Mixture		Coir		Perlite	
April	Well-irrigated	**43.87**	**a**	**42.13**	**a**	**43.93**	**a**	**43.60**	**a**
	Stressed -20	39.20	b	*35.07*	*c*	*36.13*	*c*	*35.30*	*c*
May	Well-irrigated	**62.53**	**a**	59.00	b	**61.27**	**ab**	**60.90**	**ab**
	Stressed -20	55.67	c	54.87	dc	*52.53*	*de*	*52.20*	*e*

Tipburn (damaged plants)					
		Compost	Mixture	Coir	Perlite
April	Well-irrigated	70.8%	66.7%	83.3%	37.5%
	Stressed -20	100.0%	95.8%	91.7%	40.6%
May	Well-irrigated	35.4%	20.8%	35.4%	15.6%
	Stressed -20	14.6%	37.5%	31.3%	9.4%
July	Well-irrigated	2.1%	0.0%	2.1%	0.0%
	Stressed -10	3.1%	2.1%	4.2%	2.1%
	Stressed -20	4.2%	4.2%	6.3%	3.1%

5.3.3. Lettuce development

Conventional irrigation

The evolution of lettuce head diameter both in the different substrates and in the stressed bags also presented some differences (Table 5-3).The first differences were observed in the second week. The diameters of the plants grown in the perlite were smaller (16.1 cm) than those in the rest of the substrates (approximately 19 cm). This difference was maintained throughout the rest of the growing period in all three tests. Although the plants at the end of the tests had an equal or greater size (43 cm) than those in the other substrates, the initial diameter could have conditioned the final weight in the harvested production, which was lower.

It should be noted that the plants in the second test were larger than those in the first test. For example, at harvest, the lettuce grown in the vegetable compost during the first test measured 43.9 cm, and the lettuce grown in the second test measured 62.53 cm. The same percent diameter increase was detected in the other substrates (approximately 40%). In the third test, the final diameter was similar to that in the second test, ranging from 54-62 cm, but this size occurred one week earlier. These differences could be due to the temperature (and radiation) increase inside the i-RTG Lab (Table 5-1)

Water stress effect

The effects of stress were consistent and significant on the crop growth. On the 5th week, differences between the well-irrigated crops and the stressed crops were detected in the three tests. However, there were some particularities detected in the different substrates. The decrease in growth in the compost was approximately 4.5 cm compared to the well-irrigated lettuce in all the tests. In the mixture and the coir, the major difference due to water stress was detected in the third test (6 and 8 cm, respectively) and was smaller in the second test (1.5 cm). Perlite was the substrate that showed the largest differences due to stress, and in the third test, the diameter was 11 cm smaller than that of the well-irrigated lettuce.

The loss in size did not recover once irrigation was restored, and in all the treatments, a diminution of the diameter at harvest was detected. As shown previously, stress not only implies an increase in the hydric tension of a substrate but also causes an increase in the salt concentration. Specifically, this was detected in the perlite, since the electric conductivity reached 3.45 mS cm-1 in the leachates during the first test, specifically after the stress period (an increase of 300%).

There are several studies showing the diminution of lettuce growth due to salt stress (Ahmed Al-Maskri et al., 2010).

Tipburn damage

Another factor that damaged most of the crops was a lack of calcium detected on the leaves, i.e., tipburn (Table 3). An aspect that aggravated this disorder was an elevated nighttime temperature with a decrease in relative humidity at night (Maroto Borrego and Baixauli Soria, 2017). In the i-RTG Lab, the relative humidity (RH) is usually very low (Table 1). In this study, the average RH was 51.26%, and the minimum RH was 9.2%. This means that there was a very high vapor pressure deficit, possibly causing a decrease in transpiration. This could be due to a partial closure of stomata or a high demand of water that the plant could not satisfy. Furthermore, temperature oscillations also aggravate these symptoms. For this reason, tipburn is particularly detected in crops produced during spring (the 1st and 2nd tests, when the temperature inside the greenhouse fluctuated heavily, with some peaks reaching higher than 30ºC and lower than 12ºC) (Table 1). (Saure, 1998) detected that there was a high risk of tipburn if there were changes in temperature, i.e., a rapid period of warm conditions after an extended period at a lower temperature or several days of high temperature combined with low humidity. Previous studies have detected that lettuce grown on soil were free from tipburn, while plants in a soilless culture, especially in perlite, showed significant tipburn symptoms (Siomos et al., 2001). Nevertheless, in this study, the crops in the perlite bags were not the most damaged by tipburn ($p<0.05$) (Table 5-3).

Specifically, in the first test, tipburn mostly damaged the plants grown in coir (65% of the plants damaged in the fourth week and 83% on the harvested plants). Of the plants grown in compost, 37% showed symptoms. The symptoms increased during the last week, damaging 71% of the plants in the end. In the fourth week, 43% of the plants grown in perlite presented tipburn; nevertheless, at the end of the crop this percentage did not increase, unlike occurred in the other substrates. Therefore, in the April meteorological conditions and when the compost and coir were used for the first time, both of the substrates aggravated the presence of tipburn. This could be because the lettuce grown in the compost and coir developed faster than that in the perlite. Previous studies have detected that growth rate is correlated with tipburn incidence (Wissemeier and Zühlke, 2002). Leaves with faster growth are more susceptible to developing symptoms. In this study, the plants grown in compost had a large amount of nutrients available from the fertigation and the substrate. This fact accelerated the growth of the leaves, causing a lack of calcium.

In the second test, a similar situation was detected but with a lower incidence of tipburn. The crop grown in the coir showed 31% damaged plants, the lettuces grown in the compost presented 14.6% tipburn and the lettuces grown in the perlite were significantly ($p<0.05$) less damaged (9.4%). The decrease could be due to a higher transpiration of the leaves The temperature inside the i-RTG Lab and the radiation were higher than those in the previous month (Table 5-1). This means that larger quantities of calcium were transported by flow mass to the leaves. Moreover, the diurnal-nocturnal temperature changes were less abrupt in the second test than in the first test, and the RH was higher in the second test than in the first test.

In summer, no differences were detected between the treatments, and despite the faster growth of the lettuce, the tipburn damage ranged between 0 and 4%. This result could be for two reasons. First, in this study, there was a greater influence from meteorological changes than the growth rate (as in tests 1 and 2, all the crops presented symptoms). Even small stresses may be sufficient for causing injuries (Saure, 1998). Second, because the salinity of the substrates also had an important influence (Maroto Borrego and Baixauli Soria, 2017), as presented previously in the case of the compost and the mixture, the EC of the soil decreased consecutively over the three cropping periods (Table 1). Thus, to increase the symptoms of tipburn, growth rate is an important factor, but the meteorological conditions seemed to be even more relevant. The attempts to explain the effect of external factors on the occurrence of tipburn and the damaged leaves are not conclusive. Nevertheless, the results relate the greater appearance of tipburn to periods with worse climatic conditions (high variability in temperatures and a lower RH), as was recorded during the first test. Low RH can impose stress on plants that causes some change in physiological processes, eventually resulting in injury as a physiological disorder. The next section presents the increase in tipburn incidence when water stress is applied.

Tipburn damage with water stress

According to our results, water stress aggravated the tipburn effect on the lettuce. In the first test, the stressed crops showed a tipburn appearance of 98% in the compost, 96% in the mixture and 83% in the coir. The positive behavior of the perlite regarding tipburn was demonstrated, as the symptoms in these stressed lettuce were significantly lower, 60%. During the second and third tests, no significant differences were detected in the different stressed treatments; nevertheless, in the second test, the number of damaged plants grown in perlite (15.6%) was lower than the damaged lettuces grown in compost and coir (35% in both cases).

The symptoms of tipburn detected in the crops grown in the mixture in all the tests ranged between those detected in the perlite and the compost. Tipburn was detected especially during the first test. This could be due to the fact that the mixture provided intermediate characteristics to the compost in nutrient content and the composition of the substrate. This involves faster crop growth than when using perlite but slower than when using 100% compost. This evidence supports the previous suggestion that tipburn development is related to growth rate.

Percent plant water content

Finally, the water content in the plant also changed between the irrigated crops and the stressed crops during July (the test during which major yield differences were detected due to water stress). No differences in the dry weight were observed among the treatments. Thus, the irrigation treatments had little or no effect on the biomass production, and the differences in the fresh weight resulted from differences in the plant water content. The major content of dry matter (%) was detected in the stressed crops, and the highest value was in the perlite (1.89% dm). On the other hand, the dry weight of the irrigated crops ranged between 0.59% and 1.22%. Focusing on the well irrigated crops, the lettuce grown in the compost and perlite substrates had more dried matter, but the percentages were lower than the average referenced in the bibliography (Maroto Borrego and Baixauli Soria, 2017; Siomos et al., 2001). In general, the plants harvested from the soilless cultures had a lower dry matter content (approximately 4.5%) than that of soil crops (Siomos et al., 2001). These differences in water content compared to the values shown in the bibliography could be due to the fact that in the present study, only a leaf sample was dried. The lettuce stem, which is used for nutrient storage, was not sampled (da Silva Cuba Carvalho et al., 2018).

5.3.4. Relevance in UA

As has been shown, the vegetable compost and the mixture of vegetables compost with perlite are suitable substrates in horticulture and especially in RA. In addition, 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), in this study, the production obtained was markedly competitive and higher than that of perlite in April and July. Lettuce is a crop that is moderately sensitive to salinity, similar to most of the crops used in RA (FAO 2018): pepper, tomato, spinach, cauliflower, cucumber, and eggplant. Therefore, the results obtained in this study could be directly applied to other horticultural crops.

5.4.Conclusions

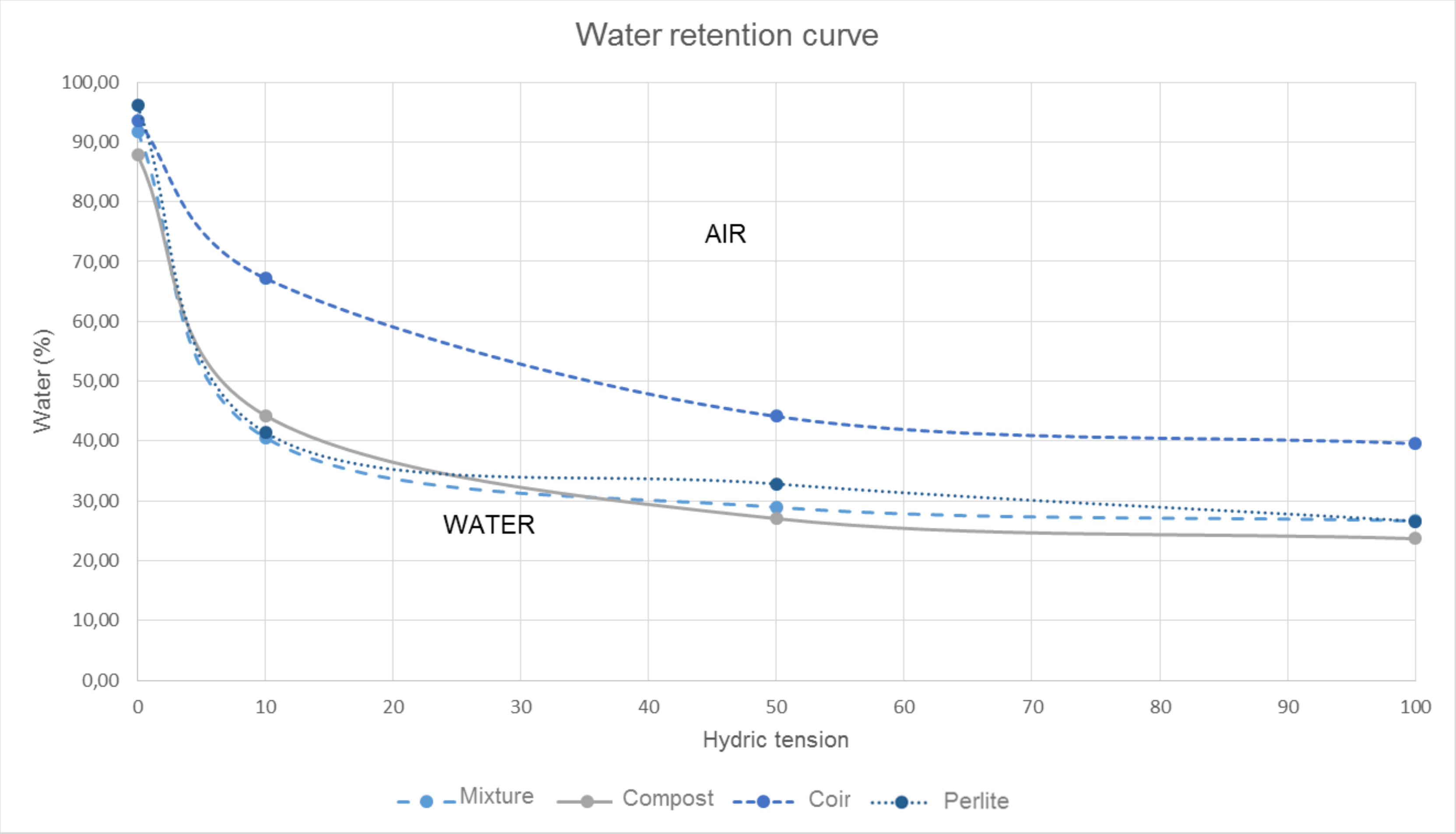
This analysis quantified the agronomic performance of lettuce grown in organic substrates, including their resilience to water stress. In the circular city context, the study of the agricultural performance of environmentally friendly substrates (recycled organic municipal waste in cities) can contribute to RA implementation in Mediterranean urban areas. Previous studies have addressed the environmental impacts and benefits of using coir and compost as substrates (Barrett et al., 2016; Grard et al., 2018), while we considered the development of the crop and commercial production. 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 greater production than the control substrate (perlite). In summer, the best results were obtained with vegetable compost alone (408.7 g plant-1) and compost mixed with perlite (1:1) (418.4 g plant-1). Nevertheless, a sequential decrease in the lettuce fresh weight grown in compost in the three tests was detected, probably due to the loss of nutrients in the substrate.

We also presented the first quantitative assessment of the agronomic response of water stress conditions in three alternative substrates of perlite in the urban Mediterranean context. We found that compared to perlite, the organic substrates improved the conditions against applied water stress and increased the yield of the crops. 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 a water stress of -20 cbar, the compost and the mixture of compost and perlite present great agronomic resilience.

These results contribute to the knowledge of environmentally friendly UA and preventive measures of droughts in Mediterranean cities with quantified data. In the current context of climate change, with increasing droughts in summer, commercial systems that utilize compost as a growing media could potentially reduce irrigation frequency, saving water without increasing the salinity of the substrate, and still produce commercially relevant yields. However, further studies should determine the optimal irrigation and nutrient inputs for improving the growing conditions to increase harvest weight. Additionally, how this optimization could minimize the environmental impacts for a unit of lettuce and for a kg of lettuce should be studied in a detailed life-cycle assessment. More research is needed to contribute to the environmental analysis of this substrate, taking into account the life of the substrates and the impacts of their waste management (probably composting).

Moreover, there was an appearance of tipburn in most of the crops, especially during spring. This symptom was largely detected in the organic substrates rather than the perlite, and it was aggravated with the highly variable meteorological conditions in the i-RTG Lab. More studies should be performed to guarantee the commercial requirements, improving the management of the substrates and the meteorological conditions.

5.5. Supporting information for chapter 5



Supporting information 1. Substrates (Compost, mixture, coir and perlite) water retention curve

Chapter

06

Analysis of the consumer's perception of urban food products from a soilless system in RA

CHAPTER 6 - Analysis of the consumer's perception of urban food products from a soilless system in RA

This chapter is based on the journal paper:

Ercilla-Montserrat, M., Sanjuan-Delmás, D., Sanyé-Mengual, E., Calvet-Mir, L., Banderas, K., Rieradevall, J., Gabarrell, X. Ercilla-Montserrat, M., Sanjuan-Delmás, D., Sanyé-Mengual, E., Calvet-Mir, L., Banderas, K., Rieradevall, J., Gabarrell, X., 2019. Analysis of the consumer's perception of urban food products from a soilless system in rooftop greenhouses: a case study from the Mediterranean area of Barcelona (Spain). Agric. Human Values 1–19. http://doi:10.1007/s10460-019-09920-7

Abstract

Soilless crops are commonly used in rooftop agriculture (RA) because they easily adapt to building constraints. However, acceptance of the produce derived from this system may be controversial. This paper evaluates consumers' acceptance of food from RA in Mediterranean cities, focusing on the quality of the product, production system, and consumers' motivations. We surveyed 238 respondents on the UAB university campus as potential consumers. The survey was distributed via an Internet-link that was provided along with a sample of tomatoes from RA. The results showed that most people approved the quality of RA products and perceived them to be local and fresh (94%). The respondents exhibited acceptance of soilless-produced tomatoes and considered them to be environmentally better than conventionally produced ones (69%). Cluster analysis revealed that consumers with high income levels and a university education had a better perception of the quality and proposed a higher price for RA products, but no difference was found regarding their environmental perception of this products. Moreover, people who possessed more information about the product also had a higher perception of the quality and production system (it was perceived to be environmentally friendly) and would pay more for them. The main concerns of consumers were related to food safety and the social impact of RA. Additional research is needed to improve the sustainability of RA, and the applied measures should be communicated to potential consumers to enhance their acceptance and success.

Keywords: urban agriculture; rooftop agriculture; local food production; local consumption; food self-supply

PART 03

Final remarks and further research

Chapter

07

Discussion of the main contributions

CHAPTER 7 - Discussion of the main contributions

This chapter discusses the main contributions of this thesis and the applications that these contributions could have in the UA development. The study is framed in urban and periurban environments and seek to provide quantitative results to assess the quality of rooftop agriculture (RA) and the products grown in the different facilities (heavy metal pollution, biological air quality). Indeed, the measurable and perceived quality is the main topic that connect the research carried out. Moreover, it provides different strategies to adapt agronomic production in the context of RA in cities to increase the system quality. From the strategies studied, the research of resilient substrates to hydric stress is the strategy with a higher climate change mitigation potential, because it integrates a solution for present and future water scarcity and also proposes more sustainable materials to be used instead of perlite (Figure 7-1).

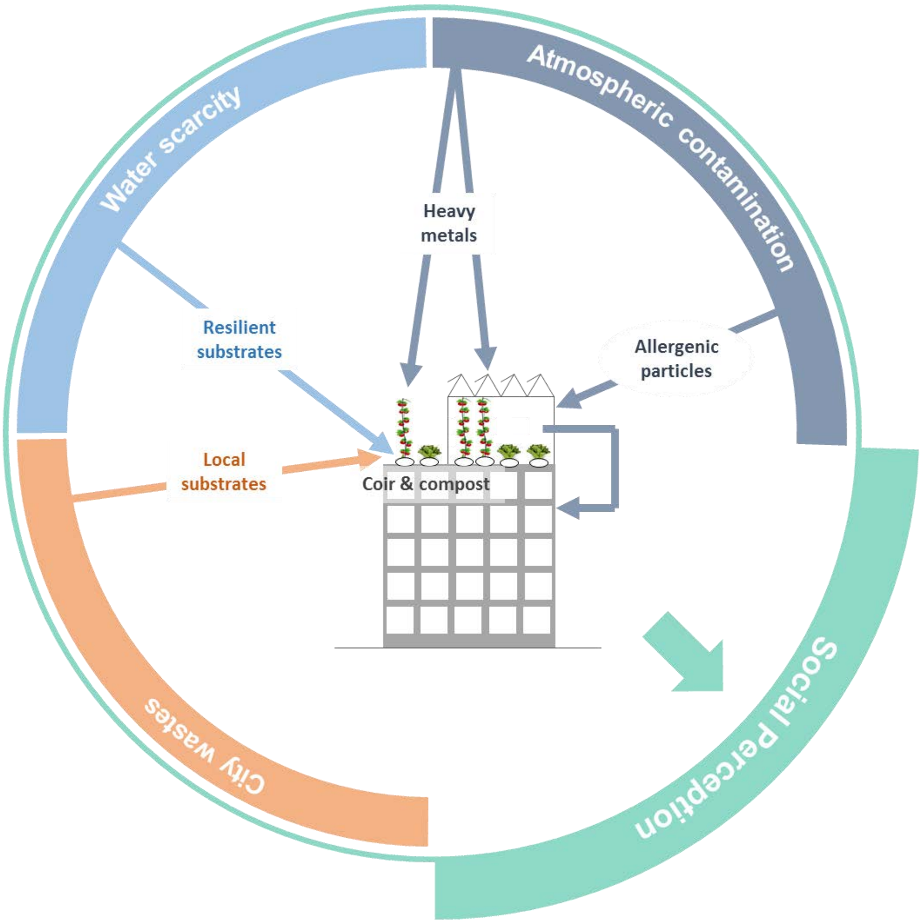


Figure 7-1 Scheme of the main research conducted in the present dissertation

7.1.1. Analysis of potential air contamination

Although there is a large amount of literature on air pollution and despite the efforts made by the administration to improve this actual problem (Direcció General de Qualitat Ambiental et al., 2017), the possible effects of air pollutants in urban crops are a key issue to be resolved. First of all, because there has been very few studies in which atmospheric concentrations and food contamination are assessed at the same time and at the same place. As in this study a soilless cultivation system was used, it is possible to evaluate separately the air as a contamination vector and remove the effects of soil contamination (Pennisi et al., 2016). This methodological proposal, presented in Chapter 3, is an advance for the planning of UA. Firstly, because ultimately it is proposed to make atmospheric pollution maps that can be overlay on UA planning maps. Second because it also allows to combine atmospheric pollution maps with soil contamination maps and detect those contaminated spaces where it is essential to implement soilless culture systems (SCSs). These pollution maps can be added to those resulting of the application of the methodology presented by Nadal (2017) where building roof parameters determine the constructing RA potential. According with bibliography (Finster et al., 2003; Pennisi et al., 2016; Peris et al., 2007) our results demonstrate that SCS are a good option in the urban context with a high potential to be used both on rooftops and in spaces with highly contaminated soils.

Another important issue it the biological air quality, especially in protected environments. Adequate assessment of human exposure to biological aerosols has been recognized as an important need, as many studies have linked adverse health effects to bioaerosol hazards (Burge and Rogers, 2000; Douwes et al., 2003). Fungal spores and pollen grains are the major components of airborne biological contaminants (Nayar and Jothish, 2013) and it were detected high levels of theme inside i-RTG under study (Chapter 4). Some studies assessed the indoor air quality, especially for occupational and public health buildings (Bonetta et al., 2010). Nevertheless it is not possible to assess if these values are able to evoke allergenic symptoms, as an official threshold for fungal spore concentrations has not been established, and different authors have proposed different levels, such as 10^5 spores/m^3 (Eduard, 2009) or 10^3 spores/m^3 (Santilli and Rockwell 2003). In terms of greenhouse air spore concentration, there are less bibliography about workers exposure and as far as we know it has never been studied in an urban greenhouse. The main contributions of this dissertation were firstly, to assess for the first time the biological contamination inside an urban greenhouse and delve into the dynamics of allergenic particles. And secondly, to provide information to advice on preventive measures for workers and for users of the building in case the air is used to heat the building: with this strategy a waste (hot air) from one system (the greenhouse) can be used for another system (the building) as a strategy to promote circular buildings in cities.

The most effective way to decrease the allergenic contaminants inside the indoor environment is to remove the conditions that favor the establishment and growth of fungi in concordance of (Haleem Khan and Mohan Karuppayil, 2012) and prevent the entering of any outdoor particles. It can be done most effectively by managing the ventilation rate –according to seasonal crop needs-taking into account the outside contamination and installing adequate filtration systems (Hänninen, O. and Asikainen, 2013). Moreover, as some agricultural management tasks could cause high levels of pollen grains and fungal spores inside the i-RTG, they have been deepen studied. As the most critical tasks have been determined (such as pollination by hand, fungal treatments, sweeps and crop removal) it is possible to give some recommendation to workers about the most critical moments to protect themselves and stop the recirculation of residual i-RTG inside the building.

An additional contribution of this dissertation is to assess the potential air contamination barrier effect of greenhouses on the rooftop crops. It should be highlighted that it is a greenhouse with higher ventilation rates than a conventional greenhouse (Montero et al., 2017; Nadal et al., 2017). According to our results in the case of heavy metals there is no detected a barrier effect on the air quality. It is important to remember that the concentration of heavy metals in the air was very low, which made it difficult to detect differences between the sampling points. However, in the case of aerobiological allergenic pollutants there were important differences between the interior and external air of the greenhouse. This divergence can be due to the dynamics of the two kinds of contaminants (heavy metals and biological particles) make the difference, considering their weight, adherence to other solid particles, susceptibility to being washed by rain and other factors.

In the case of heavy metals, a first approach of the rainwater effect was done linking with the greenhouse barrier effect. The results suggest that there are some relation between air quality, heavy metal concentrations in crops and rainfall patterns. More research is needed to determine if rainwater act as a source of contaminant into the crops or as a cleaning agent to different potentials contaminants introduced by the air.

7.1.2. New substrates in the circular economy and climate change framework

The use of compost to grown different crops is not new, but this dissertation is probably one of the first studies that adapt this material in the actual and future of the Mediterranean cities in high-tech systems. Previous studies have addressed the environmental impacts and benefits of using compost as substrates (Barrett et al., 2016), while we considered the development of the crop as well as commercial production. The strength of this thesis is first to propose a better alternative to perlite in the framework of the circular economy agronomical competitive. Secondly, evaluate if these solutions also contribute to mitigate the effects of climate change, focusing on the effect of summer droughts

In the framework of the circular economy the management of organic waste is a key issue to be solve as actually it is cause of environmental pollution and nutrient loss (UN-HABITAT, 2010). Making the compost suitable to peri-urban farmers would contribute to drive efforts in cities to collect and make the most of it. For this reason the circular economy guidelines remark the opportunity of this material. Composting is a win-win option that allows not only reducing environmental pollution derived by open dumping of waste but also recovering a material that could be used in the same place. In this research one more step was done, as it is an environmentally friendly alternative to perlite as demonstrate in previous studies (Barrett et al., 2016; Grard et al., 2018). The objective was to test if the compost obtained in a city could be used as a substrate in the same city. In agronomic terms the results obtained demonstrate that it is possible to use vegetal compost as a unique substrate. Combining the use of compost with high-tech solutions such as an adequate fertigation system and aclimate greenhouse control system, allows to produce commercial yields of high-quality food. In the same sense, previous studies suggested that crop production in compost could decrease yield due to salt concentrations (Mastouri et al., 2005), in this study, the production obtained was markedly competitive. This was because vegetable compost was used instead of compost from organic fraction of municipal solid waste (OFMSW) or livestock waste. Vegetable compost has a lower conductivity, nutrient content, organic matter stability and C/N ratio than that of OFMSW or livestock waste (Barrett et al., 2016). For this reason the use of vegetable compost is a strongly recommended option.

Nevertheless, compost not only is an interesting material in circular economy strategies because it could be produced with materials from cities and inside cities. Moreover, it is a substrate that could increase the water stress resilience of crops as it is presented in Chapter 5. In the current context of climate change, with increasing droughts in summer, this is a central topic to guarantee food segurity in cities.For example (FAO, 2018) said that a more pro-active approach based on the principles of risk reduction is needed to build greater resilience to droughts. Commercial systems that utilize compost as a growing media could reduce irrigation frequency, saving water without increasing the salinity of the substrate, and still produce commercially relevant yields.

7.1.3. The role of consumers in RA development

Another particularity of this dissertation is the social analysis approach. Previous literature has been focused on different stakeholders of RA, nevertheless, the potential consumers have never been asked about their perception of RA. In general, the dissertation provides new information regarding the perspectives of potential consumers, which would dispel the concerns detected between UA promoters. This research gap was addressed through two methodological proposes:

- Take advantage of having food from a real i-RTG in the ICTA-ICP building. The study was performed in two separate campaigns to evaluate differences between people who knew the i-RTG project and people who did not. So, this new approach uses for the first time, a demonstrative activity -as a visit to a real i-RTG- to study the effects of know the production system of food and participate in pilot projects. This is necessary to study the development and changes of RA perception. In this context, some studies can be found in previous literature analyzing from a theoretical perspective consumer perception, but there are few articles assessing real case studies. This example shows and contributes to demonstrate that people who possessed more information about environmental friendly RA products also had a higher perception of the quality and production system and would pay more for them.

- The survey was performed with the food samples that the participants were asked to taste. This means that not only the rational perception of RA was assessed but also more subjective perception (related with sensorial characteristics).

Moreover, the main concerns detected among consumers about RA were related to food safety, heavy metal contamination, the use of organic practices in soilless and the sustainability of this systems. Most of these points have been addressed in this dissertation and discussed in the previous sections. The results presented on contamination by heavy metals or the use of environmental friendly substrates shed light on the concerns of consumers. If all this information could be transferred to the consumers, their distrust could decrease and, thus, the social acceptance of these systems could increase.

For this reason, this dissertation aimed at conducting a complete and comprehensive assessment of RA quality where quantitative and subjective aspects are presented in the same document, visualizing the interactions between them. Public administration and UA companies should focus on strategies to improve the environmental performance of production, such as those presented in this dissertation (use of SCS in contaminated soils areas, use of organic substrate, control the biological air quality inside RTGs) and other strategies such as reuse of leachates or rainwater in irrigation or the use of renewable energy. All of these environmentally friendly measures should be communicated to potential consumers to improve perception of the product. Additionally, the implementation of quality control standards for products and growing facilities by administrations can help increase consumers' trust.

Chapter

08

General conclusions

CHAPTER 8 - General conclusions

This section addresses the main conclusions of this dissertation based on the four research questions defined in Chapter 1:

Question 1: Does atmospheric heavy metal pollution in cities contaminate RA and RTG crops?

This research has proven that the production of food in soilless systems in the urban and periurban environment is feasible and is free of heavy metals. It has been analyzed simultaneously the heavy metal pollution in the air and the crop. From an urban planning perspective soilless system represents a solution to produce vegetables in rooftops and areas with contaminated soils.

- Analyzing the results of heavy metal on the air, it has been shown that the concentrations of Ni, As, Cd and Pb at all sampling points were very similar, including the air inside the greenhouse and the outdoor environment.
- Specifically, Ni, As, Cd and Pb concentrations were less than 50% of the limits established in the legislation as the lower assessment threshold (EU, 2004). This is especially relevant because the chosen sampling locations were close to high-density roads (more than 50000 cars/work day) and they are more vulnerable to a high concentration of metals (Vittori Antisari et al., 2015).
- The air quality in Barcelona and its surroundings can be considered as representative of EU cities. Therefore, the results of the interaction between air and urban agriculture can serve as a reference for other cities
- Considering crop pollution, heavy metal concentrations in lettuce was below the EU-legislated limits in all studied cases. Specifically, the accumulation of Ni, Cd and As was under the detectable levels (<0.02 mg Ni/kg, <0.008 mg Hg/kg, 0.005 mg As/kg). In the case of Cd, the concentration values were at least one order of magnitude lower than the target value defined by EU legislation (0.05 mg Cd/kg). Pb concentration ranged from 0.0060 mg/kg to 0.0244 mg/kg (between 6% and 24% of the EU limit); thus, this heavy metal also does not have a prejudicial accumulation level.

For this reason, we further confirm that the air quality in Barcelona and its surroundings is not a limiting factor for the development of UA, even though the crops were close to high-density roads. Moreover, soilless systems (as an alternative to soil agriculture) can avoid introducing heavy metals into crops because it is possible to ensure that substrates are not contaminated with heavy metals.

Question 2: Are the biological air conditions in RTGs adequate to provide safe working environments? And in the case of i-RTGs, can its air be recirculated while ensuring safe environment for building's users?

- High levels of pollen grains and fungal spores were measured inside the i-RTG. These levels showed significant seasonal variations. Specifically, a total of 4,924 pollen grains/m^3 were observed inside the i-RTG during 47 days, arriving at 334 pollen grains/m^3 per day, and a total of 295,038 fungal spores/m^3 were observed during 5 months, reaching a maximum daily concentration of 26,185 spores/m^3.

- It is not possible to assess if the concentration detected are able to evoke allergenic symptoms, as it has not been established an official threshold for fungal spore concentrations and different authors have proposed different levels, such as 105 spores/m^3 (Eduard, 2009) or 103 spores/m^3 (Santilli and Rockwell 2003).

- The most important source of indoor fungi was the outdoor environment and a higher percentage of fungal spores than pollen grains entered the greenhouse by ventilation. Nevertheless, while the winter ventilation mode was in operation, the air penetration from the outdoor environment was lower than when the spring and summer modes were in operation.

- Some differences are detected in Solanaceae pollen and several fungal spore taxa, such as the allergenic Aspergillus/Penicillium, because they were likely to have originated within the i-RTG. Nevertheless part of this contamination could also be avoided by using the information presented in this dissertation. The results demonstrate that agricultural management tasks, such as pollination by hand, fungal treatments and sweeps, increased the biological air contamination and the highest daily pollen concentration recorded in the i-RTG Lab took place when the winter crop was removed. During these specific periods, preventive measures should be taken to protect workers and users of the building.

Despite not having an internationally accepted occupational exposure limits, taking into account the indoor and outdoor results, we consider that the biological air quality inside the i-RTG is adequate for the workers. Moreover, if the corresponding preventive measures are taken, it is also adequate to recirculate the residual hot air in other parts of the building without posing health risks. It is necessary to adapt the management of the i-RTG by controlling the opening and closing the ventilation system in accordance to the outside air contamination. As it has been identified the operations that increase the concentration of pollen and fungal spores, the air recirculation should be stopped during these moments, or an appropriate air filter system should be implemented.

Question 3: Are we using adequate substrates for urban agriculture to mitigate the effects of climate change and increase the drought resilience?

Focusing on the first part of the question, the results obtained in this dissertation demonstrate that organic substrates are a recommended option from both an environmental and agronomic perspective. The lettuce yields obtained with organic substrates (vegetable compost, vegetable compost and perlite mixture and coir) were almost equivalent to those obtained from perlite and greater than those obtained in open fields in the same area.

- In summer, the best results were obtained with vegetable compost alone (408.7 g plant^{-1}) and compost mixed with perlite (1:1) (418.4 g plant^{-1}).
- Nevertheless, a sequential decrease in the lettuce fresh weight grown in compost in the three tests was detected, probably due to the loss of nutrients in the substrate.

Moreover, compared to perlite, the organic substrates increased the resilience of the crops to water stress during the warm season (spring and summer):

- The coir tended to take a long time to lose water. Until – 10 cbar the agronomic effects of the stress were mostly undetectable. However, when dryness begins, the loss in water conent occurs very quickly, and yield decreases comparing with well irrigated coir crops and stressed compost crops.

- When the water stress reached -20 cbar, the vegetable compost and the substrate mixture (compost and perlite) presented more agronomic resilience. Moreover, using these substrates, it is possible to reduce irrigation frequency, and save water and nutrients.

- Tipburn was largely detected in the organic substrates rather than in perlite, especially in the spring crops. To guarantee the commercial requirement for RA profit projects, it should be further studied the management of the fertigation system and the meteorological conditions.

Question 4: Which is the consumer perception of RA and products grown in these systems?

- The perception of soilless RA production between potential consumers is generally positive for both the product quality and the agronomic production system. For example, 87% described the condition as good or very good, 74% of the sample stated that the taste was good or very good and 69% of the participants perceived that the produce from the i-RTG had a lower environmental impact than the tomatoes derived from conventional means of production

- Consumers with more knowledge and interaction with UA projects (i.e., those close to the location and those aware of the case study) had a more positive perception of the food and the production system. 100% of people who know the project considered the product to be fresh, and 62% would pay the highest possible price.

- Employees with high income levels and with university education had a better perception of the quality and they were willing to pay more for RA products.

- Consumers who identified RTG tomatoes as environmentally friendly were the ones to propose higher prices. This affected particularly the consumers who knew the RTG system, but had no relation with the consumers' income. UA companies should focus on strategies to improve the environmental performance of production, and all of these environmentally friendly measures should be communicated to potential consumers to increase the positive perception of the product and their market value.

Consumers raised some concerns about food safety, organic practices in soilless production and social impacts. UA initiatives should acknowledge this information to succeed. The implementation of quality control standards for products and growing facilities by administrations can help to increase consumers' trust.

Chapter

09

Suggestions for further research

CHAPTER 9 - Suggestions for further research

This section presents different aspects that were detected during the development of this thesis that can complete and complement the results obtained in this dissertation.

As presented in part 1 of this dissertation, in the European context, the future of UA will rely on its integration into the new emerging city model that takes different names from "smart cities", “sustainable cities”, "green cities" and "circular economy cities". Around this central topic the resulting main research lines are proposed:

9.1. Future research on air quality

Air quality is one of the key aspects to take into account when integrating agriculture in cities that affect the crops and also the growers. This affects different types of pollutants such as those studied in this thesis (heavy metals and aerobiological contamination) but also other pollutants detected in cities. For all these reasons, the following research lines are proposed (Figure 9-1).

9.1.1. Heavy metal contamination

As presented throughout the dissertation, the heavy metal contamination is one of the major concerns associated to RA. In RA the contamination of soilds is avoided because there are not contact between crops and the soil. For this reason the research has focus on air contamination only. In light of the main results, the following actions could be developed:

- To determine the heavy metal contamination in long-cycle crops. (Voutsa et al., 1996) results shown that there is a high accumulation of Pb and Cd in leafy vegetables due to the atmosphere. The dominant pathway for most trace elements in vegetable leaves appeared to originate mostly from the atmosphere while trace elements in roots was from the soil. So more research is needed to compare the results obtained in short cycle crops with long cycle crops. Moreover, more research is needed to evaluate heavy metal contamination in edible parts of fruit crops as airborne metals can directly enter into the fruit or be absorbed by leaf through stomata and then translocated.

- Another important issue of heavy metal contamination that should to be covered is the effect of rainfall patterns. Future research should include measuring all heavy metals in different meteorological conditions with different rainfall patterns and more extreme anticyclonic conditions.

- More research is needed to precise if rainwater brings heavy metal concentration on leaves, though crop produced in RTGs are protected against rainfall.

- Finally, more future studies should focus on the effect of heavy metal air contamination on soil contamination. Long exposures of soils to heavy metal in air and the deposition in soils of these contaminants could increase the concentration in soils and therefore in the crops.

9.1.2. Other chemical contaminants

The new approach proposed in this dissertation, which considers the contamination of the air and the crop simultaneously, can be very useful for promoting urban agricultural development plans, for this reason:

- This approach can be replicated with other pollutants such as AOT_{40}, SO_2, NO_x, and acid rain. It is known that pollutants concentration, constituted mainly by NO_x and its chemical derivate from atmospheric reactions with O_3, PM_{10} and SO_2, is sensibly decreased due to plant up taking (Morikawa et al., 1998). More research is need ede to study the effect of these contaminants on the crop development.

- In the case of RTG It is especially interesting to study Volatile Organic Compounds (VOCs). VOCs are considered ubiquitous, indoor and outdoor; their composition is complex and extremely unstable due to their low evaporation point and high reactivity with atmospheric compounds determining production of other compounds, sometimes harmful. In close spaces these molecules tend to accumulate increasing the contact area with people. Therefore, in the short period they can cause acute intoxication episodes and in the long even chronic pathologies of different severity. For this reason, even volatile organic compounds originated by plants must be considered and checked inside an environment where plant and people share the same space, like RTG and i-RTG

- More research is needed to study the potential barrier effect of the greenhouse to these other pollutants that are an actually problematic in cities

- The possibility of generating new maps of distribution of UA taking into account the air quality will contribute to giving new decision-making tools for individuals and administrators.

9.1.3. Aerobiological contamination

The aerobiological study conducted in this dissertation was carried out during the warm season, which coincides with the highest ventilation levels inside the i-RTG. For this reason, the following further research is needed.

- Deepen in the pollen and fungal spores dynamics during winter, when the indoor dynamics could present more relevance. As the recirculation of i-RTG air to buildings will be done especially during winter it is necessary to elaborate the best strategy to avoid causing or aggravating allergies and breathing problems in the users of the building during these months.

- Specifically, taking into account that Aspergillus/Penicillium - the most abundant fungal taxa in the i-RTG- showed their own dynamics indoors, further research is needed to understand which variables determined the increases in fungal spores of this taxon inside an RTG.

- Besides it should be studied to implement an appropriate air filter system that guarantees good air quality in the building spaces. More research should be done to specify the characteristics of these filters.

- Additionally fungal spores and pollen dynamics should be studied growing other crops inside RTGs like leafy crops or legume crops

Finally, it is necessary to establish internationally accepted occupational exposure limits for airborne fungi concentrations in greenhouses and in buildings. Also, greater efforts should be focused on determining the best personal protection equipment to protect the workers of the RA

9.2. Quantifying the potential of sustainable substrates

9.2.1. Vegetal compost

As observed in Chapter 5, the use of vegetal compost as a substrate may improve the growing conditions of the SCS crops. Nevertheless, the soil conductivity and the liberation of nutrients and the air/water relation could limit crop growth and productivity in some cases. Therefore, the following agronomic, environmental and economic strategies should be considered in future research:

Agronomic research:

- Demonstrate the feasibility of using different vegetal compost with different maturity degree and different granulometry.
- To determine the optimal irrigation and nutrient inputs for improving the growing conditions to increase harvest weight.
- Deepen in the management of the substrates and the meteorological conditions of the crops to avoid plants disorders such as (or like) tip burn.

Environmental research

- To study how this optimization could minimize the environmental impacts for a unit of lettuce and for a kg of lettuce using a detailed life-cycle assessment. More research is needed to contribute to the environmental analysis of this substrate, taking into account the life of the substrates and the impacts of their waste management (probably composting).
- To determine how vegetal compost could be integrated into local waste management systems at their end of life

Economic research

- To study the economic savings of substituting perlite by local vegetable compost and the economic burdens of its local production.

9.2.2. Other sustainable substrates

There is a need to identify robust growing media for use in low-input systems that can act as a buffer to reduce stress in crops in cases of limiting growing conditions such as nutrient / water shortages or energy outages. There the following research is needed

- To detect, quantify and characterize all city wastes and specifically those derived from food production in RA that could be used -after a transformation process- as a substrate. It includes other organic wastes like crop biomass but also plastic wastes that after a treatment could be used as inert substrates.

- Additionally, the reutilization of agricultural (such as almond shells, rice hulls, peanut hulls or shredded maize stems) and industrial waste by-products (such as from olive mills, breweries wineries and paper mills) as new feedstocks for growing media can allow for the generation of circular economies and can enable the use of hydroponics by smallholders

- Assessing the agronomic, environmental and economic potential of these “new substrates” in order to o increase crop productivity and make them less vulnerable to possible disturbances in the supply of water,

9.3.Assessing the perceptions around urban rooftop farming

The exact perception of UA food and conventional food is very difficult to predict. The consideration of consumers has an important role that can represent a possible barrier to the implementation of RA, this dissertation presents a first approach to determine the consumer perception. So, further research is required focused on consumers concerns about city pollution and the techniques to evaluate food quality with precise and objective ways.

Effect of city pollution

- To discuss which is the perception among consumers about the effects of city pollution on UA. Specific studies should focus on the change of consumers perceptions if quantitative results of the quality of the system and the product are provided to them.

- In this sense, efforts should focus on the study of further parameters, such as the effect of knowing the origin of the UA and the technical details of the production system.

- This study was conducted as a pilot project and all the people who visited the RA always tasted the food. Further research is needed to asses if there are differences in RA perception between people who tasted or not the food.

Organoleptic assessment

- Deepening in the perception of quality through organoleptic studies with trained panels would allow to compare the products of the UA with conventional agriculture

- In addition, other techniques of characterization of food as Near-infrared (NIR) spectroscopy and mid-infrared (MIR) spectroscopy, should be studied to compare the quality of food produced in RA and other systems (on soil, away from the city, with different substrates, etc.).

Around the perception of high quality food there are the dichotomy between “natural” and “environmental sustainability” associated to high-tech engineering and agro-ecology approaches. Controversies on which approach is best for sustainability in agriculture focus on yields and land use, agriculture production vs other ecosystem services, health and nutritional value of food, and the “naturalness” or “artificiality” of production systems. Nevertheless, agriculture is already far from natural conditions and works on artificial environments not only when plants grown without soil. It relies on human-modified environments and water and nutrients are supplied artificially. So, the actual industrialized production sector is far from being natural as many people imagine. In this context, high-tech solutions -as the systems presented in this dissertation- that do no link to natural environment (while they still link to natural process) are considered in some cases as “unnatural”.

As mentioned, the consumer perceives that common agriculture is natural because of blindness. In general if agriculture has to be organic or not it is far away of this dissertation but it should be clarified that being natural does not mean being sustainable, albeit it clearly can. We need an agriculture that ensures food security and at the same time it is as environmentally sustainable as possible. In RA, organic agriculture does not have sense because the main key aspect in this approach is the relation with the soil. Therefore, in RA efforts should be done to guarantee the most sustainable strategies to grown crops in SCS in cities. And, as it has been presented, to have knowledge of a system improves the perception of consumers.

The sustainability of high-tech projects must be reflected in a "Quality identifier" that incorporates all quality aspects such as a) the good practices of RA: local food production, Km 0 and environmentally friendly management and b) quality healthcare: without contaminants (as heavy metals) and with quality nutrition and organoleptic characteristic. It is necessary to distinguish those foods that have been produced taking to account all the aspects of sustainability in the complexity of the agricultural symbiosis-cities.

Future studies should focus on adapted varieties that have better organoleptic characteristics and better nutritional content (lycopenes, vitamins, carotenes, etc.) while reducing the consumption of inputs and optimizing irrigation and fertilizers. Taking advantage of the RA short distribution chain, other tomato varieties with different characteristics from those produced in conventional agriculture (thick skin, easily transportable shape, shock resistant, etc.) should be tested to assess other advantages such as nutritional quality. At the same time, changes in the agronomic techniques (irrigation, fertilization, moderate stress management) could induce sugar content and flavor and increase antioxidants and vitamins. These aspects are very agronomic and are far from the scope of this thesis.

Future environmental assessment should focus not only in the system but also in the functional unit. Previous studies detected that there are some differences comparing different production systems for tomato crops with different productivity units and quality units (Martínez-Blanco et al., 2011).

Additionally, implementing quality control standards for products and growing facilities by administrations can help increase consumers' trust, but more research is needed to develop this quality standards.

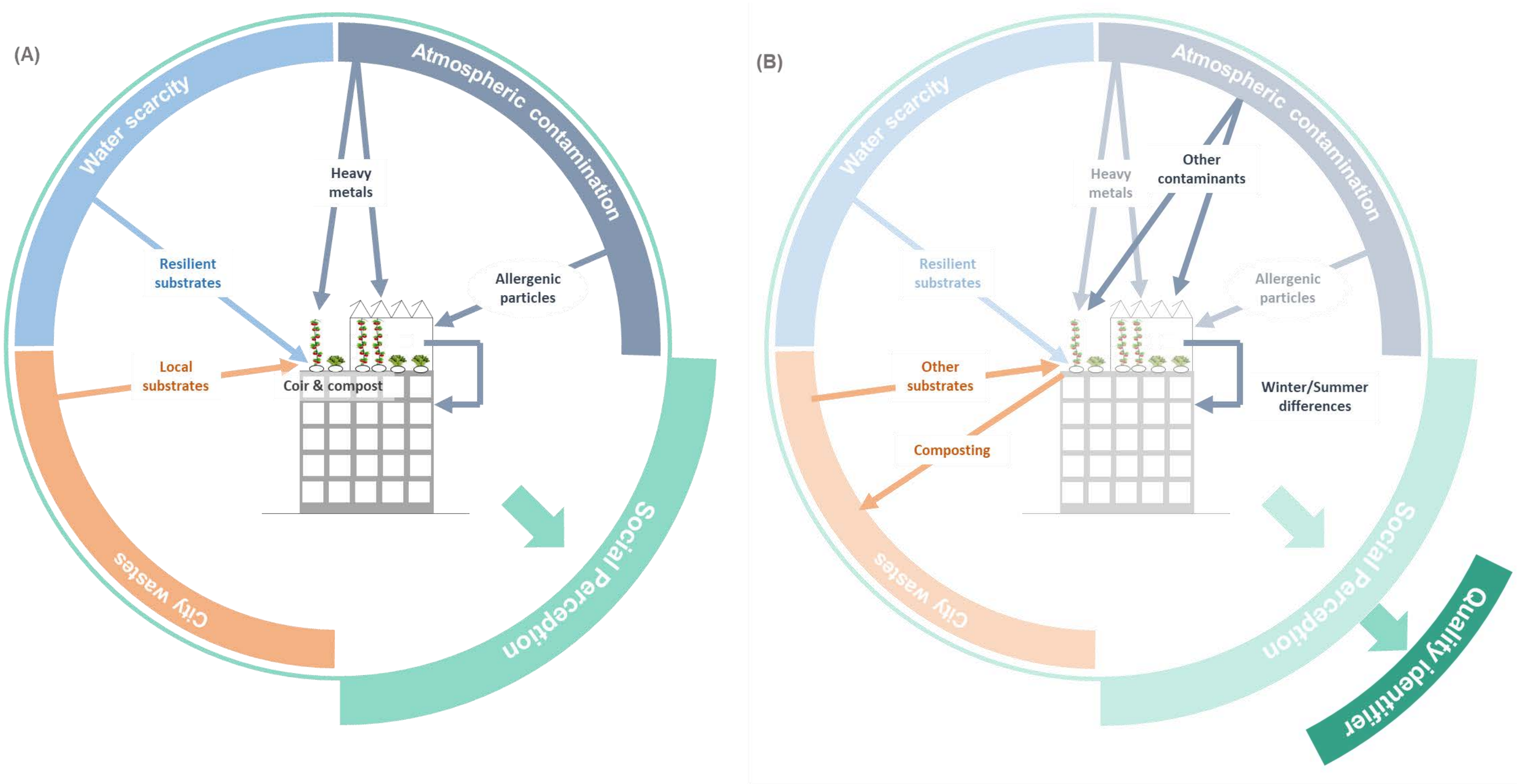


Figure 9-1 Scheme of the main research conducted in the present dissertation (A) and future research lines (B)

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