Universitat Autònoma de Barcelona

Mitigating the environmental impacts of Urban Agriculture: innovative materials, GHG emissions analysis and new by-products

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Doctoral thesis

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EXCELENCIA MARÍA DE MAEZTU

The present thesis entitled *Mitigating the environmental impacts of Urban Agriculture: innovative materials, GHG emissions analysis and new by-products* has been carried out at the Institute of Environmental Science and Technology (ICTA) at Universitat Autònoma de Barcelona (UAB) by Pere Llorach Massana

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“The world is big enough to satisfy everyone’s needs,
but will always be too small to satisfy everyone’s greed”

Mahatma Gandhi

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Abbreviations

A-LCA – Attributional life cycle assessment

C – Carbon

CC – Climate Change

CED – Cumulative Energy Demand

C-LCA – Consequential Life Cycle Assessment

CLM - Institute of Environmental Sciences (Leiden)

CO_2 – Carbon dioxide

EPS – Expanded polystyrene

FAO - Food and Agriculture Organisation

FD – Fossil Depletion

FE – Freshwater Eutrophication

FU – Functional Unit

GC – Gas Chromatography

GWP – Global Warming Potential

GHG – Greenhouse Gases

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 – Life Cycle Assessment

LCCA – Life Cycle Costs Assessment

LCI – Life Cycle Inventory Assessment

LDPE – Low Density Polyethylene

N_2O – Nitrous Oxide

NMVOC – Non-Methane Volatile Organic Compounds

P – Phosphor

PC – Polycarbonate

PCM – Phase Change Material

POF – Photochemical Oxidant Formation

PU – Polyurethane

PVC – Polyvinyl Chloride

RTG – Rooftop Greenhouse

SO_2 – Sulfur Dioxide

TA – Terrestrial Acidification

TES – Thermal Energy Storage

UA – Urban Agriculture

WD – Water Depletion

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Introduction

"Acknowledgements" is the title of a section in text documents (i.e. books) which aims to thank all people who have helped, directly or indirectly, to develop the content of the text. People who are thanked can contribute to text in different ways; for example: (1) by helping to develop an experience (i.e. travel) that is described in the text; (2) by giving emotional support to writer when she or he wants to send everything to hell; or (3) by reviewing or writing part of the text. Sometimes, for those who have helped, the fact that their name appears in the acknowledgement section is irrelevant. However, this feeling changes after writing your own document. At that moment, authors feel the emotional need to write in their texts the name of everybody who gave them support, to make sure that their help will not be forgotten from here to eternity. After that, it is when people really appreciates reading their name in an acknowledgements section.

Acknowledgements are also written in thesis dissertations (see any of the dissertations of the Sostenipra research group). As for the case of the author of the present dissertation, almost all researchers may feel the need to express their feelings after years of extreme rationality. This could explain why thesis dissertations usually contain an acknowledgement section. According to author's needs, that is to say according to my needs, the present section aims to emotionally acknowledge all people that gave me support during the thesis.

Materials and methods

The acknowledgements were written by listening my heart and letting emotions flow.

Results and discussion

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Conclusions

Maybe the acknowledgements section does not provide interesting results to the scientific community but it makes you feel good. In future thesis dissertations it is highly recommended the development of a acknowledge section for the well-being of the PhD candidates.

Summary

Rooftop greenhouses (RTGs) are an urban agriculture (UA) modality which allows intensive food production on the roof of cities. RTGs can be connected with the building they are placed on to exchange water, heat or CO_2 flows. These types of RTGs are named integrated RTGs (i-RTGs). i-RTGs can use the rainwater harvested by the building to irrigate crops, take advantage of the thermal inertia of the building to warm crops without using heating systems or use the residual air of the building, with high CO_2 concentration due to human respiration or other processes, to increase the CO_2 concentration of crops. These strategies are of great interest to mitigate the environmental burdens of i-RTGs.

In comparison with conventional decentralized agriculture, previous studies show that i-RTGs could reduce the environmental implications of feeding cities. Benefits are mainly obtained due to reduced food transportation distances, minimized food losses during transportation and improved packaging logistics which allows its reutilization. However, no advantages were detected for the other life cycle stages; therefore, further research is still lacking in this area. This doctoral thesis aims to fill this gap by addressing the following research questions:

1. *Can passive systems made with phase change materials (PCMs) replace conventional heating in greenhouses and reduce the carbon footprint of i-RTGs?*

2. *Can the residual air of a building be used for CO_2 enrichment in i-RTGs?*

3. *Could the GHG emissions of i-RTGs be calculated with more accuracy?*

4. *Is the creation of new by-products, with UA wastes, a strategy to sink the CO_2 emissions captured by crops grown in i-RTGs?*

Life cycle assessment (LCA) was the main method used to answer these questions. In addition, other specific methods and materials (i.e.; open chamber system, pyranometers; anemometers; temperature sensors; CO_2 sensors and gas or liquids chromatography) were used according to the requirements of each specific research line.

With the aim to answer the first research question, a theoretical study was carried out to determine the technical and environmental feasibility of using phase PCMs, as passive system, to replace conventional heating systems for greenhouses. Later, this study was expanded with a practical study to verify first data obtained and increase its precision. Main results demonstrate that PCMs will not be of interest to reduce the energy consumption of conventional heating systems until its prices decrease and the efficiency of its production increases, as more than the 90% of the environmental impacts and costs are generated during the production stage of PCMs. However, its technical feasibility is high, since the application of PCMs in the root zone of soil-less crops does not hinder agricultural maintenance tasks. Nonetheless, in cloudy days with low solar radiation, PCM may not accumulate enough thermal energy to heat crops during night. Therefore, it can be necessary to use complementary systems to heat crops in a timely manner.

The second research question was studied by collecting data from the ICTA-ICP building and its i-RTG. The design of the building allows to inject residual air from the laboratories into the i-RTG. CO_2 concentrations of residual air and the i-RTG were measured to assess if residual air can be used for the carbon enrichment of crops grown in the i-RTG. The CO_2 concentration measured in the residual air was equal or lower than 500 ppm. So, the CO_2 concentration of the residual air is not high enough to allow the carbon enrichment of the i-RTG from the ICTA-ICP building. Nevertheless, due to the high CO_2 concentration in household and office buildings, which is between 350 and 2500 ppm, the residual air from their ventilation systems could be used for the carbon enrichment of i-RTGs.

Nowadays, N_2O direct emissions from conventional crops and for i-RTGs are being quantified by using generic emission factors, like that of IPCC (0.0125 kg N_2O^{-1} per kg N^{-1}). As previous research demonstrates, emission factors vary according to the type of soil used, irrigation frequency or daily solar radiation, among others. So, the application of generic emission factors to quantify the direct N_2O emissions from crops, which have a climate change potential 298 times higher than CO_2, can cause

the over o underestimation of crop's carbon footprint. With the purpose of determining the error that the use of generic emission factors can generate on the carbon footprint calculation of i-RTGs, it was measured the emission factor of a soil-less crop grown in the i-RTG of the ICTA-ICP building through a nitrogen balance. The emission factor measured was 0.0079 kg N_2O^{-1} per kg N^{-1}, that is significantly lower than that of the IPCC. This result responds to the third research question and demonstrates that the carbon footprint of i-RTGs, which have been calculated until today with generic emission factors, has not been estimated with accuracy. The application of non-specific nitrogen emission factors can have caused the overestimation of i-RTGs carbon footprint by 7.5%.

Finally, the fourth research question have been analyzed through the study of the technical and environmental feasibility of producing biochar and insulation materials with tomato plant residues. When waste biomass generated in i-RTGs is used to produce new by-products, biomass waste management is avoided. Moreover, if efficient production systems are used and transportation distances are minimized, the emissions fixed within agricultural wastes could be higher than the emissions released during the obtaining process of the by-product. Producing by-products with tomato plants residues, such as biochar or insulation materials, has the potential to fix between 450 y 550 kg de CO_2 per ton of dry waste reused. The results evidence that the creation of by-products with UA wastes can be the strategy studied with the higher feasibility to reduce the environmental implications of i-RTGs. This strategy is also of great interest to reduce the environmental impact of conventional agriculture.

In the near future, further research would be of interest to address in more detail the new topics studied during this dissertation and develop research on other methodological aspects detected.

Resum

El hivernacles en cobertes són una de les tipologies d'Agricultura Urbana (AU) que permet la producció intensiva d'aliments a les cobertes de les ciutats. Aquests poden ser connectats amb l'edifici sobre el qual estan instal·lats, amb la finalitat de generar un intercanvi de fluxos entre els dos sistemes. Les aigües pluvials recollides per l'edifici poden ser utilitzades per regar els cultius. A més a més, la inèrcia tèrmica de l'edifici pot ser aprofitada per escalfar els hivernacles durant l'hivern, sense haver d'utilitzar sistemes de calefacció; o bé l'aire residual de l'edifici, amb una alta concentració de CO_2 degut a la respiració dels seus ocupants o altres processos, pot ser emprat per dur a terme l'enriquiment carbònic dels cultius. Aquestes estratègies poden ser de gran interès per reduir els impactes ambientals dels hivernacles en coberta.

En comparació amb l'agricultura convencional descentralitzada, els estudis previs mostren que els hivernacles en coberta poden reduir les conseqüències ambientals d'alimentar les ciutats. Aquestes millores són obtingudes principalment per la reducció de les distancies de transport dels aliments, l'atenuació de les pèrdues d'aliments durant el seu transport i la reutilització del packaging del transport gràcies a una logística més simplificada. No obstant això, no s'han detectat beneficis ambientals en la resta d'etapes de cicle de vida; per tant, cal realitzar una recerca més profunda per millorar en aquest aspecte. La present tesis doctoral pretén cobrir aquest àmbit de recerca a través d'intentar donar resposta a les següents preguntes:

1. *Pot un sistema passiu fet amb materials de canvi de fase substituir els sistemes convencionals de calefacció agrícoles i reduir la petjada de carboni dels hivernacles en coberta?*

2. *Pot l'aire residual dels edificis ser utilitzat per l'enriquiment carbònic dels hivernacles en coberta?*

3. *És possible millorar la precisió del càlcul de la petjada de carboni dels hivernacles en coberta?*

4. *És una estratègia viable crear subproductes a partir de residus agrícoles per fixar el CO_2 capturat pels cultius dels hivernacles en coberta?*

La principal metodologia aplicada per respondre les preguntes plantejades és l'anàlisi de cicle de vida (ACV). A més a més, en cada línia de recerca estudiada s'han utilitzat altres materials i mètodes complementaris per l'obtenció de dades específiques; com per exemple: un sistema de cambra oberta; anemòmetres; piranòmetres; sensors de CO_2; sensors de temperatura; cromatògrafs de gas os i líquids o la realització de termogravimetries.

Amb l'objectiu d'abordar la primera pregunta de recerca, s'ha realitzat un estudi teòric sobre la viabilitat tècnica i ambiental de l'aplicació dels materials de canvi de fase, com a sistema passiu, per substituir els sistemes convencionals de calefacció en hivernacles. Posteriorment, aquest estudi s'ha complimentat amb un estudi pràctic, el qual ha permès verificar i millorar la precisió de les primeres dades obtingudes. Els principals resultats demostren que els materials de canvi de fase no podran ajudar a minimitzar les conseqüències ambientals dels sistemes de calefacció agrícoles actuals fins que el seu preu disminueixi i la seva producció sigui més eficient, ja que més del 90% dels seus impactes ambientals i costos són generats durant la seva producció. Tanmateix, el sistema estudiat és viable tècnicament, ja que l'aplicació de materials de canvi de fase en la zona radicular de cultius sense sòl no dificulta les tasques agrícoles de manteniment. Tot i això, en dies nuvolats i de baixa radiació solar, els materials de canvi de fase poden no acumular prou energia tèrmica per mantenir els cultius a temperatures estables durant la nit. Per tant, pot ser necessari fer ús de sistemes complementaris que permetin escalfar els cultius de manera puntual.

La segona qüestió ha sigut estudiada mitjançant la recol·lecció de dades a l'edifici ICTA-ICP i l'hivernacle en coberta que aquest acull. El disseny de l'edifici permet que l'aire residual dels laboratoris de recerca sigui injectat a l'hivernacle. S'han monitoritzat les concentracions de CO_2 de l'aire residual i l'hivernacle, amb la finalitat de determinar si l'aire residual pot ser emprat per l'enriquiment carboni dels cultius. La concentració de CO_2 de l'aire residual mesurada és igual o inferior

a 500 ppm. Així doncs, la concentració de CO_2 de l'aire residual no és prou elevada per permetre l'enriquiment carbònic de l'hivernacle en coberta. Tot i això, tenint en compte les altes concentracions de CO_2 dels espais tancats d'habitatges i edificis d'oficines, d'entre 350 i 2.500 ppm, l'aire residual d'aquests immobles sí podria ser emprat per l'enriquiment carboni dels hivernacles en coberta.

A dia d'avui, les emissions directes de N_2O en cultius, i per tant dels hivernacle en coberta, són quantificades mitjançant factors d'emissions genèrics per cultius en sòls, com el de l'IPCC (0.0125 kg N_2O^{-1} per kg N^{-1}). Tal i com la recerca prèvia ha demostrat, els factors d'emissions dels cultius poden variar segons el tipus de sòl emprat, freqüència de reg o les hores de radiació solar, entre altres. Així doncs, l'aplicació de factors d'emissions genèrics per quantificar les emissions de N_2O en cultius, amb un potencial de canvi climàtic 298 cops superior al CO_2, pot causar la sobre o subestimació de la petjada de carboni del cultius. Amb la finalitat de determinar l'error que pot generar l'ús de factors d'emissions genèrics sobre la petjada de carboni dels hivernacles en coberta, s'ha mesurat el factor d'emissions d'un cultiu sense sòl produït en l'hivernacle en coberta de l'edifici ICTA-ICP. El factor d'emissions mesurat mitjançant un balanç de nitrogen és de 0.0079 kg N_2O^{-1} per kg N^{-1}, notablement inferior al de l'IPCC. Aquest resultat dona resposta a la tercera pregunta de recerca plantejada i demostra que la petjada de carboni dels hivernacles en coberta, determinada fins a dia d'avui amb factors d'emissions genèrics, no ha sigut calculada amb precisió. L'ús de factors de d'emissions de nitrogen no específics pot haver causat una sobreestimació del 7.5% de la petjada de carboni calculada.

Finalment, la quarta pregunta de recerca ha sigut analitzada mitjançant l'estudi de la viabilitat tècnica i ambiental de la producció de biochar (carbó orgànic) i aïllants tèrmics amb residus de tomaqueres. L'ús de residus agrícoles per produir subproductes evita la gestió final d'aquests residus. A més a més, si s'utilitzen sistemes de producció eficients i es minimitza el transport dels residus i els subproductes un cop elaborats, les emissions fixades en els residus poden ser majors que les generades per la obtenció dels subproductes. La producció de subproductes amb residus de tomaqueres, tals com aïllants tèrmics o biochar, té el potencial de fixar entre 450 i 550 kg de CO_2 per cada tona de residu sec reutilitzat. Els resultats obtinguts mostren que la creació de subproductes, amb residus de l'AU, és l'estratègia d'entre les estudiades amb major viabilitat per mitigar els impactes ambientals dels hivernacles en coberta. Aquesta també seria viable per minimitzar els impactes de l'agricultura convencional.

En futures recerques, pot ser de gran interès profunditzar amb més detall les línies de recerca iniciades i començar noves recerques sobre altres aspectes metodològics detectats, encara pendents d'estudi.

Resumen

Los invernaderos en cubierta son una de las tipologías de Agricultura Urbana (AU) que permite la producción intensiva de alimentos en las cubiertas de las ciudades. Éstos pueden ser conectados con el edificio sobre el cual están instalados, con la finalidad de generar un intercambio de flujos entre los dos sistemas. Las aguas pluviales recogidas por el edificio pueden ser utilizadas para regar los cultivos. Además, la inercia térmica del edificio puede ser aprovechada para calentar los cultivos durante el invierno, sin necesidad de utilizar sistemas de calefacción; o bien el aire residual del edificio, con una alta concentración de CO_2 debido a la respiración de sus ocupantes u otros procesos, puede ser inyectado en los invernaderos en cubierta como solución para el enriquecimiento carbónico de los cultivos. Estas estrategias pueden ser de gran interés para mitigar los impactos ambientales de los invernaderos en cubierta.

En comparación con la agricultura convencional descentralizada, los estudios previos muestran que los invernaderos en cubierta podrían reducir las consecuencias ambientales de alimentar las ciudades. Estas mejoras podrían ser obtenidas principalmente por la reducción de las distancias de transporte de los alimentos, la atenuación de las pérdidas de alimentos durante su transporte y la reutilización del packaging del transporte gracias a una logística más simplificada. Sin embargo, no se han detectado mejoras ambientales en el resto de las etapas de ciclo de vida; por lo tanto, parece ser que todavía queda pendiente realizar una investigación más profunda sobre estos aspectos. La presente tesis doctoral pretende cubrir este ámbito de estudio a través de intentar dar respuesta a las siguientes preguntas:

1. *¿Puede un sistema pasivo hecho con materiales de cambio de fase substituir los sistemas convencionales de calefacción agrícolas y reducir la huella de carbono de los invernaderos en cubierta?*

2. *¿Puede el aire residual de los edificios ser utilizado para el enriquecimiento carbónico de los invernaderos en cubierta?*

3. *¿Es posible mejorar la precisión del cálculo de la huella de carbono de los invernaderos en cubierta?*

4. *¿Es la creación de subproductos, a partir de residuos agrícolas, una estrategia viable para fijar el CO_2 capturado por los cultivos de los invernaderos en cubierta?*

La principal metodología de investigación aplicada, para responder las preguntas planteadas, es el análisis de ciclo de vida (ACV). Además, en cada línea de investigación estudiada se han utilizado otros materiales y métodos complementarios para la obtención de datos específicos; como por ejemplo: un sistema de cámara abierta; anemómetros; piranómetros; sensores de CO_2; sensores de temperatura o cromatógrafos de gases y líquidos.

Con el objetivo de abordar la primera pregunta planteada, se ha realizado un estudio teórico sobre la viabilidad técnica y ambiental de utilizar materiales de cambio de fase, a modo de sistema pasivo, para substituir los sistemas convencionales de calefacción en invernaderos. Posteriormente, este estudio ha sido ampliado con un estudio práctico, que ha permitido verificar la precisión de los primeros datos obtenidos. Los principales resultados demuestran que los materiales de cambio de fase no podrán ayudar a minimizar las consecuencias ambientales de los sistemas de calefacción agrícolas actuales hasta que su precio disminuya y su producción sea más eficiente, ya que más del 90% de los impactos ambientales y costes son generados durante su producción. Sin embargo, su viabilidad técnica es elevada, ya que la instalación de materiales de cambio de fase en la zona radicular de los cultivos sin suelo no dificulta las tareas agrícolas de mantenimiento. No obstante, en días nublados y de baja radiación solar, los materiales de cambio de fase pueden no acumular suficiente energía térmica para mantener los cultivos a temperaturas estables durante la noche. Por lo tanto, puede ser necesario utilizar sistemas complementarios que permitan calentar los cultivos de manera puntual.

La segunda cuestión ha sido estudiada mediante la recolección de datos en el edificio ICTA-ICP y el invernadero en cubierta que éste acoge. El diseño del edificio permite que el aire residual de los

laboratorios de investigación sea inyectado en el invernadero. Se han monitorizado las concentraciones de CO_2 del aire residual y del invernadero, con la finalidad de determinar si el aire residual puede ser utilizado para el enriquecimiento carbónico de los cultivos. La concentración de CO_2 medida en el aire residual es igual o inferior a 500 ppm. Así pues, la concentración de CO_2 del aire residual no es lo suficientemente alta para permitir el enriquecimiento carbónico de los invernaderos en cubierta. Sin embargo, teniendo en cuenta las elevadas concentraciones de CO_2 de los espacios cerrados en viviendas y edificios de oficinas, de entre 350 y 2.500 ppm, el aire residual de estos inmuebles sí podría ser inyectado dentro de los invernaderos en cubierta para enriquecer con carbono los cultivos.

A día de hoy, las emisiones directas de N_2O de los cultivos, y por lo tanto de los invernaderos en cubierta, están siendo cuantificadas mediante factores de emisiones genéricos para cultivos en suelo, como el del IPCC (0.0125 kg N_2O^{-1} per kg N^{-1}). Tal y como las investigacions previas han demostrado, los factores de emisiones de los cultivos pueden variar según el tipo de suelo utilizado, la frecuencia de los riegos o las horas de radiación solar, entre otros. Así pues, la aplicación de factores de emisiones genéricos para cuantificar las emisiones de N_2O de los cultivos, con un potencial de cambio climático 298 veces superior al CO_2, puede causar la sobre o subestimación la huella de carbono de los cultivos. Con la finalidad de determinar el error que puede generar el uso de factores de emisiones genéricos sobre la huella de carbono de los invernaderos en cubierta, se ha medido el factor de emisiones en un cultivo sin suelo producido en el invernadero en cubierta del edificio ICTA-ICP. El factor de emisiones medido mediante un balance de nitrógeno es de 0.0079 kg N_2O^{-1} per kg N^{-1}, notablemente inferior al del IPCC. Este resultado da respuesta a la tercera pregunta de investigación planteada y demuestra que la huella de carbono de los invernaderos en cubierta, calculada hasta día de hoy con factores de emisiones genéricos, no ha sido cuantificada con precisión. El uso de factores de emisiones de nitrógeno no específicos puede haber causado una sobreestimación del 7.5% de la huella de carbono calculada.

Finalmente, la cuarta cuestión ha sido analizada mediante el estudio de la viabilidad técnica y ambiental de la producción de biochar (carbón orgánico) y aislantes térmicos con residuos de tomateras. El uso de residuos agrícolas para producir subproductos evita la gestión final de estos residuos. Asimismo, si se utilizan sistemas de producción eficientes y se minimiza el transporte tanto de los residuos como de los subproductos una vez producidos, las emisiones fijadas en los residuos podrían ser mayores que las generadas para la obtención de los subproductos. La producción de subproductos con residuos de tomatera, tales como aislantes térmicos o biochar, tiene el potencial para fijar entre 450 y 550 kg de CO_2 por cada tonelada de residuo seco reutilizado. Los resultados obtenidos muestran que la creación de subproductos, con residuos de la AU, podría ser la estrategia estudiada con una mayor viabilidad para mitigar los impactos ambientales de los invernaderos en cubierta. Esta estrategia también sería viable para minimizar los impactos ambientales de la agricultura convencional.

En futuras investigaciones, podría ser de gran interés profundizar con más detalle las líneas de investigación iniciadas y empezar nuevas investigaciones sobre otros aspectos metodológicos detectados, todavía pendientes de estudio.

Preface

The present doctoral thesis was elaborated, from June 2013 to April 2017, within the research group of Sustainability and Environmental Prevention (Sostenipra) at the Institute of Environmental Science and Technology (ICTA) of the Universitat Autònoma de Barcelona (UAB), which was awarded with María de Maeztu program for Units of Excellence in R&D (MDM-2015-0552). Moreover, the thesis was developed within the framework of the Fertileicty I project (MINECO: CTM2013-47067-C2-1-R) "*Agrourban sustainability through rooftop greenhouses. Ecoinnovation on residual flows of energy, water and CO_2 for food production*" and the Fertilecity II project (MINECO/FEDER, UE: CTM2016-75772-C3-1-R; CTM2016-75772-C3-2-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*". These projects were coordinated by the Institute of Environmental Science and Technology (ICTA), with the participation of the Universitat Politècnica de Catalunya (UPC) and the Environmental Horticulture Unit at the Institute of Agriculture and Food Research and Technology (IRTA).

The dissertation consists of a multidisciplinary approach which intends to combine industrial design, environmental science, agronomic sciences and material sciences to reduce the environmental implications of rooftop greenhouses. The novelty of the dissertation relies on the scenario under study, the i-RTG-Lab (a research oriented integrated rooftop greenhouse), and on:

- The environmental, technical and economic assessment of a passive system with phase change materials to replace conventional heating systems in both conventional and rooftop greenhouses.
- The characterization of buildings' residual air for its possible use for carbon enrichment of crops grown in rooftop greenhouses.
- The calculation of a N_2O emission factor for fertilized crops developed in integrated rooftop greenhouses to improve the accuracy of its carbon footprint calculation.
- The environmental and technical assessment of developing specific by-products with wastes generated by urban agricultural.

The central chapters of this dissertation consists on a paper published, or under review, in peer-reviewed journals from the first quartile, except chapter 5 which corresponds to a conference participation:

- Pere Llorach-Massana, Javier Peña, Joan Rieradevall, J. Ignacio Montero. 2016. *"LCA & LCCA of a PCM application to control root zone temperatures of hydroponic crops in comparison with conventional root zone heating systems*". Renewable Energy Journal 85, 1079–1089 (DOI:10.1016/j.renene.2015.07.064)

- Pere Llorach-Massana, Javier Peña, Joan Rieradevall, J. Ignacio Montero. 2016. "*Analysis of the technical, environmental and economic potential of phase change materials (PCM) for root zone heating in Mediterranean greenhouses"*. Renewable Energy Journal 103, 570-581, (10.1016/j.renene.2016.11.040)

- Pere Llorach Massana, Aurélie Pichon, Mireia Ercilla Montserrat, Javier Peña, Joan Rieradevall, J. Ignacio Montero. 2017. *"CO_2 enrichment potential in i-RTGs with residual air from buildings"*. International symposium on green cities 2017. 12th – 15th September 2017 – Bologna (Italy).

- Pere Llorach-Massana, Pere Muñoz, M. Rosa Riera. Xavier Gabarrell, Joan Rieradevall, J. Ignacio Montero, Gara Villalba. 2017. "*N_2O emissions from protected soil-less crops for more precise food and urban agriculture life cycle assessments."* Journal of cleaner production (10.1016/j.jclepro.2017.02.191)

- Pere Llorach-Massana, Elisa Lopez-Capel, Javier Peña, Joan Rieradevall, J. Ignacio Montero, Neus Puy. 2017. *"Technical feasibility and environmental benefits of biochar co-production with tomato plant residue".* Waste Management Journal (under review)

- Pere Llorach-Massana, Jorge Sierra, Gianfranco Rizzo, Maria la Gennusa, Javier Peña, Joan Rieradevall, J. Ignacio Montero. 2017. *"Environmental assessment of a renewable thermal insulation material produced with tomato plant stems derived from urban agriculture wastes".* International Journal of Life Cycle Assessment (under review)

Also the following oral communication and posters were presented in conferences as part of the doctoral thesis:

- Pere Llorach-Massana, Javier Peña, Joan Rieradevall, J. Ignacio Montero. 2014. "*Passive systems for the climate control of rooftop greenhouses (RTGs): Phase change materials (PCMs) to heat the root zone*". International Conference on Vertical Farming and Urban Agriculture 2014. 9th – 10th September 2014 - The University Of Nottingham (United kingdom)

- Pere Llorach-Massana, Esther Sanyé-Mengual, David Sanjuan-Delmàs, Jordi Oliver-Solà, Joan Rieradevall, J. Ignacio Montero. 2014. "*The Rooftop Greenhouse Lab: optimising food production on buildings through integrated Rooftop Greenhouses in Barcelona, Spain*". International Conference on Vertical Farming and Urban Agriculture 2014. 9th – 10th September 2014 - The University Of Nottingham (United kingdom).

- Pere Llorach-Massana, Javier Peña, Joan Rieradevall, J. Ignacio Montero. 2015. "*LCA of Phase Change Materials application to heat hydroponic crops' root zone in substitution of a conventional root zone heating System".* CILCA 2015. 13th – 16th July 2015 - Pontificia Universidad Católica del Perú (Perú).

- Esther Sanyé-Mengual, Pere Llorach-Massana, David Sanjuan-Delmàs, Anna Nadal, Jordi Oliver-Solà, Alejandro Josa, J. Ignacio Montero, Xavier Gabarrell, Joan Rieradevall. 2015. "*The ICTA-ICP Rooftop Greenhouse Lab: coupling industrial ecology and life cycle thinking to assess innovative urban agriculture".* CILCA 2015. 13th – 16th July 2015 - Pontificia Universidad Católica del Perú (Perú).

- Pere Llorach-Massana, David Sanjuan-Delmàs, Mireia Ercilla, Anna Nadal, M. Rosa Rovira, Alejandro Josa, J. Ignacio Montero, Pere Muñoz, Xavier Gabarrell, Joan Rieradevall. 2016. "*Potential environmental and economic benefits from local food production in Mediterranean rooftop greenhouses*". LCA food 2016. 19th – 21th October 2016 - University College Dublin (United kingdom).

- David Sanjuan-Delmás, Mireia Ercilla, Pere Llorach-Massana, Ana Nadal, Pere Muñoz, J. Ignacio Montero, Alejandro Josa, Xavier Gabarrell, Joan Rieradevall. 2017. "*Environmental assessment of hydroponic tomato crops in an urban building integrated rooftop greenhouse using LCA".* 2nd Agriculture and Climate Change Conference. 26th – 28th March 2017 – Sitges (Spain).

- Ana Nadal, Pere Llorach-Massana, Eva Cuerva, Carla Planas, Elisa López-Capel, Juan Ignacio Montero, Aniol Alabert, Alejandro Josa, Joan Rieradevall, Mohammad Royapoor. 2017. *"Integrated rooftop greenhouses: Energy efficiency of buildings metabolism for local food production".* ISIE-ISSST 2017: Science in Support of Sustainable and Resilient Communities. 25th – 29th June 2017 – Chicago (USA).

- Pere Llorach-Massana, Javier Peña, Joan Rieradevall, Juan Ignacio Montero. 2017. *"Carbon cycles in urban vertical farming from a circular economy approach".* Life Cycle Management Conference 2017, 3rd September – 6th September 2017 - Luxembourg (Luxembourg).

- Ana Nadal, Pere Llorach-Massana, Joan Rieradevall, Aniol Alabert, Eva Cuerva, Elisa López-Capel, Juan-Ignacio Montero, Alejandro Josa, Mohammad Royapoor. 2017. *"Promoting local food production in Mediterranean cities. Energy efficiency of buildings metabolism through integrated rooftop greenhouses (i-RTGs)".* International symposium on green cities 2017. 12th – 15th September 2017 – Bologna (Italy).

In addition, during the thesis period has been given the opportunity to work in other research contributions and projects related with the goals of the dissertation or to the acquisition of skills on ecodesign:

- Projects:
  - ECO-SCP-MED. Capitalizing experiences for MED sustainable future. Funded by the European Commission (FEDER funds).
  - AQUAENVEC Life Project. Assessment and improvement of the urban water cycle eco-efficiency using LCA and LCC. Funded by the European Commission (Life projects funds).
  - Proyecto M-ECO, Investigación para la mejora de la sostenibilidad del sector de la madera y mueble en Andalucía a través de la Eco-innovación. Funded by Junta de Andalucía.

- Scientific papers:
  - Maria De Giacomo, Arianna Loprieno, Mario Tarantini, Rovena Preka, Maria Litido, Anne Furphy, Victor Calvo, Pere Llorach-Massana, Carles Martínez-Gasol, Joan Rieradevall, Ramon Farreny, Xavier Gabarrell. 2014. "*Eco-innovative Practices for Sustainable Consumption and Production: What are the Possible Benefits for Companies?*" Adm. Sci. 4, 242–275. doi:10.3390/admsci4030242
  - Pere Llorach-Massana, Ramon Farreny, Jordi Oliver-Solà. 2015. "*Are Cradle to Cradle certified products environmentally preferable? Analysis from an LCA approach"*. Journal of Cleaner Production, 93, 243–250. doi:10.1016/j.jclepro.2015.01.032
  - Oriol Pons, Ana Nadal, Esther Sanyé-Mengual, Pere Llorach-Massana, Eva Cuerva, David Sanjuan-Delmàs, Pere Muñoz, Jordi Oliver-Solà, Carla Planas, and Maria Rosa Rovira. 2015. "*Roofs of the Future: Rooftop Greenhouses to Improve Buildings Metabolism*." Procedia Engineering 123: 441–48. doi:10.1016/j.proeng.2015.10.084.
  - Ana Nadal, Pere Llorach-Massana, Eva Cuerva, Elisa López-Capel, Juan Ignacio Montero, Alejandro Josa, Joan Rieradevall, and Mohammad Royapoor. 2017. "*Building-Integrated Rooftop Greenhouses: An Energy and Environmental Assessment in the Mediterranean Context*." Applied Energy 187: 338–51. doi:10.1016/j.apenergy.2016.11.051.
  - Anna Petit-Boix; Esther Sanyé-Mengual; Pere Llorach-Massana; David Sanjuan-Delmás; Jorge Sierra-Pérez; Elisabet Vinyes; Xavier Gabarrell; Joan Rieradevall. 2016. "*Research on sustainable cities from a life cycle perspective: a review."* Journal of cleaner production. (Under review)
  - Maria La Gennusa, Pere Llorach-Massana, Juan Ignacio Montero, F. Javier Peña, Joan Rieradevall, Patrizia Ferrante, Gianluca Scaccianoce, Giancarlo Sorrentino. 2017. *"Composite building materials: thermal and mechanical performances of samples realized with hay and natural resins"*. Sustainability 9. 373. doi:10.3390/su9030373

- Books chapters:

  - Esther Sanyé-Mengual, Pere Llorach-Massana, David Sanjuan-Delmás, Jordi Oliver-Solà, Alejandro Josa, Juan Ignacio Montero, and Joan Rieradevall. 2014. "*Chapter 5.4. The ICTA-ICP Rooftop Greenhouse Lab (RTG-Lab): Closing Metabolic Flows (Energy, Water, CO_2) through Integrated Rooftop Greenhouses*." In Finding Spaces for Productive Cities. Proceedings of the 6th AESOP Sustainable Food Planning Conference, edited by Rob Roggema and Greg Keeffe, 693–701. VHL University of Applied Sciences. doi:10.13140/RG.2.1.5016.7206.

  - Sara González-García, Esther Sanye-Mengual, Pere Llorach-Masana, Gumersindo Feijoo, Xavier Gabarrell, Joan Rieradevall, and Maria Teresa Moreira. 2016. "*Sustainable Design of Packaging Materials*." In Environmental Footprints and Eco-Design of Products and Processes, edited by Subramanian Senthilkannan Muthu, 23–46. Springer Singapore. doi:10.1007/978-981-287-913-4_2.

- Conference contributions:

  - Pere Llorach-Massana; Esther Sanyé-Mengual; David Sanjuan-Delmás; Xavier Gabarrell; Joan Rieradevall; Carles M. Gasol;Ramon Farreny; Raul Garcia-Lozano. 2015. "*edTOOL: new free qualitative Ecodesign Tool to promote SCP policies".* Life Cycle Management Conference 2015, 30th August – 2nd September 2015 - Bordeaux (France).

  - Anna Petit-Boix, Esther Sanyé-Mengual, Pere Llorach-Massana, Joan Rieradevall, Xavier Gabarrell, Raul Garcia Lozano, Carles M Gasol, Víctor Vázquez, Rafael Rodríguez, Gloria Rodríguez. 2015. *Sustainable production through innovation in the furniture sector: promoting policy-making and eco-design tools from a joint research-industry project.* Cleaner Production 2015, 1st-5th November 2015 – Sitges (Spain).

  - Maria LaGennusa, Gianfranco Rizzo, Gianluca Scaccianoce, Giancarlo Sorrentino, Joan Rieradevall, J. Ignacio Montero, Javier Peña, Pere Llorach-Massana. 2016. *"Performance evaluation of a bio-based composite building material made of natural resin mixed with hay."* 16th CIRIAF National Congress, 7th-9th April 2016 – Assisi (Italy).

  - Pere Llorach-Massana; Anna Petit-Boix; Esther Sanyé-Mengual; Raul Garcia; Xavier Gabarrell; Joan Rieradevall; Carles Martínez Gasol; Víctor Vázquez; Gloria Rodríguez; Rafael Rodríguez-Acuña*. 2016. "Tools for implementing and communicating eco-design in the furniture sector*." ISIE Americas 2016 Meeting, 25th-27th May 2016 - Bogotá (Colombia).

Moreover, during the dissertation there has been the possibility to teach (1) the Simapro life cycle assessment software in the official master's degree in Interdisciplinary Studies in Environmental, Economic and Social Sustainability from the Institute for Environmental Science and Technology (ICTA), in the Urban and Industrial Ecology specialization, and (2) teach ecodesign, sustainable materials and supervise final degree projects in Elisava, Barcelona School of Design and Engineering.

Structure of the dissertation

The dissertation is organized in five main parts and ten chapters as shown in the following table:

PART I - Introduction and methodology	
Chapter 1	Introduction and objectives
Chapter 2	Materials and methods
PART II – Phase change materials (PCM) for more efficient root zone heating systems in RTGs	
Chapter 3	LCA & LCCA of a PCM application to control root zone temperatures of hydroponic crops in comparison with conventional root zone heating systems
Chapter 4	Analysis of the technical, environmental and economic potential of PCM for root zone heating in Mediterranean greenhouses
PART III – Analyzing i-RTGs' GHG flows	
Chapter 5	CO_2 enrichment potential in i-RTGs with residual air from buildings
Chapter 6	N_2O emissions from protected soil-less crops for more precise food and urban agriculture life cycle assessments
PART IV - Carbon sink through by-products design with tomato plant feedstocks	
Chapter 7	Technical feasibility and environmental benefits of biochar co-production with tomato plant residue
Chapter 8	Environmental assessment of a renewable thermal-insulation material produced with tomato plant stems derived from urban agriculture wastes
PART V – Conclusions & further research	
Chapter 9	General conclusions
Chapter 10	Suggestions for further research

PART I

Introduction and methodology

Chapter 1

Introduction and objectives

"When we get into the wild, we need to explore the unknown"
Skimountainering, Val Maira (Italy)

CHAPTER 1 - Introduction and objectives

This chapter introduces the general background of urban agriculture and provides more specific data for the main typology of urban agriculture, on which this dissertation focuses: rooftop greenhouses. Moreover, design methodology and some technical materials are described to help the reader understand the content of the document. Finally, this section also highlights the motivations and objectives of the dissertation.

1.1. Feeding urban areas in a finite but growing world

World population is foreseen to reach 9.550 million inhabitants by 2050 (United Nations, 2013). By then, more than 70% of population will live in cities, while population in rural areas will decrease slightly (United Nations, 2014), see Figure 1.1. Currently, in developed countries approximately 80% of population lives in urban areas and in emerging countries, where megacities are expanding, urban population is expected to grow significantly (United Nations, 2014).

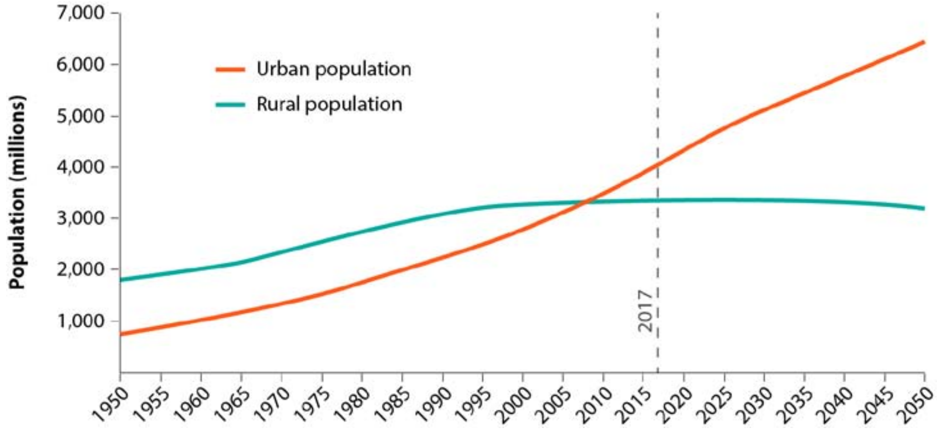
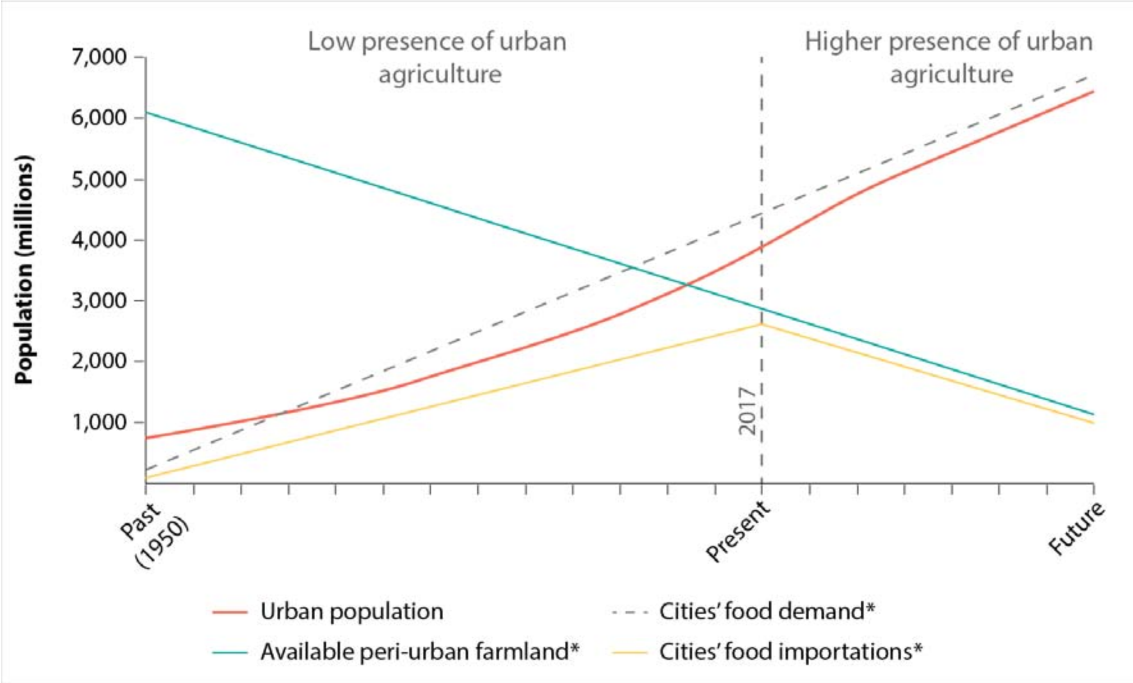


Figure 1.1. *Evolution and previsions of urban and rural population in the world (1950-2050)*
Source: Own elaboration from United Nations (2014).

This growing population rates will be responsible of an increase of global food demand, at least, for the next 35 years. In fact, by 2050 food production is estimated to grow by 30% (Alexandratos and Bruinsma, 2012). Nevertheless, our ability to produce food will be affected negatively by urgent requirements to reduce the environmental impacts from food production (IPCC, 2014a), the overexploitation of fisheries (Neubauer et al., 2013), the land transformation and degradation produced during the last 40 years by humans (Hooke and Martín-Duque, 2012) and the growing effects of climate changes on water availability (Oki and Kanae, 2006). Consequently, world regions under higher economic, social and environmental pressure could suffer several difficulties to guarantee food access to their population.

With the aim of reducing the discrepancies of food access between world regions, the term "*food security*" was coined in 1945 by the United Nations Food and Agriculture Organization (FAO) 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*" (Burton et al., 2013).

Due to high population concentration in urban areas, not all food required to feed cities can be produced in their surroundings. Moreover, increasing population implies a higher food demand and expansion of urban areas, which reduces local farmland and disconnects production areas from consumers (Paül and McKenzie, 2013; Seto et al., 2011). Therefore, peri-urban areas devoted to agriculture are being significantly reduced (Allen, 2003; Paül and McKenzie, 2013; Thapa and Murayama, 2008; Zasada, 2011). As consequence, importation of food from larger distances is required to feed urban areas (see Figure 1.2). This situation decreases cities' self-sufficiency making them dependent from global food markets, which are not stable in terms of prices and productivity, and consequently reduces food security of cities (Godfray et al., 2010).



**Trends conceptually estimated by the author according to previsions found in literature (Seto et al. 2011; Paül and McKenzie 2013; Allen 2003; Thapa and Murayama 2008; Zasada 2011; Godfray et al. 2010)*

Figure 1.2. *Conceptual urban expansion and its food implications in developed countries*

Cities are open systems whose development depends on available external resources (Dunster, 2010). Despite occupying less than 3% of the earth's surface, cities produce 75% of the global economic output, are responsible for 75% of global environmental impacts and consume 80% of global energy and resources demand (UN - HABITAT, 2011; UNEP, 2012). If cities and their population keep growing, as main predictions show (United Nations, 2014, 2013), impacts from feeding cities and their contribution to global change will grow too. Related impacts from feeding such big urban areas will rise because of food demand increase and the need to import more food from further away. Therefore, it seems imperative to enhance local food production and consumption to improve food security in urbanized regions and reduce the environmental burdens derived from feeding cities. In fact, government entities, such as the European commissions or the United States Department of Agriculture, are starting to introduce the concept of urban agriculture in their agendas (European Commission, 2016; United States Department of Agriculture, 2016) as a key element for the development of sustainable cities.

1.2. Urban agriculture: a new sustainable paradigm for feeding cities

The present section introduces the concept of urban agriculture, describes different crop typologies derived from this concept and points to multiple benefits derived local food production.

1.2.1. The concept and urban agriculture typologies

Urban areas devoted to food production have expanded during the last years with the aim of increasing urban food security (Mok et al., 2013; Orsini et al., 2014; Specht et al., 2015; Tornaghi, 2014). The concept of "*Urban Agriculture*" (UA, from now on) has been described by many institutions such as FAO[1], the US EPA[2] (United States Environmental Protection Agency), the Five Borough Farm Project[3] or the RUAF fundation[4]; however, their definitions depend on the framework were UA is developed.

[1] http://www.fao.org/
[2] https://www3.epa.gov/
[3] http://www.fiveboroughfarm.org/
[4] http://www.ruaf.org/

For example, FAO definition includes in the definition of UA animal production while the US EPA definition does not.

The framework of the present dissertation is the application of commercial instensive UA in developed countries, which mainly refers to the northen hemisphere countries. The definition chosen for the present dissertation is that of Working group 1 of the Cost Action “Urban Agriculture Europe” (Lorhberg and Timpe, 2012):

> *“Urban agriculture are farming operations taking place in and around the city that beyond food production provide environmental services (soil, water and climate protection; resource efficiency; biodiversity), social services (social inclusion, education, health, leisure, cultural heritage) and support local economies by a significant direct urban market orientation”*

Nowadays, within the framework of this definition, many forms of UA have been developed (see Figure 1.3). Soil-based UA, depending on its location, can be divided into two main groups: urban and peri-UA. Building-based UA includes all the agriculture developed in new or retrofitted buildings. Vertical farming encompasses buildings specifically oriented to food production and buildings that combine housing with food production (Despommier, 2008). In contrast to indoor farming, vertical farming refers to food production in height which means that food is not produced at ground or underground level. Table 1.1 shows the main characteristics of the different forms of UA described in Figure 1.3. As can be observed, building-based UA provides some advantages that might not be achieved with soil-based UA. One of the most important benefits is its potential to optimize land occupation, by means of the use of soil for more than one purpose (i.e. combining household use with crops) or cropping at different levels in the same land area as skyfarming does.

Table 1.1. *Urban agriculture classification and main characteristics*

			Land occupation optimization	Shared spaces with households	Potential for community projects	Intensive agriculture	R&D required
Soil-based UA		Peri-urban			●	●	
		Urban			●	●	
Building-based UA	Vertical Farming	*Skyfarming*	●			●	●
		Edible walls	●	●		●	●
		Rooftop farming	●	●	●	●	●
		Indoor farming	●	●		●	●

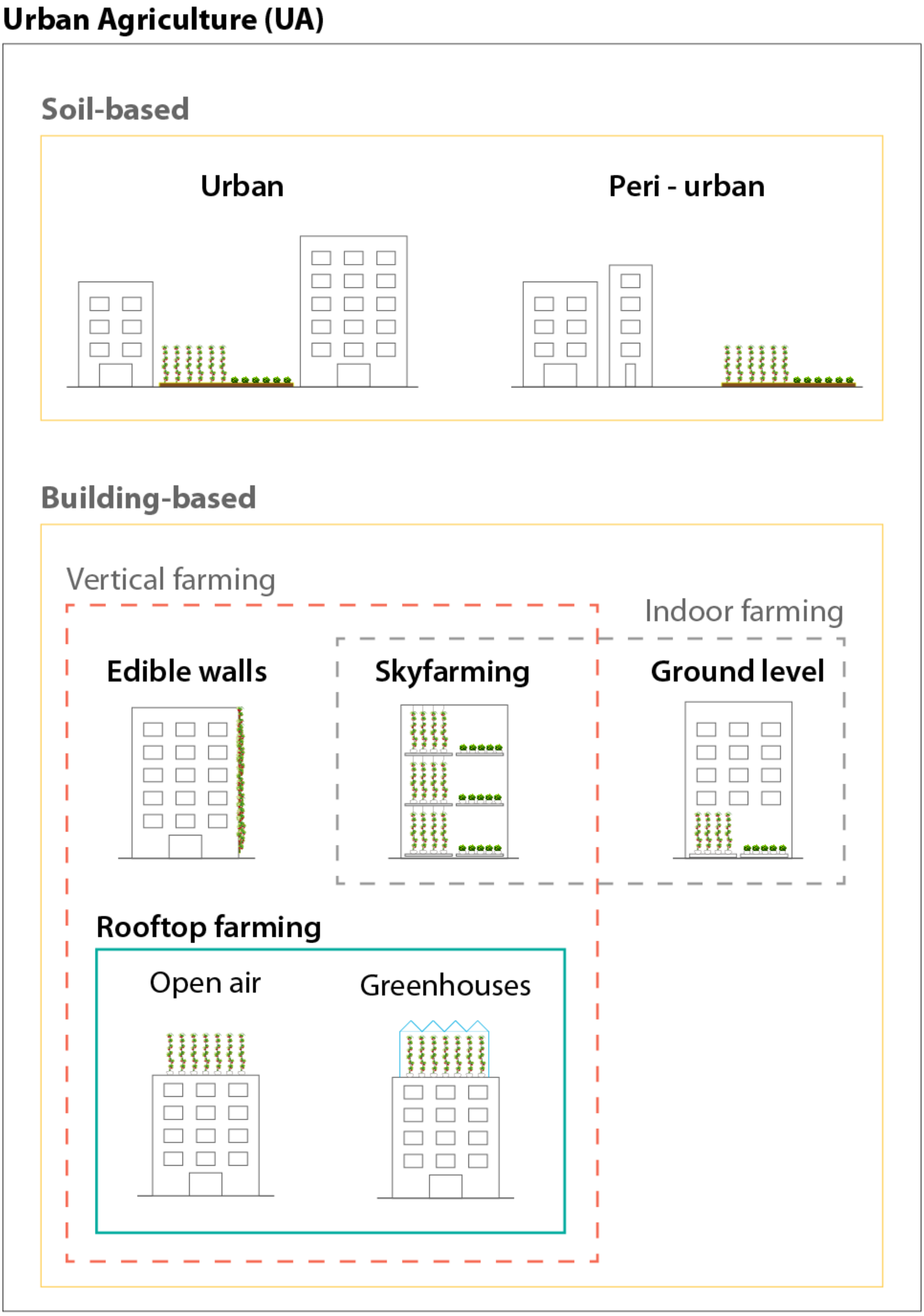


Figure 1.3. *Urban agriculture classification and typologies*

1.2.2. Social and commercial urban agriculture

In many cases, especially in poorest regions, UA is conceived as a social activity which provides sustainable food, increases food security and educates societies by promoting healthy habits (Altieri et al., 1999; Hu et al., 2013; Kortright and Wakefield, 2011; Orsini et al., 2014). UA can also be used as a tool to integrate disadvantaged people or discriminated social groups, by means of their participation in the social texture and providing them better living conditions (Novo and Murphy, 2001). UA disconnects them from food market fluctuations, promotes knowledge exchange, increases their interpersonal relations and improves their recreational activities (Konijnendijk and Gauthier, 2006; Orsini et al., 2009). Other social experiences of UA, such us UA as an educational activity in schools (Morgan et al., 2010; Morris et al., 2002), have been developed. Nevertheless, UA can also be understood as an economic activity to produce local food through sustainable and intensive food production systems.

Unlike social UA, commercial UA provides different social benefits, see Table 1.2. It can create jobs for both qualified workers and for disadvantaged people. In addition, commercial UA has the potential to produce sustainable food, to improve local economy and to enhance urban areas' self-sufficiency. In recent years, commercial UA experiences have increased significantly. Most of them are oriented to provide technical material for the installation of intensive crops in households buildings (i.e. Urban Crops[5]; Aero Farms[6]; Aponix[7]). Nowadays, few companies have their own urban farms where they produce UA products (see Figure 1.4).

Present dissertation focuses on rooftop farming with greenhouse, which aims to be an intensive and commercial food production system in urban areas. For that reason, next sections provide a specific introduction about this food production system.

Table 1.2. *Main benefits and characteristics of social and commercial UA*

	Social integration	Quality recreational activities	Educational activity	Increases food security	Resources optimization	High productivity	Job creation	Economic profits
Social	●	●	●	●				
Commercial	●			●	●	●	●	●

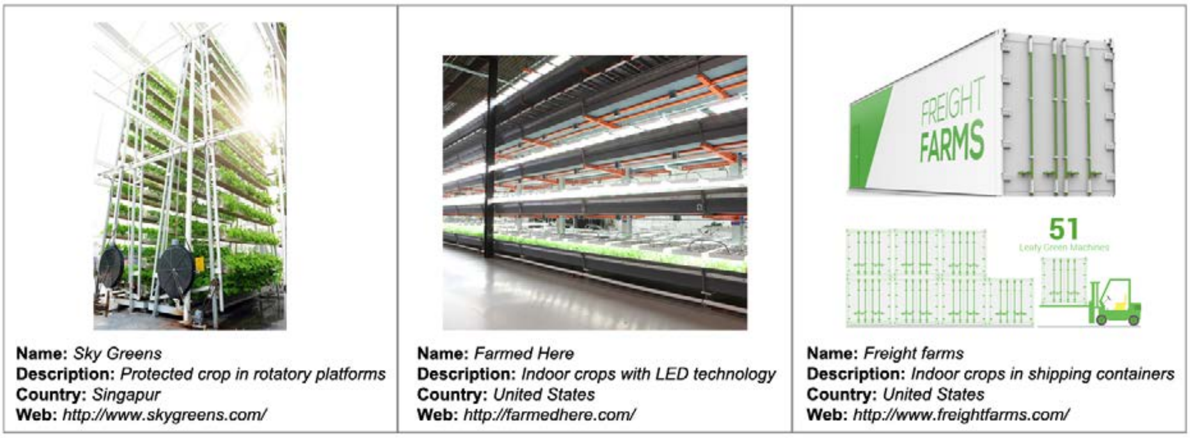


Figure 1.4. *Example of three commercial UA experiences*

[5] https://www.urbancrops.be/
[6] http://aerofarms.com/
[7] http://www.aponix.eu/

1.3. Rooftop greenhouses as a commercial UA food production system

The present dissertation focuses its attention on UA commercial rooftop greenhouses because of their potential to reduce the environmental impact of food production (Sanyé-Mengual et al., 2015c); the potential to install them in new or old buildings (Sanyé-Mengual et al., 2015b) and the possibility to exchange flows with buildings in order to increase both building and crop efficiency (Cerón-Palma et al., 2012; Pons et al., 2015). This section defines the concept of protected rooftop farming, reviews the state of the art of UA forms and analyses its opportunities and threats.

1.3.1. Rooftop greenhouses: an issue of coexistence between buildings and agriculture

Rooftop farming can be conceived in open air or protected systems by using greenhouses located on the top of buildings (see Figure 1.3), named "*Rooftop Greenhouses*" (from now on, RTGs). RTGs, as its name indicates, consist in installing greenhouses on the top of buildings that allow a better control of climate conditions than open rooftop farming systems. This control may increase crop yields, allow longer crop periods and probably make possible winter crops with low energy requirements (Pons et al., 2015).

RTGs can be installed in both new and old buildings. When greenhouses are installed in old buildings many limitations can be found (Sanyé-Mengual et al., 2015b):

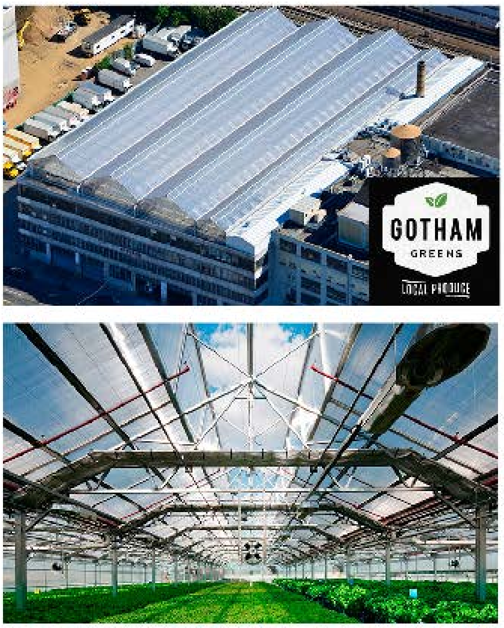
- Legal limitations due to a lack of regulations which determine the requirements that rooftop greenhouses must comply.
- Technical limitations because of: (1) the structural requirements that a building needs to support the extra weight of installing a greenhouse on its top; (2) the possible need to reinforce the greenhouse structure, for example, due to wind speed (at the top of buildings) or (3) the lack of a proper access to the top of the building which may require additional modifications.
- Economic limitations due to possible extra works required to adapt the building (i.e. flatten the roof) for the installation of RTGs.

When RTGs are installed at the same time as a building is being built, these limitations might be solved by designing both the building and greenhouse together. It could allow designing new solutions to integrate both structures. The ICTA-ICP building, located at the Universitat Autònoma de Barcelona, is one of the first buildings in the world that integrates a RTG since its construction. In next years, with the experience obtained from this RTG and other RTGs built on old buildings, it will be easier to design RTGs which solve adequately limitations mentioned.

RTGs can be installed on industrial buildings or households. On the one hand, in industrial buildings higher crop areas could be created, which may create more jobs, generate more economic profits and produce food more efficiently because of the economy of scale concept (Paul et al., 2004). On the other hand, RTGs located in households could find some barriers. For the installation of these RTGs would be required the agreement of the entire community of a building; moreover, the dimensions of the greenhouse could be smaller, so it would be more difficult to ensure the payback of capital invested. However, they would be located in the city center and not in the peri-urban industrial areas; therefore, food transportation distances could be reduced near to zero.

1.3.2. RTGs: State of the art

Few experiences of commercial RTGs can be found nowadays (see Figure 1.5). Most of them were developed after 2010, following the financial crisis of 2007. At this time, UA popularity enhanced among developed countries and, since then, there is a growing concern for food security. RTGs development is still at early stage and, probably, will experience further development in the near future.



Company: Gotham greens
Description: Local food production through RTGs
Country: United States
Web: http://www.gothamgreens.com/

Company: Nexus Greenhouse systems
Description: RTGs designer and developer
Country: United States
Web: http://www.nexuscorp.com/

Company: Lula farms
Description: Local food production through RTGs
Country: United States
Web: https://www.lufa.com/

Company: Urban farmers
Description: Combined RTGs with aquaponics
Country: Switzerland
Web: https://www.urbanfarmers.com/

Figure 1.5. *State of art of RTGs commercial experiences*

1.3.3. Integrating rooftop farming and buildings

Inspired in an industrial ecology approach, RTGs can integrate their flows with the metabolism of buildings they are placed on, to optimize both building and greenhouse efficiency (Nadal et al., 2017; Pons et al., 2015), see Figure 1.6. Integrate RTGs (form now on i-RTGs) have the potential to exchange the following flows with buildings:

- i-RTGs could take advantage of the thermal inertia and waste heat (i.e. from a burn process) of buildings to avoid using additional heating systems.
- The waste air of buildings, with high CO_2 concentration, could be used for the carbon enrichment of crops.
- Crops could be used to produce renewed air (with low CO_2 concentration) which could be injected in the building to increases its air quality.
- Rainwater and buildings' grey water could be used to irrigate crops. Also, leachates from crops could be used for sanitary purposes.

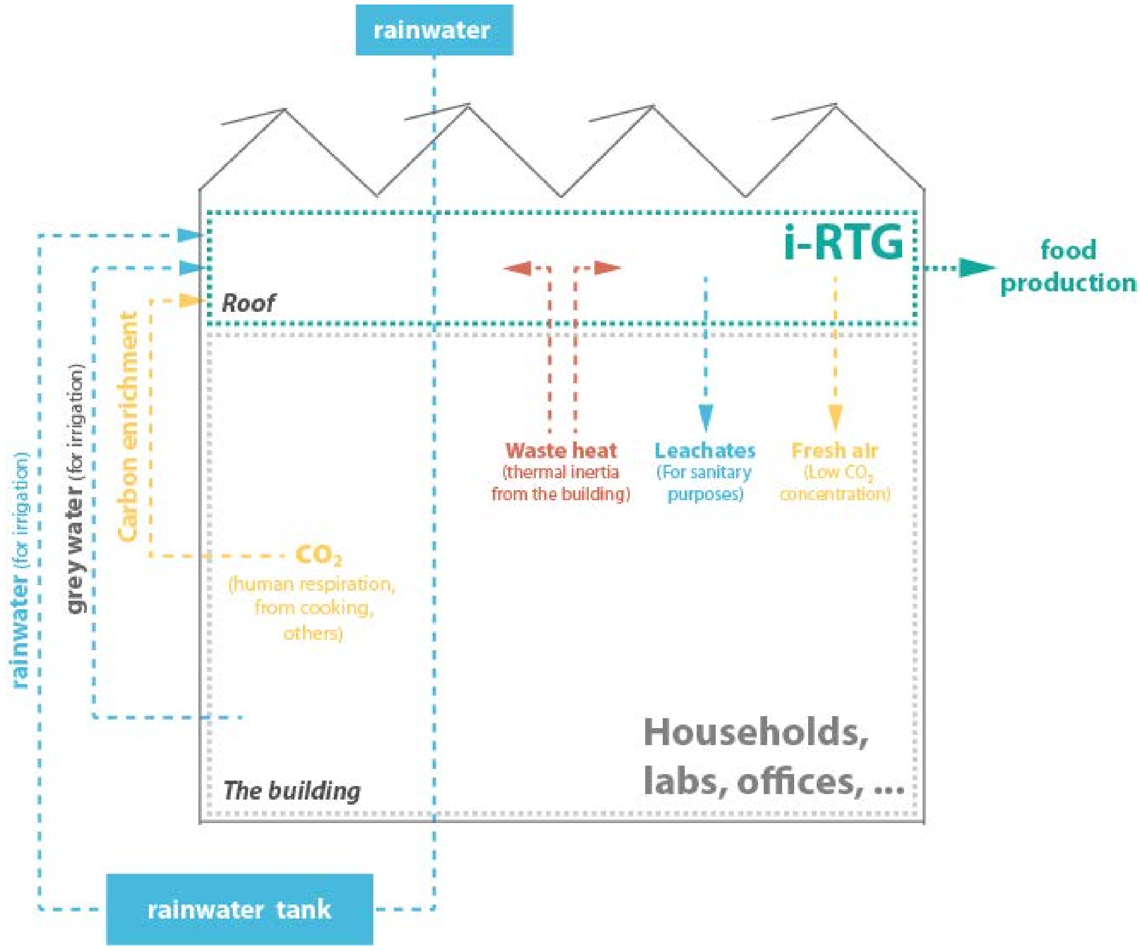


Figure 1.6. *Scheme of the i-RTG concept*

In addition to the mentioned potential flows that i-RTGs and buildings could exchange, depending on the use of buildings (i.e. industrial purposes, households) new flows of interest (i.e. crop wastes could be used as raw materials in an industrial plant) could be detected to further increase both systems efficiency. The present dissertation studies i-RTGs, from an industrial design point of view, to reduce its environmental implications by studying some of its flows.

1.4. Industrial design: making rooftop farming environmentally friendly

Since the 1990s, there is certain ambiguity about the definition of industrial design. Some definitions prioritize the function of the product while other the appearance (Marxt and Hacklin, 2005).To approach the present dissertation following definition by the World Design Organization was chosen (WDO, 2017):

"Industrial design bridges the gap between what is and what is possible. It is a trans-disciplinary profession that harnesses creativity to resolve problems and co-create solutions with the intent of making a product, system, experience or a business. Industrial designers place the human at the centre of the process. They acquire a deep understanding of user needs through empathy and apply a pragmatic, user centric problem solving process to design. They are strategic stakeholders in the innovation process and are uniquely positioned to bridge several professional disciplines and business interests. They value the economic, social and environmental impact of their work and their contribution towards co-creating a better quality of life"

Design is a process that leads to an outcome. It aims to give solutions to specific problematics. Such solutions, in most cases, result in the development of new products (Ashby and Johnson, 2002). During World War II new techniques and methods, which attracted the attention of designers, were used for developing arms and wartime equipment (Bayazit, 2004). Later, the first creative methods were developed in U.S. after the launch of the Soviet's Union's satellite named "Sputnik", which enhanced American government to invest money on creativity (D. Henry, 1967). Nowadays, multiple innovative and creative product design methods have been developed according to market needs. Some examples of such methods are the usability based design (Chang et al., 2017), the user experience based design (Chien et al., 2016) or the GLIDs method to enhance ecodesign (Van Mechelen et al., 2017). All of them agree that design process is the stage when most design decisions are taken. During this stage, all requirements concerning product design are detected, collected and then treated as pieces of a big puzzle to develop specific solutions through the creation of innovative products (see Figure 1.7). The difference between methods falls on the fact that each one prioritizes a specific requirement ("puzzle piece"). Product design and its related creative processes should be used to look for new solutions to increase the efficiency of greenhouses and i-RTGs.

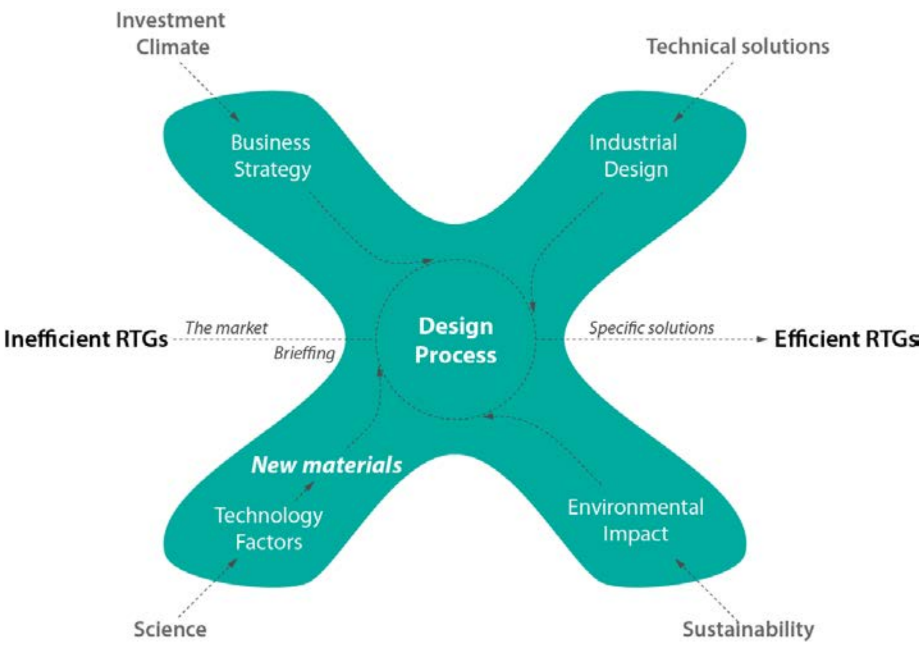


Figure 1.7. *Inputs to the design process*
Source: Adaptation from (Ashby and Johnson, 2002)

Process design is subject to multiple external influences which may be combined to develop specific solutions. It is mainly influenced by four drivers: science, economic investment, sustainability and technical solutions (see Figure 1.8) (Ashby and Johnson, 2002). Among these, science provides new technologies that enable innovation in materials and processes. Better materials and processes increase the number and quality of specific solutions that can be developed to satisfy market demand. Simultaneously, new materials are inspiration tools for designers (see Figure 1.8). Due to the importance of materials in design process, this dissertation pay special attention to innovative and new materials which can be used or created to solve specific problems.

Figure 1.8. *Steps to move new materials into successful products*
Source: Adaptation from (Ashby and Johnson, 2002)

1.4.1. Passive systems to control greenhouse temperatures

Thermal inertia is the property from a material (at liquid, solid or gas state) that describes its capacity to keep heat and the slowness with which the material temperature approaches that of its surroundings. It mainly depends on its mass, specific heat and thermal conductivity. It has been demonstrated that keeping greenhouse day-time and night-time temperatures at an appropriate level increase crop productivity (Gosselin and Trudel, 1984; Kawasaki et al., 2014). To reduce temperature oscillations in greenhouses their thermal inertia of can be increased, which reduces the effect of outside temperatures on crops (Benli and Durmuş, 2009a; Berroug et al., 2011; Boulard and Baille, 1987).

Until today, to keep greenhouse temperatures stable active climate control systems, such as cooling and heating systems or automatic ventilation solutions, have been used (Chen et al., 2015; Okada and Takakura, 1981). These require energy consumption. Few studies analyze the potential of passive, no-energy dependent systems to increase the thermal inertia of greenhouses and, for example, reduce the speed with which greenhouse temperature falls during night (Benli and Durmuş, 2009a; Berroug et al., 2011; Bouadila et al., 2014; Kürklü, 1998). These are of great interest because of their potential to reduce the fuel dependence and environmental impacts of food production systems.

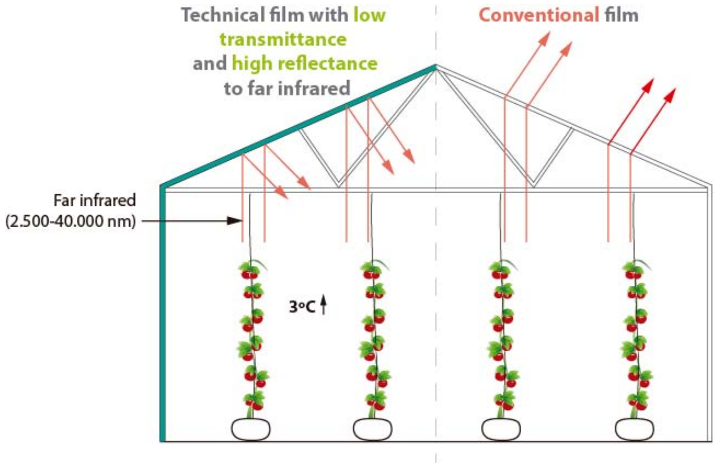
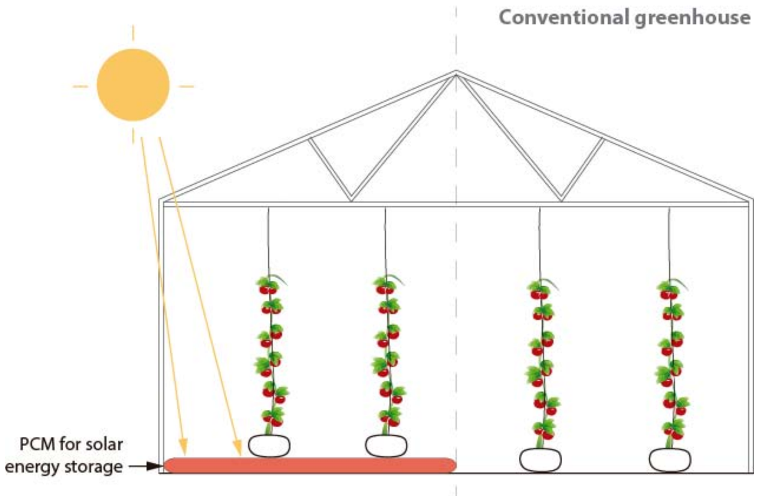
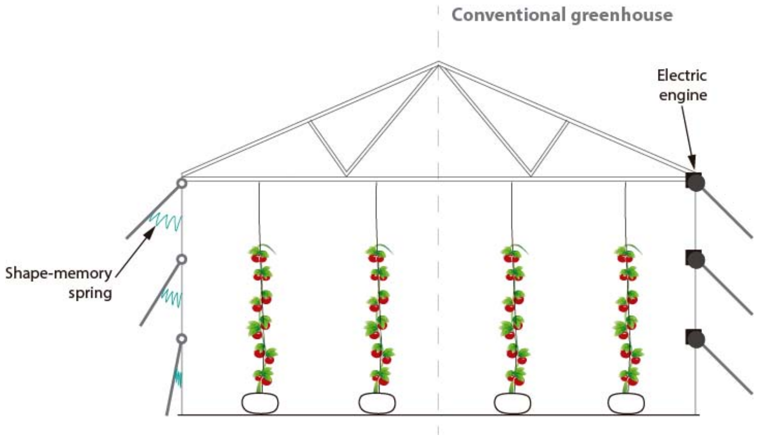
Passive systems are solutions which allow automatic actions, without using any energy input, when a parameter of a system changes. If innovative materials are applied in greenhouses, multiple solutions could be designed to developed passive systems which may help to improve their thermal inertia and climate control. Table 1.3 shows some conceptual applications of innovative materials that may help to develop passive systems for greenhouses.

Materials' heat storage capacity can be divided into two typologies (see Figure 1.9):

- **Sensible heat:** is the capacity of a material to store heat without changing its state from solid to liquid, liquid to gas or conversely
- **Latent heat:** is the capacity of a material to store heat by using the energy required to produce a phase change (solid-liquid-gas).

Phase change materials (PCMs) are materials with a high latent heat capacity Its latent heat can be used to store thermal energy. These materials could be applied in greenhouses (see Table 1.3) to increase their thermal inertia. In this application PCMs located inside a greenhouse may melt during day and reduce inner temperatures, by absorbing excess heat from inside the greenhouse. At night, due to cold temperatures, PCMs may solidify by observing cold from the greenhouse, fact that results in an increase of greenhouse temperatures without using conventional heating systems. The mature state of PCM experiences and development (Delgado et al., 2012; Mehling and Cabeza, 2008; Sarı, 2004) makes possible studying applications of these materials, concretely for greenhouses as done in the present dissertation.

Table 1.3. *Conceptual potential applications of innovative materials in greenhouses to create passive systems which may help to control greenhouse and i-RTG temperatures*

Figure of the concept	Description & comments
	*A new materials for the greenhouse cover which reflects and does not transmit far infrared may help to avoid heat losses from the greenhouse during night-time* (Piscia et al., 2013). *This new material still requires scientific research and economic investment.*
	*PCM could be used to store solar energy during the day that can be released at night in terms of heat. PCM could replace conventional heating systems.* *PCM application have already been tested in the building sector* (Cabeza et al., 2011; Cabeza and Pérez, 2014; Castell et al., 2010).
	*Shape-memory allow materials could be used to replace the conventional electric engines that control side gates of the greenhouse for its ventilation. These materials can modify their shape at certain temperatures* (Schwartz, 2002). *Shape-memory springs would open side gates at one specific temperature. However, current greenhouse climate control software allow the modification of this parameter easily, according to the thermal requirements of the greenhouse during each season.*

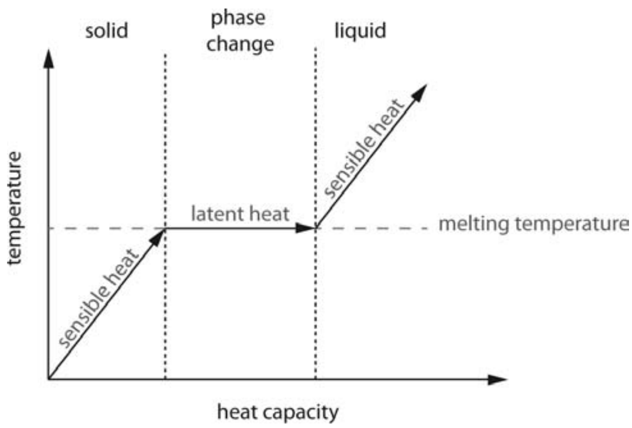


Figure 1.9. *Simplification of heat storage typologies of materials according to their phase state*

1.4.2. Designing with wastes

The current waste management systems of agricultural residues generate by-products which could be considered raw materials for other processes to create new products (see Figure 1.10). Industrial design could be a drivers to look for new technologies, which allow to transform such wastes and create new products that may satisfy our society's needs. Nowadays, some agricultural or silvicultural wastes have been used to create new materials and products. A clear example on how science, technology and design method meet to create new products with agricultural wastes is Piñatex[8]. It is a high quality textile that simulates skins, also known as vegetal leather, made with waste pineapple leaves generated during the pineapple harvesting process. Figure 1.11 shows different products made with the Piñatex material. To develop this material it was required a full Dissertation (Hijosa, 2015), during which the pineapple wastes were characterized in order to determine the available technologies to transform it into a new material with interesting properties for designers (i.e. pleasant texture and smell, multiple colors finishes). Piñatex demonstrates the potential of agricultural wastes to create new materials.

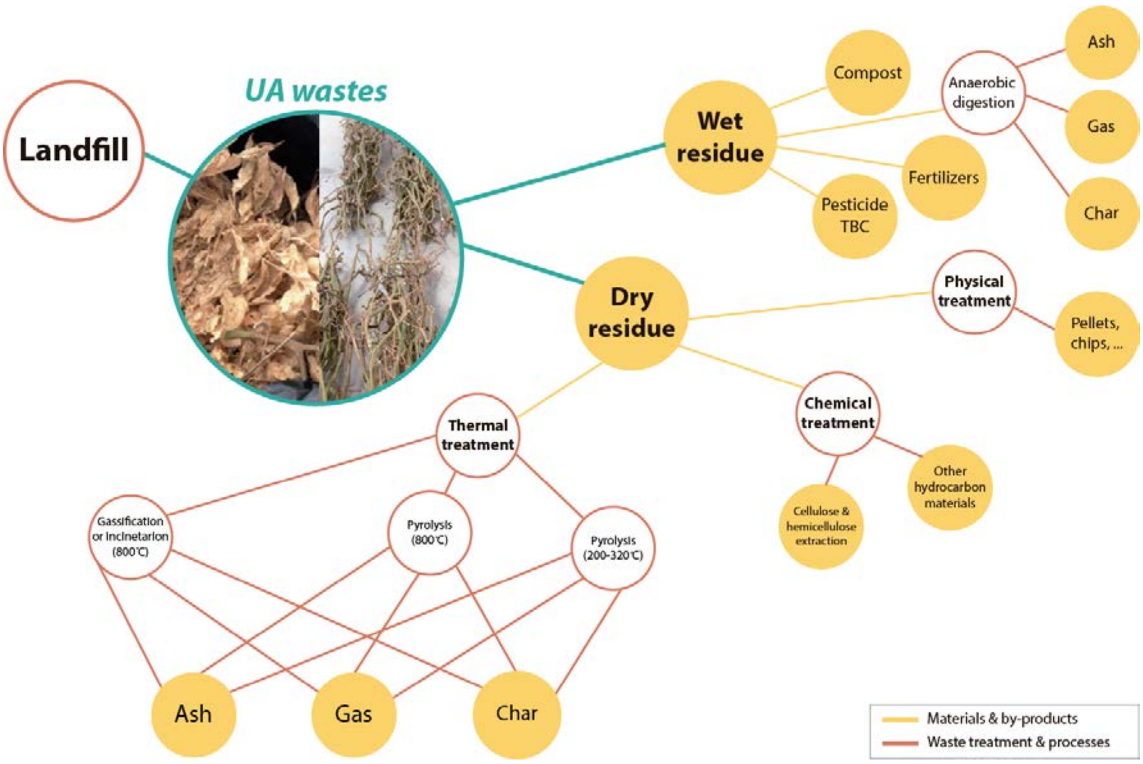


Figure 1.10. *Scheme of multiple possible waste management solutions for the creation of new materials and by-products with UA wastes*

[8] http://www.ananas-anam.com/

Figure 1.11. *Products elaborated with the Piñatex vegetable leather. From left to right: piñana vegan shoes; piñana bag and piñana laptop case*

1.5. Motivations of the dissertation

Commercial RTGs have the potential to provide social and economic profits from as mentioned in section 1.2.2. Moreover, in environmental terms previous studies have proved the capacity of i-RTGs to reduce the carbon footprint from food production systems in comparison with conventional production. The environmental benefits are mainly obtained due to (Esther Sanyé-Mengual et al., 2013; Sanyé-Mengual et al., 2015c):

- Reduced food transportation distances.
- Minimized food losses during transportation.
- Improved packaging logistics which allows its reutilization.

From a life cycle approach, the environmental benefits are obtained during transportation and packaging stages. Previous environmental studies did not find a reduction of the impacts in production and waste management stages, as illustrated in Figure 1. 12. Production technologies (i.e. hydroponics) and waste management solutions (i.e. composting, incineration) used in i-RTGs are the same that nowadays are being used in conventional crops (Sanyé-Mengual et al., 2015c). Therefore, to use the same production systems and waste management solutions hinders to reduce the environmental implications of these stages. For this reason, the present dissertation focused on specific studies which intend to reduce the environmental burdens of i-RTGs mainly from production and waste management stages (see Figure 1.12):

(a) Energy consumption and carbon footprint reduction during production stage

In conventional Mediterranean greenhouses, it is required to use heating systems to grow winter crops. These are conventionally based on the use of non-renewable fuels, as oil or gas (Chau et al., 2009; Pehnt, 2006). Heating systems can increase crop productivity (Gosselin and Trudel, 1984; Kawasaki et al., 2014); however, they have several environmental implications associated (Gasol et al., 2009). Passive heating systems could be an interesting solution to reduce the environmental impacts of crop heating systems(Benli and Durmuş, 2009a, 2009b; Bouadila et al., 2014). Nowadays, not heating systems have been designed for i-RTGs. Before thinking in using conventional heating systems in i-RTGs, if we want to create sustainable commercial UA food production experiences, it seems imperative to look for new environmentally-friendly solutions to heat crops grown in i-RTGs, which could also be applied in conventional greenhouses.

(b) Crops' carbon enrichment with residual air from buildings

CO_2 concentration inside buildings can rise up to 2,500 ppm due to human respiration (ACGIH, 1991); so, high ventilation rates are required in closed environments to ensure proper air quality and avoid damages on human health (Seppanen et al., 1999). Moreover, in industrial buildings large amounts of CO_2 can be generated by specific production processes. Residual air from ventilation systems of households, offices or industrial buildings could concentrate high CO_2 levels that make residual air interesting for the carbon enrichment of crops grown in i-RTGs located on the top of these buildings. The carbon enrichment of crops grown in i-RTGs would stimulate productivity (Yelle et al., 1990), fact that reduces the costs and environmental implications of each unit of food produced.

Nowadays, it has not been studied yet the potential of residual air from buildings for its use to enrich with carbon crops grown in i-RTGs. Moreover, according to: (1) the high CO_2 concentrations that could be found in buildings' residual air and (2) the potential economic and environmental advantages of doing carbon enrichment in i-RTGs; it is of great interest to study the potential of residual air of buildings for its use to enrich with carbon crops grown in i-RTGs.

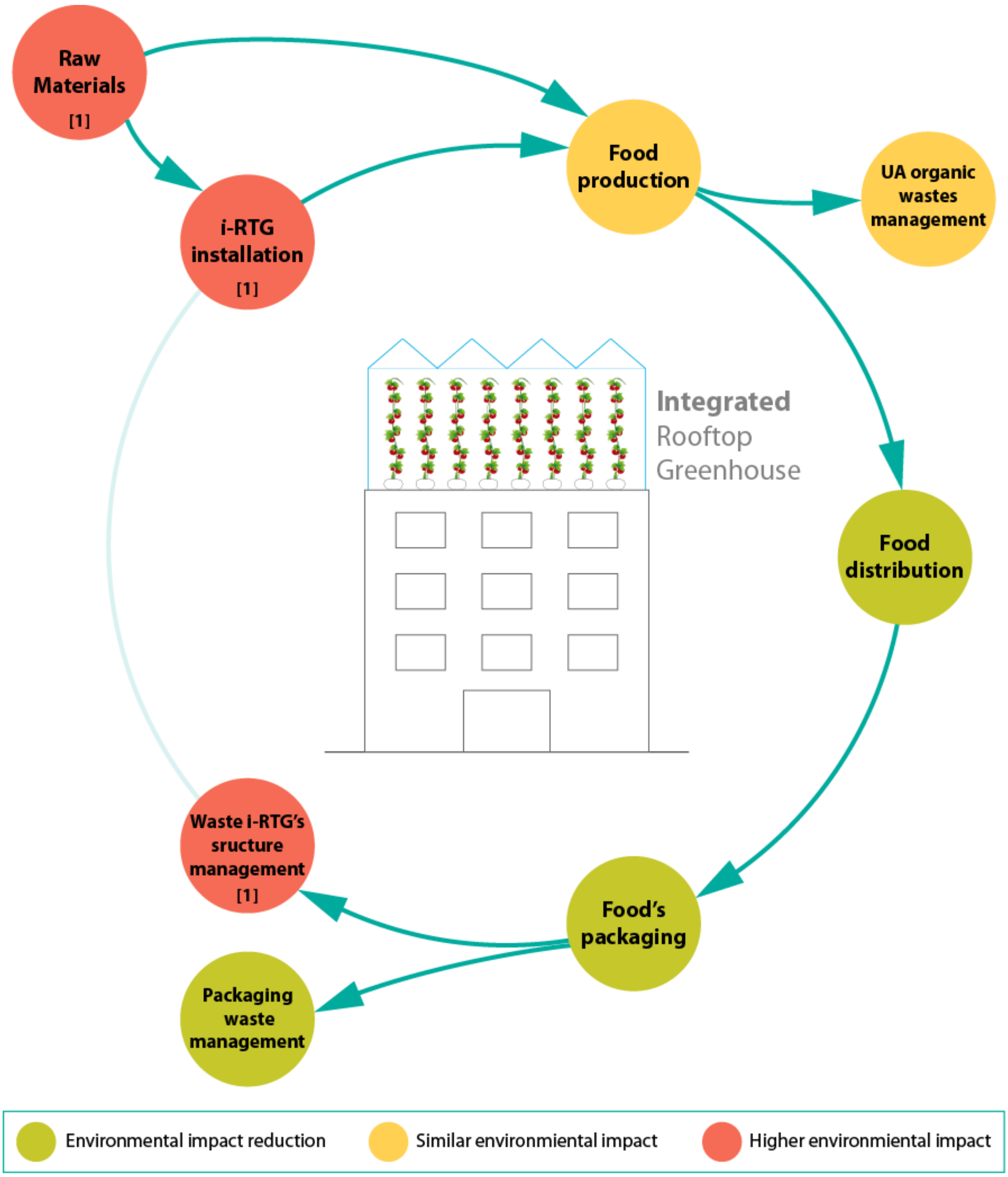
(c) Improvement of the carbon footprint calculation of UA crops

After reviewing the previous publications which analyze the environmental implications of i-RTGs (Sanyé-Mengual et al., 2015c), we detected a possible overestimation of greenhouse gas (GHG) emissions calculated. Questioning these results does not implicate a direct environmental improvement of i-RTGs' production stage but it is important to correct the possible overestimation of GHG emissions to ensure a proper calculation of i-RTGs' carbon footprint. If finally GHG were overestimated, i-RTGs could be more interesting from an environmental point of view than we have thought until today.

Part of the nitrogen fertilizers applied in crops result in nitrous oxide (N_2O) emissions (Daum and Schenk, 2013; Yoshihara et al., 2014), which have a global warming potential (GWP) 298 higher than CO_2 for a 100 years horizon (IPCC, 2013). In Sanyé-Mengualet al. (2015b) study the derived N_2O emissions from nitrogen fertilizers in an i-RTG where calculated by using the IPPC emission factor (IPCC, 2006). This factor provides an estimation of the amount of N_2O emissions that are generated per unit of fertilizer provided. Nevertheless, the emission factor provided by IPPC was calculated with soil-based crops whilst i-RTGs studied in Sanyé-Mengualet al. (2015b) research consist of soil-less systems. Therefore, as a different soil is used the N_2O calculated might not be accurate. So, seems necessary to verify the real emissions from soil-less technologies used in i-RTGs.

(a) Carbon fixation from UA wastes

UA experiences have increased in last years and seems that will keep growing in the near future (Orsini et al., 2013; Specht et al., 2013). UA gives place to the creation of new urban organic wastes that many urban areas could not be ready to manage adequately. Conventional agricultural waste management solutions could be applied to manage UA wastes; nevertheless, for a proper sustainable UA we need to go one step beyond that means to look for new agricultural waste management solutions, which could be applied in urban areas and, if possible, in conventional crops. Nowadays, most common waste management solutions consist of composting; incineration or feeding animals. These waste scenarios could be considered sustainable if are carried out adequately (Litterick et al., 2004); however, do not always ensure the fixation of carbon emissions as well managed forests do (Johnson, 1992). Using wastes to create new materials or by-products (see Figure 1.10) could be a feasible strategy to avoid conventional waste management treatments and, maybe, ensure the carbon sink of CO_2 emissions captured and fixed by tomato plants in their stems and leaves.



[1] The increase of environmental impact is caused by the over-reinforced structure of the i-RTG required to meet the architectural requirements that the Spanish law stablishes.

Figure 1.12. *Life cycle of a i-RTG and environmental results in comparison with conventional food production systems according to Esther-Sanyè et al. (2015b) study.*

1.6. Objectives of the dissertation

The present thesis aims to reduce the environmental implications of protected urban rooftop farming through the application of innovative materials in crops; the analysis of the GHG emissions flows of i-RTGs and the creation of new by-products with i-RTGs wastes. To do so the following main research questions were addressed:

- **Question 1:** Can passive systems made with phase change materials (PCMs) replace conventional heating in greenhouses and reduce the carbon footprint of i-RTGs?
- **Question 2:** Can the residual air of a building be used for CO_2 enrichment in i-RTGs?
- **Question 3:** Could the GHG emissions of i-RTGs be calculated with more accuracy?
- **Question 4:** Is the creation of new by-products, with UA wastes, a strategy to sink the CO_2 emissions captured by crops grown in i-RTGs?

To explore these questions following specific objectives were thoroughly studied:

- **Objective I:** To evaluate the economic and environmental feasibility of using PCMs to create a passive root zone heating system for soil-less crops (Chapter 3).
- **Objective II:** To study the technical feasibility of creating a passive heating system for soil-less crops with PCMs (Chapter 4).
- **Objective III:** To determine the potential of using residual air from buildings for the carbon enrichment of i-RTGs (Chapter 5).
- **Objective IV:** To determine the emission factor (ratio between N fertilizers provided and derived direct N_2O emissions) of a soil-less lettuce crop grown in an i-RTG (Chapter 6).
- **Objective V:** To analyze the technical and environmental viability of producing biochar with UA tomato waste plants as a carbon capture and storage solution (Chapter 7).
- **Objective VI:** To evaluate the environmental potential of producing a renewable thermal insulation material with UA tomato waste plants (Chapter 8).

Chapter 2

Materials and methods

"Good strategies guarantee good results to stay alive"
Material organization before climbing

CHAPTER 2 - Materials and methods

This section introduces the methods applied in the present dissertation and lists the main materials used in each case study. The thesis focuses on the reduction of the carbon footprint of i-RTGs, therefore, environmental tools are of common use in almost all chapters of the document. Table 2.1 shows the different methods used in each chapter. In some chapters experimental and analytical methods are used too (see Table 2.2); however, these methods are specific for each chapter. For this reason, experimental and analytical methods are deeper described explicitly in each chapter.

Table 2.1. *Overview of the methods applied in each chapter*

			LCA	LCCA	Experimental	Analytical
PART II	Chapter 3	LCA & LCCA of a PCM application to control root zone temperatures of hydroponic crops in comparison with conventional root zone heating systems	■	■		
	Chapter 4	Analysis of the technical, environmental and economic potential of phase change materials (PCM) for root zone heating in Mediterranean greenhouses	■	■	■	
PART III	Chapter 5	CO_2 enrichment potential in i-RTGs with residual air from buildings			■	
	Chapter 6	N_2O emissions from protected soil-less crops for more precise food and urban agriculture life cycle assessments	■		■	■
PART IV	Chapter 7	Carbon fixation of urban agriculture residues through biochar co-production: technical feasibility and environmental potential benefits	■			■
	Chapter 8	Environmental assessment of a renewable thermal insulation material produced with tomato plant stems derived from urban agriculture wastes	■		■	■

Table 2.2. *List of the main devices, processes and analysis used during the dissertation*

		Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7	Chapter 8
Experimental	Temperature sensor		■		■		
	Humidity sensor				■		
	Open chamber system				■		
	CO_2 sensor			■	■		
	N_2O sensor				■		
	Anemometer			■	■		
	Piranometer			■			
	Developing samples of a material					■	■
Analytical	Gas chromatography				■		
	Liquids chromatography				■		
	Elemental analysis (C or N content)				■	■	■
	Two step process analysis to determine N content in perlite				■		
	Cellulose, hemicellulose and lignin content through gravimetric method					■	
	Thermogravimetric analysis (TGA)					■	
	Metal content analysis					■	
	Characterization of material properties					■	■

2.1. Environmental tools: LCA

The carbon footprint and the other environmental burdens under study were calculated with Life Cycle Assessment (LCA) methodology, which is a recognized method supported by the UNEP (UNEP, 2002) and the European Commission (European Comission, 2001). It is defined as follows (ISO, 2006a):

"LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (i.e. consecutive and interlinked stages of a product system, from raw materials acquisition or generation from natural resources to final disposal)"

The LCA methodology is divided into 4 main steps, as shown by Figure 2.1 which are later described.

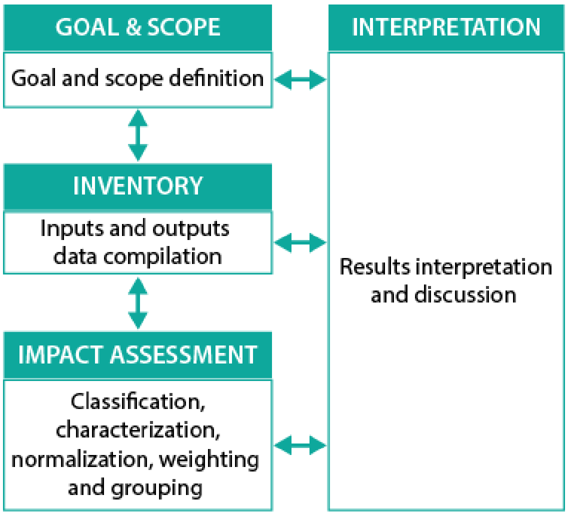


Figure 2.1. *Steps of the LCA methodology*
Source: Own elaboration from ISO 14040 and 14044 (ISO, 2006a, 2006b)

2.1.1. Goal & Scope

The goal & scope definition is the first step of the LCA methodology. It consists in a detailed description of the objective of the study and the definition of the specific product or service that is going to be studied. This section should clearly include the following information collected in Table 2.3.

Table 2.3. *Main content of goal & scope phase of the LCA methodology*

Goal of the study	Scope of the study
• Objective of the study. • Applications of the study. • Target Audience. • Limitations of the study.	• Description of the system under study: definition of the system boundaries, cut-off rules assumed, functional unit and reference flows. • Description and discussion of possible allocations. • Description of databases used. • Determining the selected impact categories under study.

The functional unit is a key element in LCA studies. It provides information about the "what", "how much" or "for how long" the product or service gives a specific function. The functional unit is a very important feature in comparatives studies in which the element under study is the function or service that products provide and not the product per se. For example, a conventional mobile phone could not be directly compared with a smart phone. Smart phones provide to users much more functions (i.e. internet access, camera). Therefore, for a fair comparison of both products in a LCA study, the environmental impact of the function of doing phone calls can be compared but not the products.

If more than one product is produced from one process, the environmental impacts of the production process should be distributed between these products. This distribution is named allocation. The ISO 14044 (ISO, 2006b) recommends to avoid allocations. However, if it cannot be avoided the environmental implications calculated should be associated to the different products obtained from the process by physical relationships (mass), economic aspects (i.e. profits) or other relationships such as energy contents.

2.1.2. Life cycle inventory (LCI) assessment

The life cycle inventory assessment (LCI) consists in the recompilation of all the inputs and outputs of the system under study. That means the data collection of all the resources required by the system from nature (i.e. raw material, water) and technosphere (i.e. energy, refined petrol), and all the emissions generated to the environment (i.e. waste water, gas emissions) and the technosphere (i.e. wastes which require treatment) for its entire life cycle. Nowadays, multiple databases exist which facilitate inputs and outputs of some products or services, such as the Ecoinvent database, which is the most complete LCI database existing (Swiss Center for Life Cycle Inventories, 2015). In this dissertation two main databases were used: Ecoinvent 2.0. and Ecoinvent 3.0 (see Table 2.4). Ecoinvent 2.0. was used in the first studies of the thesis until the database was uploaded to Ecoinvent 3.0 (Swiss Center for Life Cycle Inventories, 2015).

The LCI can be modelled from two different perspectives: attributional (A-LCA) and consequential (C-LCA) (Thomassen et al., 2008; UNEP-SETAC, 2011; Weidema, 2003). On the one hand, an A-LCA consist in defining a fixed FU and static system boundaries without considering market effects. The A-LCA describes the present state of a product or service under study. On the other hand, a C-LCA considers market effects on environmental results by adapting the FU to changes of markets demands. Moreover, it considers expanded system boundaries which include processes and material flows directly and indirectly used by the system (UNEP-SETAC, 2011).

Table 2.4. *LCI databases used for each chapter of the dissertation (chapter 5 is not included as a LCA was not conducted in that chapter)*

		Ecoinvent 2.0	Ecoinvent 3.0
		Attributional	Attributional
Chapter 3	LCA & LCCA of a PCM application to control root zone temperatures of hydroponic crops in comparison with conventional root zone heating systems		
Chapter 4	Analysis of the technical, environmental and economic potential of phase change materials (PCM) for root zone heating in Mediterranean greenhouses		
Chapter 6	N_2O emissions from protected soil-less crops for more precise food and urban agriculture life cycle assessments		
Chapter 7	Carbon fixation of urban agriculture residues through biochar co-production: technical feasibility and environmental potential benefits		
Chapter 8	Environmental assessment of a renewable thermal-insulation material produced with tomato plant stems derived from urban agriculture wastes		

In addition, during the LCI assessment it is necessary to do some assumptions due to a lack of data available. This phase may explain all the possible data limitations and highlights its possible influence on results.

2.1.3. Impact assessment

According to ISO 14040 (ISO, 2006a) the impact assessment stage consists of two main mandatory steps: classification and characterization. The classification aims to group the different inputs and outputs from the LCI in impact categories according their effect on the environment (i.e. CO_2 emissions contribute to climate change). The characterization, which is done after the classification, intends to calculated the environmental impact of each impact category under study by using characterization factors from the literature (i.e. 1kg of N_2O emissions equals to 298 kg of CO_2 emissions eq. according to the IPCC characterization factor[9]) (EC-JRC, 2010).

Other optional steps can be done during the impact assessment: normalization, weighting and grouping. The normalization compares results of indicators (i.e. kg CO_2 eq.) with other references to understand the importance of environmental results. The weighting consists in the conversion of results from different impact categories, which cannot be directly aggregated, by applying numerical factors which can therefore be aggregated. Grouping is a process which sorts and ranks results from the different impact categories under study. It allows the periodization of some impact categories. Both weighting and grouping are useful to understand the importance of indicators from the different impact categories.

Impact assessment stage applies specific methods (i.e. CML; Recipe) which translate the LCI inputs and outputs into quantitative environmental impacts (EC-JRC, 2010; ISO, 2006a). Depending on the level of impact quantified, methods can be classified as midpoint or endpoint. Midpoint methods give problem-oriented results which describe the direct quantitative effect of a product or service on the environment (i.e. kg CO_2 emissions eq.). Endpoint methods give information about the area were the impact affects (natural resources, human health or natural environment).

In the present dissertation the Recipe Midpoint Hierarchical (H) method (Goedkoop et al., 2009) was applied in all the LCA studies realized. The climate change impact category was used as an environmental indicator in all the chapters because of the relevance of this impact at planetary scale (IPCC, 2014a). Nevertheless, as the dissertation are described in Table 2.6.

Table 2.5 illustrates, in some chapters it was considered necessary to study other impact categories to proceed with a deeper environmental assessment of the specific objective under research. For example, in chapter 3 a passive system for protected crops is studied; therefore, it was taken into consideration to analyze other impact categories to gain a deeper vision of the environment burdens of the system which had not been previously analyzed. The impact categories analyzed in the dissertation are described in Table 2.6.

Table 2.5. *Impact categories selected for each chapter of the dissertation (chapter 5 is not included as a LCA was not conducted in that chapter)*

	Recipe Midpoint (H)						
	Climate Change	**Cumulative Energy demand**	**Photochemical oxidant formation**	**Terrestrial acidification**	**Freshwater eutrophication**	**Water depletion**	**Fossil depletion**
Chapter 3							
Chapter 4							
Chapter 6							
Chapter 7							
Chapter 8							

[9] https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html

Table 2.6. *LCA indicators from Recipe midpoint (H) method*

	Abbreviation	Definition	Reference of the characterization factor	Units
Climate Change	CC	Accounts for the gas emissions contributing to the increase of global temperature due to the block of infra-red radiation into earth atmosphere.	(IPCC, 2014a) and updates	kg CO_2 eq.
Cumulative Energy demand	CED	Accounts for the direct and indirect primary energy use, including energy from both renewable and non-renewable sources.	(Goedkoop et al., 2009)	MJ
Photochemical oxidant formation	POF	Accounts for the presence of substances that produce photochemical oxidation (mainly NMVOC and NO_x) which is the main cause of smog in cities with several negative effects on human health.	(Goedkoop et al., 2009)	kg NMVOC eq.
Terrestrial acidification	TA	Account for acidification substances (NO_x, NH_3, SO_2) into air which have negative effect on terrestrial ecosystems	(Goedkoop et al., 2009)	kg SO_2 eq.
Freshwater eutrophication	FE	Accounts for the presence of nutrients accumulated in fresh water which produce eutrophication.	(Goedkoop et al., 2009)	kg P eq.
Water depletion	WD	Accounts for the depletion of available freshwater due to anthropogenic activities.	(Goedkoop et al., 2009)	m^3
Fossil depletion	FD	Accounts for the depletion of non-biological resources (i.e. fuels) due to anthropogenic activities.	(Goedkoop et al., 2009)	kg oil eq.

2.1.4. Results interpretation

The fourth and last step of the LCA methodology is results interpretation. It reports and discusses results and provides main conclusions and recommendations. In this stage, the other steps of the methodology (i.e. FU selection, LCI analysis) are also analyzed transversely (see Figure 2.1) to determine if previous decisions may affect results. Results interpretation must be a transparent process which reduces subjectivity as much as possible. Results obtained should be explained adequately, which means that the cause of the different environmental impacts should be described and justified.

2.2. Economic tools: LCCA

The life cycle cost analysis (LCCA) is a methodology used to assess the economic performance of products or services. This methodology can follow the same life cycle approach as LCA (see Figure 2.2), fact that allows the combination of both methodologies results, for example, to generate eco-efficiency indicators (Huppes and Ishikawa, 2005; UNEP, 2011). ISO 15.686-5 (ISO, 2008a) provides recommendations for the LCCA analysis of buildings and constructed assets. This guideline was used as reference for the development of LCCA studies in the dissertation. ISO 15.686-5 describes the LCCA analysis as (ISO, 2008a):

"A tool and technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational and asset replacement costs, through to end of life, or end of interest in the asset – also taking into account any other non-construction costs and income, defined as in scope"

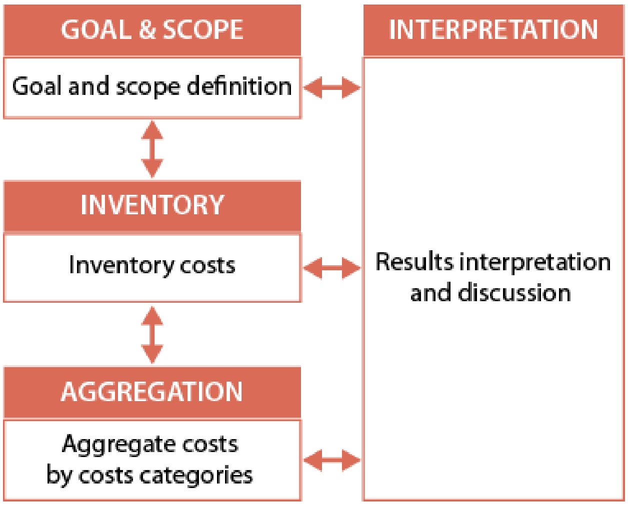


Figure 2.2. *Steps of the LCCA methodology* (ISO, 2008a; UNEP, 2011)

Source: Own elaboration from UNEP (2011)

Similarly to ISO 14040 (ISO, 2006a), for the LCCA method the goal and scope stage aims to define the goal of the study, a functional unit, specify system boundaries and apply allocation procedures or discount rates if more than one product is produced. In inventory phase, costs are inventoried separately for each life cycle stage and unit process. In this section the quality and origin of sources may be discussed. During aggregation step, costs are aggregated by life cycle stages and costs categories (i.e. investments, labor costs). Finally, interpretation stage may describe with transparency results and discuss them to obtain well-argued conclusions.

As LCCA analysis method is only applied in chapter 3 and 4 of the dissertation, more detail of the inventories used is specifically provided in each chapter.

2.3. Scenarios of the dissertation

The dissertation was developed in two different scenarios: a conventional greenhouse and the i-RTG-Lab (see Table 2.7). Conventional greenhouses were used for chapter 3 and 4, which study the feasibility of creating a new passive system for RTGs. Nowadays, as far as we know no information regarding the thermal performance of a RTG have been published yet. Therefore, it was considered proper to develop a first study of passive system with PCMs for conventional greenhouses which could be later adapted for RTGs. Both conventional greenhouses and the i-RTG-Lab are deeper described in this section.

Table 2.7. *Scenarios for each chapter of the dissertation*

		i-RTG-Lab	Conventional greenhouse
PART II	Chapter 3		•
	Chapter 4		•
PART III	Chapter 5	•	
	Chapter 6	•	
PART IV	Chapter 7	•	
	Chapter 8	•	

2.3.1. Conventional greenhouses

The research done in Part II of the dissertation (chapter 3 and 4) was developed in two different conventional greenhouses that means greenhouses at ground level. Chapter 3 realizes a theoretical environmental and economic study about a passive system made with PCMs for greenhouses. In this chapter no experimental research was required; however, for the LCA conducted it was necessary to look for inventory data (i.e. environmental information, dimensions, properties, raw materials) of a greenhouse in the literature. After a deep research, the most complete study found in the literature to obtain the required inventory data was a LCA study of a tomato crop grown in Almeria. It was developed within the framework of the Euphoros project and published in the Deliverable 5 of the project (Montero et al., 2011). More information and details of the inventory data used from the Euphoros project is specified in chapter 3.

The experimental stage of chapter 4 was conducted in a greenhouse situated in Cabrils (see Figure 2.3), north Barcelona (Latitude: 41° 31' 2.6''N, Longitude: 2° 22' 39.3''E) under a Mediterranean climate with a tomato crop. More properties, such as average temperatures of the greenhouse and dimensions, are deeper detailed in chapter 4.

Figure 2.3. *Conventional greenhouse used for the experimental stage of chapter 4*

2.3.2. The ICTA-ICP building and the i-RTG-Lab

The name of the ICTA-ICP building (see Figure 2.4) was conceived in honor to the two research institutions that it hosts: the Environmental Science and Technology Institute (ICTA) and the Catalan Institute of Paleontology (ICP). The building is located in the campus of the Autonomous University of Barcelona (UAB) in Bellaterra (Barcelona, Spain - Latitude 41°29'51.6"N; Longitude 2°06'31.9"E). It is a five floors construction which was designed with the most demanding sustainability criteria: renewable materials, passive heating systems, energy efficiency, multifunctionality, modularity or building-integrated agriculture. Thanks' to these criteria, the building has been awarded with the LEED-Gold® certification.

On the top of the ICTA-ICP building there is a research-oriented i-RTG named the Integrated Rooftop Greenhouse Laboratory (from now on, i-RTG-Lab). It is the case study of the "Fertilecity" project[10], which focuses on the analysis of the technical, environmental, economic and social feasibility of Mediterranean i-RTGs. The i-RTG-Lab exchanges energy, rainwater and CO_2 flows with the building in different ways (see Figure 2.4) to improve both building and food production efficiency (Nadal et al., 2017; Pons et al., 2015):

- The i-RTG-Lab could help (have not been demonstrated yet) to isolate the roof of the ICTA-ICP building, thereby reducing its energy consumption of heating and cooling systems.
- The thermal inertia of the building can be used to maintain the i-RTG-Lab above 14°C, without using heating systems, during the coolest periods of the year when outside night-time temperatures are lower than 0°C (Nadal et al., 2017).
- A rainwater harvesting system provides water to the i-RTG-Lab for the irrigation of crops, thereby reducing the pressure on local freshwater stocks.

[10] www.fertilecity.com/en

- Waste air from offices and laboratories, with a stable temperature between 20-24°C can be collected and injected to the i-RTG-Lab into heat or cool it without an added energy consumption.
- Waste air from offices and laboratories with high CO_2 concentration, due to human respiration, can be collected and injected into the i-RTG-Lab to increase its CO_2 concentration and consequently stimulate productivity.

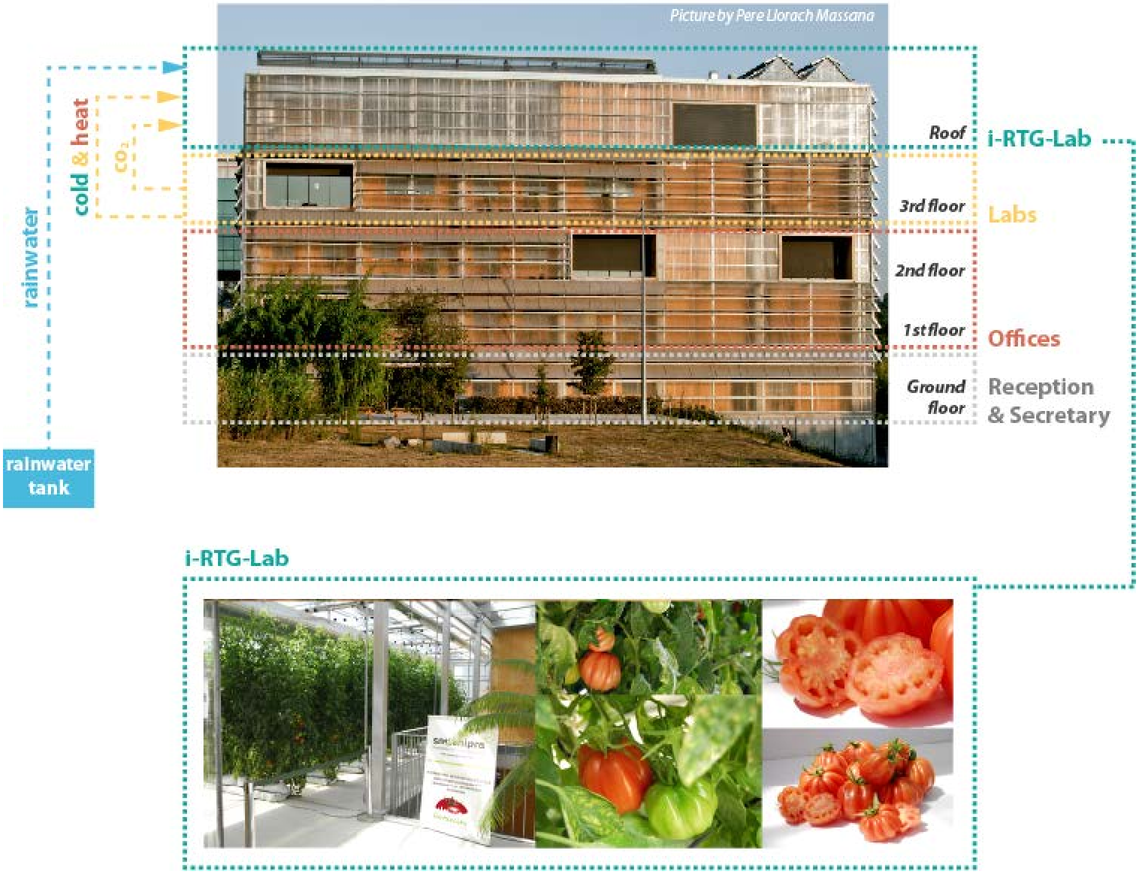


Figure 2.4. *The ICTA-ICP building, its i-RTG-Lab and the exchange of flows between both systems*

The i-RTG-Lab has an area of 122m^2, from which 84 m^2 are devoted to food production with intensive soil-less crops, concretely hydroponics systems with perlite substrate conventionally used for tomato production in Southern Spain. Perlite substrates were used instead of soil because its low density which reduces the extra weight added on the top of the building to allow food production. The greenhouse structure is made of steel and polycarbonate sheets which are controlled (opened or closed) by an intelligent system to achieve the desired temperature and humidity inside the greenhouse.

Since the i-RTG-Lab was installed on September 2014 two different type of crops have been harvested:

- Three lettuce crops between September and December 2014 to tests the facilities.
- Three tomato crops between January 2015 and July 2016 during which experiments from the dissertation and the Fertilecity project were done.

For chapter 5 of the dissertation CO_2 concentrations in the i-RTG-Lab and in the waste air of the ICTA-ICP building were measured during the summer and winter crops from 2016. Also, three experiments were developed between April and November 2015 next to the tomato crop of the i-RTG-Lab to develop chapter 6. Moreover, wastes generated from the first tomato crop produced in the i-RTG-Lab from January to July 2015 were used to address chapter 7 and 8, which consist of the study of producing high value by-products with tomato plant biomass.

PART II

PCM for more efficient root zone heating systems in RTGs

Chapter 3

LCA & LCCA of a PCM application to control root zone temperatures of hydroponic crops in comparison with conventional root zone heating systems

"Ice was the first PCM used by humans to conserve food"
Icebergs in Hallormsstadhur (Icdeland)

CHAPTER 3 - LCA & LCCA of a PCM application to control root zone temperatures of hydroponic crops in comparison with conventional root zone heating systems

This chapter is based on the journal paper:

Pere Llorach-Massana, Javier Peña, Joan Rieradevall, J. Ignacio Montero. 2016. "LCA & LCCA of a PCM application to control root zone temperatures of hydroponic crops in comparison with conventional root zone heating systems." Renewable Energy Journal 85, 1079–1089 (DOI:10.1016/j.renene.2015.07.064)

Abstract

The present study analyzes the environmental and economic performance of the use of PCM as a root zone temperature control system in substitution of conventional gas, oil and biomass heating systems by using life cycle assessment (LCA) and life cycle costs analysis (LCCA) methodologies. This study is focused on the possible application of these systems in a multitunel greenhouse situated in southern Spain. For the study was assumed a crop productivity increase of 20% when root zone temperature control systems are applied. Results showed that gas, oil and biomass conventional heating systems reduce farmer's net benefit and increase the environmental impact of each kg of produced tomato despite the assumed increase of productivity. Significant environmental and economic profits are obtained for PCM in relation with the use of gas and oil root zone heating systems. In relation with biomass, heating system economic advantage is obtained but environmental results are similar. When analyzing PCM scenario in comparison with conventional production without heating systems, no significant positive results were obtained.

Keywords: phase change materials (PCMs); root zone; heating system; LCA; LCCA; greenhouses

Chapter 4

Analysis of the technical, environmental and economic potential of phase change materials (PCM) for root zone heating in Mediterranean greenhouses

"Nowadays, humans use PCM, such ice, for new purposes"
Icefall climbing (Italy)

CHAPTER 4 - Analysis of the technical, environmental and economic potential of phase change materials (PCMs) for root zone heating in Mediterranean greenhouses

This chapter is based on the journal paper:

Pere Llorach-Massana, Javier Peña, Joan Rieradevall, J. Ignacio Montero. 2017. "Analysis of the technical, environmental and economic potential of phase change materials (PCMs) for root zone heating in Mediterranean greenhouses." Renewable Energy Journal 103, 570-581, (10.1016/j.renene.2016.11.040)

Abstract

Root zone heating systems offer increasing crops quality and productivity. However, these systems are based on the use of nonrenewable fuels. This paper reports on a study of different design solutions for a root zone heating system, based on thermal energy storage with PCMs. The objective of the study was to define, through multiple experiments, the most efficient PCM melting/freezing temperature and location with respect to the substrate (i.e. under the substrate) for the application under study; as well as, to determine the system's environmental and economic feasibility with life cycle assessment and life cycle cost methodologies. Results show that the best melting temperature for the application under study is 15°C. To increase the efficiency of the system, PCMs may be macro encapsulated and wrap the entire perlite bag. Moreover, it seems that PCMs are far to replace conventional root zone heating systems because it does not provided enough heat during nights. Nevertheless, PCMs can help to reduce the operation time of conventional systems. Based on one n ight results it seem that PCM could provide annual saving of between 22 and 30 kg of eq. $CO_2 \cdot ha^{-1} \cdot day^{-1}$. However, it does not seem to be economically feasible if PCM prices ($8€ \cdot kg^{-1}$) do not decrease significantly.

Keywords: phase change materials (PCMs); root zone heating; soil-less crops; environmental assessment; economic assessment

PART III

Analyzing i-RTGs' GHG flows

Chapter 5

CO_2 enrichment potential in i-RTGs with residual air from buildings

"Not everything is solid in our world and can be climbed. Rocks can be transformed into liquid and gases"

Volcano lava in Mÿvatn (Icdeland)

CHAPTER 5 - CO_2 enrichment potential in i-RTGs with residual air from buildings

This chapter is based on the following accepted conference contribution:

Pere Llorach-Massana, Aurélie Pichon, Mireia Ercilla-Montserrat, Joan Rieradevall, Javier Peña, J.Ignacio Montero. 2017. CO_2 enrichment potential in i-RTGs with residual air from buildings. International symposium on green cities 2017. 12^{th} – 15^{th} September 2017 – Bologna (Italy).

Abstract

Rooftop greenhouses (RTGs) could be integrated with the building they are place on to allow exchanges of f lows (i.e. water, ener gy and gas flows) and to reduce both bui lding and c rop environmental impacts. The i-RTG-Lab is a pilot scale integrated rooftop greenhouse (i-RTG) located on the ICTA-ICP building, in Barcelona. It was built to allow the injection of the residual air, which is expected to have a hi gh CO_2 concentration, from laboratories into the i-RTG-Lab. CO_2 is of great importance for its positive effect on plant growth. Buildings' residual CO_2 could be used for the carbon enrichment of rooftop greenhouses to enhance crop productivity and capture emissions from buildings. The present research aims to determine the CO_2 concentration of residual air generated by the ICTA-ICP building for its potential use for the carbon enrichment of crops grown in the i-RTG-Lab.

Two CO_2 sensors, an anemometer and a specific software for data collection were used for data acquisition. Measurements were done for a winter (2015) and a summer (2016) crops.

The first results show that CO_2 concentration in residual air is between 400 and 500 ppm, which is not enough for the carbon enrichment of the i-RTG-Lab. The CO_2 concentration in laboratories is low as there is an important air renewal because of laboratories requirements. It would be advisable to find other sites in the building where CO_2 concentration is higher (between 500 and 1,000 ppm). Moreover, it's necessary to keep in mind that the i-RTG-Lab is ventilated while residual air is injected during daytime. Therefore, ventilation should be adjusted to effectively provide CO_2 in the i-RTG-Lab and achieve a carbonic enrichment.

Keywords: CO_2 enrichment; Buildings' residual air; integrated urban agriculture

5.1. Introduction

Previous research has encountered that in indoor environments CO_2 concentration is between 350 ppm (similar to air concentration) and 2,500 ppm (ACGIH, 1991). These higher CO_2 concentrations in indoor environments are mainly caused by human respiration. Concentrations over 800 ppm in closed rooms may damage human health (Seppanen et al., 1999). Therefore, high ventilation rates are required to ensure a proper CO_2 concentration in households and offices buildings.

CO_2 enrichment is a strategy applied in protected crops which intends to increase CO_2 concentration in greenhouses, over 500 ppm, to stimulate crop productivity (Mortensen, 1987). It can consist on (1) the use of refined pure CO_2 that is homogeneously distributed in greenhouses through gas hoses; (2) the combustion of fuel in greenhouses in small burners or (3) the combustion of fossil fuels outside greenhouses in plants that also produce heat or energy, which could be used to heat or apply artificial lighting in the same greenhouses (Fennell and Allenby, 2004). Previous studies have demonstrated that CO_2 enrichment at 900 ppm has the potential to increase productivity of tomato crops around 18% and 30% depending on the tomato variety (Yelle et al., 1990). Here lies the interest of this strategy. Increasing productivity means reducing production costs and environmental impacts.

According to what has just been mentioned, residual air from buildings, with high CO_2 concentration due to human respiration, could be used for the carbon enrichment of protected crops grown on top of buildings. The i-RTG-Lab is a pilot scale integrated rooftop greenhouse (i-RTG) that was built in order to exchange energy, water and CO_2 with the ICTA-ICP building where it is placed on (see Figure 5.1). Concretely, residual air from labs (located in the 3rd floor of the building), that is expected to have a high CO_2 concentration, could be injected into the i-RTG-Lab for carbon enrichment of crops.

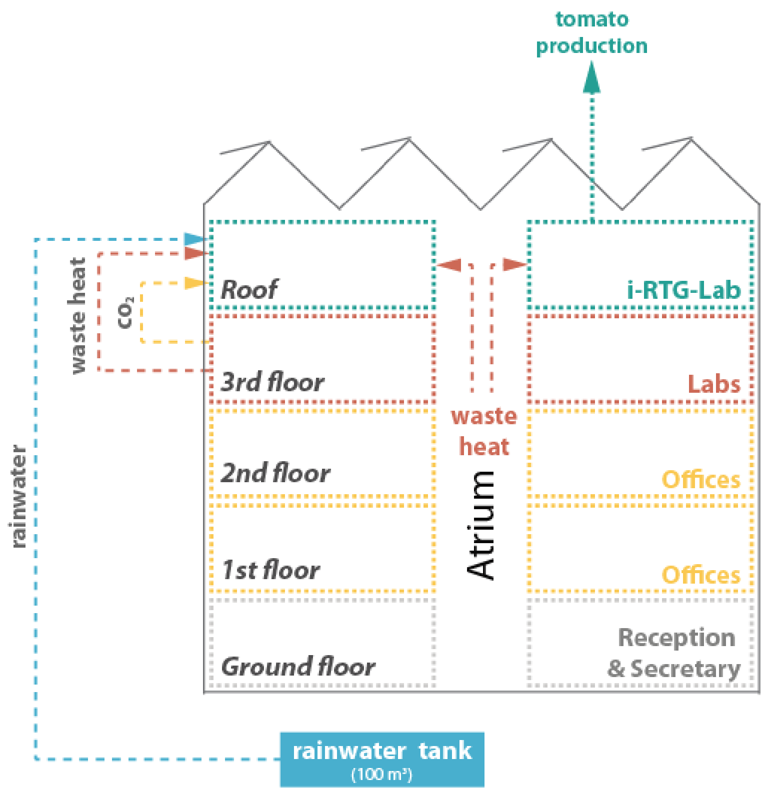


Figure 5.1. *Flow exchanges between the i-RTG-Lab and the building it is placed on*

The present study aims to determine if the residual air of the ICTA-ICP building could be used for the carbon enrichment of the i-RTG-Lab. Therefore, this research collects data regarding the CO_2 concentration of the i-RTG-Lab; as well as, the CO_2 concentration of the residual air from the labs of the building. The research provides a preliminary study, with which the authors aim to provide the basis for future research on carbon enrichment in i-RTGs by taking advantage from the possible CO_2 emissions generated in the buildings where i-RTGs are placed on.

5.2. Materials and methods

5.2.1. Equipment

SIEMENS' sensors explicit for architecture sector (model QPA2062D) were used to determine the CO_2 concentration in the i-RTG-Lab and in the residual air of labs. These sensors have an accuracy of ±50 ppm. For this reason the error of the sensors was verified and corrected by using a Siemens's CO_2 analyzer, concretely a Ultramat 23 model with an accuracy of 1% over measured value. The sensor that provided the CO_2 concentration from the i-RTG-Lab was located in the middle of the crop, between tomato plants (see Figure 5.2). The CO_2 concentration in the residual air of labs was measured at the gate through which residual air is injected in the i-RTG-Lab (see Figure 5.2). At this sampling point an anemometer was installed to determine the flow (m^3 of air) injected into the i-RTG-Lab. Building's software used for data acquisition could not collect data for periods of time shorter than 10 minutes. For that reason, a punctual measurement was taken for both the residual air CO_2 concentration and speed every 10 minutes. To estimate the total volume of residual air injected formula 1 was applied:

$$[1]\ residual\ aire\ volume = S_{R.air} \cdot A \cdot t$$

where $S_{R.\ air}$ refers to the speed of the air injected ($m \cdot s^{-1}$); A is the area (m^2) of the section where speed of the air was measured, which is used to determine the instantaneous volume of air injected; and t is the period of time that a specific volume of residual air is injected (10 minutes).

As shown in previous studies CO_2 evolution in greenhouses is directly affected by solar radiation, which stimulates photosynthetic activity of plants (Fennell and Allenby, 2004). A higher solar radiation stimulates CO_2 absorption by plants that produces CO_2 depletion inside the greenhouse at noon, when there is high solar radiation. Therefore, daily solar radiation was also measured in order to determine if the i-RTG-Lab follows similar trends. Due to a lack of quality pyrometers in the ICTA-ICP building, this parameter was obtained from a public weather station located 6km far away from the i-RTG-Lab, north-east direction in Sabadell (Generalitat de Catalunya, 2015).

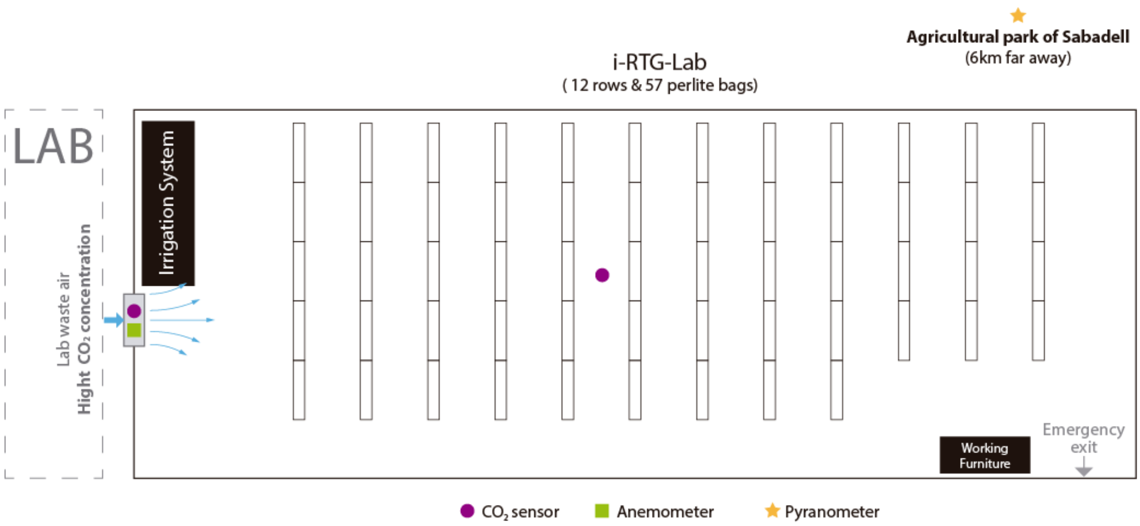


Figure 5.2. *Sensors used to describe the carbon flows of the i-RTG-Lab*

5.2.2. Crops

The i-RTG-Lab, where experiments were developed, had a surface of 122 m^2, from which 84.3 m^2 were dedicated to the crop. In the present study two tomato crops were grown:

- Winter crop *(S. lycopersicum tomawak):* 15/09/2015 - 04/03/2016 (170 days)
- Summer crop *(S. lycopersicum arawak):*) : 08/03/2016-21/07/2016 (135 days)

5.3. Results and discussions

Results obtained show that daily CO_2 evolution in the i-RTG-Lab (Figure 5.3) is similar to the patterns of conventional greenhouses without carbon enrichment (Fennell and Allenby, 2004): CO_2 depletion takes place when solar radiation increases due to the increase of plants' photosynthetic activity. During the hours of greater solar radiation CO_2 concentration drops to almost 350 ppm in the i-RTG-Lab. This low CO_2 concentration may significantly limit plants growth and productivity (Hickleton and Jollliffe, 1978; Yelle et al., 1990). Therefore, in order to increase i-RTG-Lab productivity, and consequently its efficiency, it is required to increase the CO_2 concentration by increasing ventilation rates to provide the i-RTG-Lab with more outside fresh air or by installing a carbon enrichment system.

Previous researchers suggest that increasing CO_2 concentrations between 500 ppm and 1,000 ppm stimulates productivity; however, concentrations higher than 1,000 ppm may cause foliar damage and appear to be relatively ineffective in increasing productivity (Hickleton and Jollliffe, 1978). As shown by Figure 5. 3, despite providing the i-RTG-Lab with residual air of the labs, its maximum CO_2 concentrations were near or lower than 500 ppm. Moreover, CO_2 concentration from the residual air was in average 60 ppm and 50 ppm higher than the i-RTG-Lab concentration, respectively for winter and summer crop. According to these results, it seems that residual air CO_2 concentration is not high enough to ensure the carbon enrichment of the i-RTG-Lab. Provably, in the present main CO_2 sources of the i-RTG-Lab come from the atrium of the ICTA-ICP building and outside air, which may have a similar concentration as the building is not 100% airtight and has high ventilation rates. The low CO_2 concentration in the residual air from labs could be explained by the following:

- Few people works in the labs at the same time. Therefore, few CO_2 is generated by human respiration.
- Labs are over-pressured to prevent them from dust and other particles which could damage analytical devices. To keep labs over-pressured it is required to inject air in the labs, which means that the air in the labs is continuously renewed. Consequently, there is not enough time for the accumulation of CO_2 from human respiration.

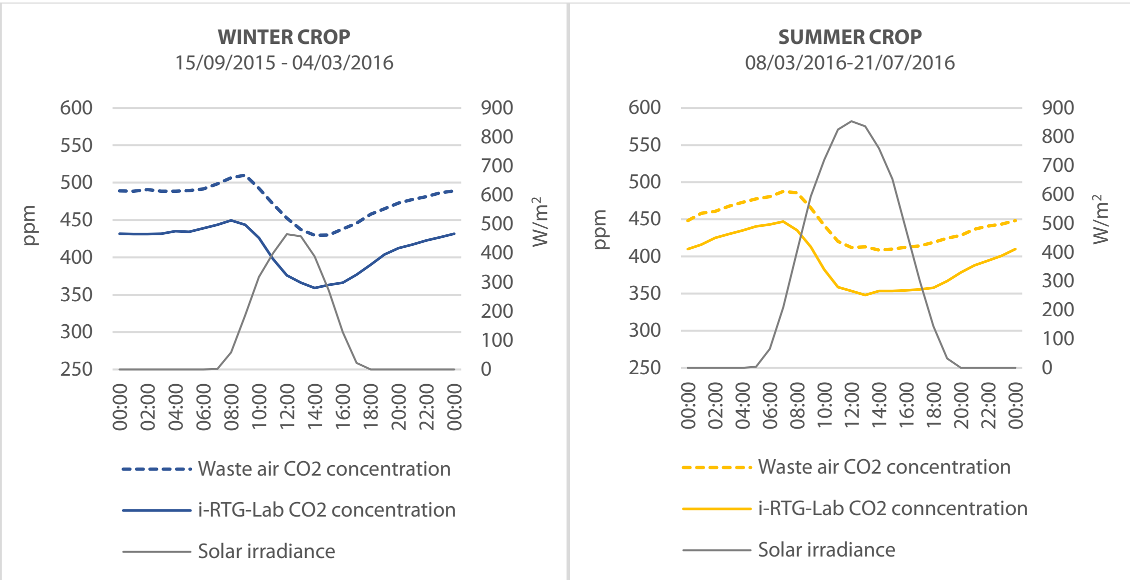


Figure 5.3. *Hourly average CO_2 concentrations in the i-RTG-Lab and in the waste air from the labs for an entire tomato winter crop (2015) and summer crop (2016)*

Results obtained reflect that there is a need to look for other CO_2 sources in the ICTA-ICP building which could be used to enrich with carbon the i-RTG-Lab. Offices could be of great interest as the ratio between air volume per person is higher than in labs. Moreover, offices do not require to be over-pressured; so, air renovations are lower. This may allow the concentration of CO_2 because of by human respiration.

In addition, to ensure a proper carbon enrichment with residual air flows it is required a minimum volume of residual air generation. It is essential to ensure that air renovations provided through residual air are high enough to avoid opening the windows of the i-RTG-Lab for its ventilation, fact that would dissolve CO_2 injected. Table 5.1 shows that, during winter crop, air renovations produced by residual air could be high enough to reduce the natural ventilation of the i-RTG-Lab. However, for summer crop natural ventilation must be required to cool it making CO_2 enrichment ineffective. The lower air renovations measured during summer crop may be explained by the different requirements of labs during winter and summer.

Labs equipment emit large amounts of heat. During winter, cold air from outside is used to cool labs. Then, air in labs is constantly renewed. However, during summer is required to use a cooling engine to cool labs. The cooling system of the ICTA-ICP building is a closed loop system, which means that air from labs can be collected, cooled and later injected in labs again. This system avoids using hot air from outside which requires higher energy consumption to be cooled than air from labs which has already been treated. Therefore, during hot periods air renovations in labs and residual air generation are reduced. More measurements may be of interest to determine if the volume of residual air generated is similar year after year and to deeper study how other parameters (i.e. outside temperature or humidity) could influence on this value.

Table 5.1. *Recommended air renovations by ASAE (1982) and air renovation that the residual air of the ICTA-ICP building provides to the i-RTG-Lab*

		Recommended by ASAE		Residual air injected in the i-RTG-Lab		
		Winter crop	Summer crop	Avg. Winter crop (2015)	Avg. Summer crop (2016)	Max. residual air injection measured
Volume injected	$m3 \cdot h^{-1}$	-	-	5,523	2,441	10,206
Number of air renovations	$u \cdot h^{-1}$	4.5-30	45-60	8.1	3.6	15

5.4. Conclusions

- The CO_2 concentration in the i-RTG-Lab when there is high solar radiation is to low (around 350ppm). It is recommended to enrich crops with carbon to increase their productivity.
- The volume and CO_2 concentration (below 500 ppm) of the residual air from the labs of the ICTA-ICP buildings are not high enough to be used for the carbon enrichment of the i-RTG-Lab. Concentration over 500 and 600 ppm and higher volumes of air are required.
- Further research is required to look for other CO_2 sources in the ICTA-ICP building which could be used to enrich with carbon the i-RTG-Lab.
- Residual air from households or institutional buildings, which could have a CO_2 concentration of 350 and 2,500 ppm, could be used for the carbon enrichment of crops grown in i-RTGS.
- For the case of new buildings, which integrate RTGs, it would be of great interest to develop previous studies to determine which would be the main sources of CO_2 production from where CO_2 could be collected for the carbon enrichment of crops.

Chapter 6

N_2O emissions from protected soil-less crops for more precise food and urban agriculture life cycle assessments

"We must keep our planet cold if we want to continue enjoying nature"

Vapor emissions in Mÿvatn (Icdeland)

CHAPTER 6 - N_2O emissions from protected soil-less crops for more precise food and urban agriculture life cycle assessments

This chapter is based on the journal paper:

Pere Llorach-Massana, Pere Muñoz, M. Rosa Riera. Xavier Gabarrell, Joan Rieradevall, J. Ignacio Montero, Gara Villalba. 2016. "N_2O emissions from protected soil-less crops for more precise food and urban agriculture life cycle assessments." Journal of cleaner production (under review) DOI?

Abstract

Due to population growth and the subsequent increase in the demand for food, low carbon food chain production systems are a necessity to reduce the effects on climate change as much as possible. Urban agriculture is of great interest because of its potential in reducing the indirect CO_2 emissions of a city's food supply by reducing transportation distances, the packaging required and the food losses that occur during transportation. However, intensive urban agriculture production, which often relies on the use of soil-less substrates, requires synthetic fertilizers rich in nitrogen, resulting in N_2O emissions. Presently, there is a lack of studies that determine the generation of N_2O from soil-less crops to properly account for their global warming potential. In this study, an open chamber system was used to quantify N_2O emissions from lettuce crops with perlite bags as their substrate in a Mediterranean rooftop greenhouse located in the metropolitan area of Barcelona (Spain). N_2O generation, through nitrifying and denitrifying reactions, was limited by assuring an aerobic environment, negligible water retention, the absence of NH_3, and controlled dosage of NO_3- in the most favorable pH conditions for plant assimilation. The emission factor (EF) measured for the soil-less lettuce crop (0.0072 - 0.0085 kg N_2O^{-1} per kg N^{-1}) was half the EF of the IPCC method (0.0125 kg N_2O^{-1} per kg N^{-1}) for soil crops, which is commonly used in life cycle assessment (LCA) studies to approximate direct N_2O emissions, for lack of a better method. Using a more appropriate EF for an LCA study of a tomato crop grown under similar conditions to those used to generate the EF resulted in a 7.5% reduction (0.06 kg CO_2 eq. per kilogram of tomato production) in total global warming potential. This study shows that soil-less crops reduce N_2O emissions when compared to conventional crops, making urban agriculture an attractive practice for reducing GHG emissions. The results highlight the need to determine a standard method for determining an emission factor applicable to soil-less protected crops, which, based on the parameters described here, such as the type of substrate, fertilizers and irrigation system, would allow for a more accurate environmental evaluation of soil-less conventional and urban crops.

Keywords: N_2O emissions; Soil-less crops; Low carbon food chain; Nitrogen balance; Urban agriculture; Carbon footprint

PART IV

Carbon sink through by-products design with tomato plant feedstocks

Chapter 7

Technical feasibility and environmental benefits of biochar co-production with tomato plant residue

© Pere Llorach-Massana

"Natural cycles must be closed to guarantee our mountains and jungles preservation"

Ashes resulting from the thermogravimetry of different tomato plants

CHAPTER 7 - Technical feasibility and environmental benefits of biochar co-production with tomato plant residue

From this chapter, a paper has been extracted and submitted in a peer-review indexed journal.

Abstract

World tomato production is in the increase. It generates large amounts of organic agricultural wastes, which are currently incinerated or composted; processes that release CO_2 into the atmosphere. Organic waste is not only produced from conventional agriculture but also urban crops that has recently gained popularity. An alternative to current waste management practices and carbon sequestration opportunity is the production of biochar (thermally converted biomass) from tomato plant residues and use for soil amendment.

To address the real contribution of biochar for greenhouse gas mitigation, it is necessary to assess the whole life cycle from the production of the tomato biomass feedstock to the actual distribution and utilisation of the biochar produced. This study is the first step to determine the technical and environmental potential of producing biochar from tomato plant (*Solanum lycopersicum arawak* variety) waste biomass and its utilisation as a soil amendment.

The study includes the characterisation of tomato plant residue as biochar feedstock (cellulose, hemicellulose, lignin and metal content); feedstock thermal stability; and the carbon footprint of biochar production under an urban agriculture framework at pilot and small-scale plant and under a conventional agriculture framework at large-scale plant.

Tomato plant residue is a potentially suitable biochar feedstock according to current European Certifications thanks to its lignin content (19.7%) and low metal concentration. Biomass conversion yields of over 40%-50% carbon stabilization and low pyrolysis temperature conditions (350-400°C) would be required for biochar production to sequester carbon under urban pilot scale conditions. Nevertheless, large-scale biochar production from conventional agricultural practices have not the potential to sequestrate carbon because its logistics, which could be improved. The diversion of tomato biomass waste residue from incineration or composting to biochar production, for use as a soil amendment, could environmentally be beneficial, but only if high biochar yields could be produced.

Keywords: tomato plant feedstock; biochar; carbon footprint; heavy metals; urban Agriculture

7.1. Introduction

7.1.1. Biomass waste generation from tomato crops

World tomato production increased 42.9% between 2000 and 2013 (FAOSTAT, 2015). Consequently, tomato crop wastes have increased too. In 2013, 163.43 Mt of tomatoes were produced worldwide (FAOSTAT, 2015). Assuming a dry waste production (leaves and stems) of 9 $t{\cdot}ha^{-1}{\cdot}year^{-1}$ for tomato crops (López et al., 2004), in 2013, approximately 42.19 Mt of dry waste may have been produced worldwide (Table 7.1).

As the amount of tomato waste residues increase with increased crop production, waste management solutions should be used to minimize their environmental impacts and help to mitigate climate change (IPCC, 2013). Sustainability is included in most conventional tomato plant waste management scenarios as waste is re-used or recycled to feed farm animals, produce compost or for energy valorisation (i.e. incineration). Some institutions have already developed waste management solutions that could help to fix the C captured by tomato plants and reduce resources depletion. Wageningen University has developed a technology to produce cardboard for packaging with tomato plant stems and leaves (Wageningen UR, 2014). Ford Motor Company, in collaboration with Heinz ketchup, is developing new bio-composites based on tomato processing wastes (Ford Motor Company, 2014). Moreover, the Biocopac Project has developed bio-resins based on tomato processing wastes to cover the inside part of food cans (Biocopac Project, 2013).

Although greenhouse gas (GHG) emissions may be reduced or delayed under such waste management scenarios, carbon sequestration into stable carbon forms is not considered. The carbon content of tomato plant (corvey variety) stem and leaves is 18% of total dry tomato plant weight (Mota et al., 2008). Consequently, the annual world tomato waste (stems and leaves) would contain approximately 7.6 million tonnes of C, equal to an approximate 27.9 million tonnes of CO_2 (Table 7.1), which is returned to the atmosphere.

Table 7.1. *Total world, European and Spanish tomato production, crop area, waste generation* (FAOSTAT, 2015) *and C fixed within waste biomass during 2013. Waste production was calculated assuming 9 tons of biomass waste per ha of crop* (López et al., 2004) *and fixed C by supposing that 18% of the total dry biomass weight corresponds to the C content* (Mota et al., 2008)

	Annual total values for 2013					
	Tomato production (Mt)	**Area harvested (ha)**	**Approx. wet waste* (Mt)**	**Approx. dry waste* (Mt)**	**C fixed in dry waste* (Mt)**	**CO_2 eq. fixed in dry waste* (Mt)**
World	163.43	4,688,335	332.87	42.19	7.6	27.9
Europe	20.96	500,872	35.56	4.51	0.81	2.97
Spain	3.68	45,300	3.22	0.41	0.07	0.26

**Only stems and leaves are considered*

7.1.2. Agricultural wastes & biochar production

A potential waste management solution that captures and stores carbon from agricultural waste into stable forms by reductive thermal processes is the production of biochar (Lehmann et al., 2006). Biochar is defined as 'a solid material obtained from the thermochemical conversion of biomass in oxygen-restricted conditions which is used for any purpose that does not involve its rapid mineralisation to CO_2 (Shackley et al, 2016). Due to its long-term storage of stable carbon, biochar is commonly used for soil improvement (Lehmann et al., 2008; Woolf et al., 2010). Other 50 biochar applications have been already listed (Hans-Peter and Kelpie, 2014), such as (1) a feed complement in farms (Gerlach and Schmidt, 2014); (2) to increase the biogas production efficiency (Inthapanya, 2012); (3) to produce thermal insulation materials (Lin and Chang, 2008) and (4) to fill mattresses and pillows (Hans-Peter and Kelpie, 2014).

The use of biochar depends significantly on its quality (i.e. porosity, nutrient content or heavy metal content). In the case of biochar for soil amendment, in Europe, two different voluntary certifications, without legal implications, have been developed: the Biochar Quality Mandate (BQM) elaborated by the British Biochar Foundation (Hackley et al., 2014) and the European Biochar Certification (EBC) criteria (EBC, 2012). In USA and Canada, can be applied the International Biochar Initiative (IBI) mandate (IBI, 2015). These voluntary certifications provide minimum quality parameters of biochar for its application in soils. The information supplied by these schemes has been compiled into the Biochar testing protocol (BTP) to provide information on biochar materials and biochar products. This information allows the user to describe and define the properties of the biochar product (Shackley et al., 2016).

Agricultural wastes have previously been considered as feedstocks and used to produce biochar as a solution for carbon sequestration (Lehmann et al., 2006; McHenry, 2009). Some examples of agricultural feedstocks include rice hull, groundnut shells, olive husk and tea (Lehmann et al., 2006; McHenry, 2009). One study analysed the use of biochar produced with tomato plant feedstocks as a substrate for tomato hydroponic crops (Dunlop et al., 2015). This research focuses on the specific properties for the application under study (i.e. N, P, and K contents; thermal conductivity; and pH) but does not communicate other important parameters such as the metal content of tomato plant feedstock or its environmental performance with life cycle assessment (LCA) methodology. LCA is a recognised methodology to quantify the environmental impacts of systems, products or services for proper decision making (European Comission, 2001; UNEP, 2002). Present study uses LCA methods to determine the carbon footprint of biochar co-production with tomato plant feedstocks.

7.1.3. Urban agriculture (UA): new organic feedstocks and by-products in cities.

The United Nations predicts that the world population will reach 9.550 million habitants by 2050, of which more than the 70% will live in urban areas (UN, 2012); consequently, the food demand in cities will increase. Some strategies, such as UA, are gaining presence in urban areas to increase cities' food self-sufficiency (Orsini et al., 2013; Specht et al., 2013).

UA has a great potential to provide social and environmental benefits to cities' feeding systems (E Sanyé-Mengual et al., 2013; Sanyé-Mengual et al., 2015c; Tomlinson, 2011) due to social integration, job creation, simpler logistics and packaging reduction. However, UA produces organic wastes that increase the organic fraction generation of urban areas (Baumgartner and Belevi, 2001). The circular economy concept (Andersen, 2007) promotes the conversion of wastes back to resources. Biochar opens a wide range of possibilities for the creation of new local products with local UA wastes, helping to reduce the organic fraction volume of urban areas while reducing resources depletion.

One of the multiple UA typologies consists of installing greenhouses on the top of buildings, named Rooftop Greenhouses (RTGs). Inspired by the Industrial Ecology concept (Jacobsen, 2008), RTGs can be integrated with buildings to exchange energy, water and CO_2 (from human respiration) flows and increase system efficiency. Integrated RTGs (i-RTGs) allow an intensive food production, which will generate organic wastes that could be used to produce new products. Therefore, urban production systems, conceptually, could also be considered raw material farms.

The present research was developed within the framework of the Fertilecity Project[13]. This project aims to study the potential environmental, economic and social benefits of urban food production through i-RTGs. During the project, there were a lack of solutions that could sink the C captured by urban crops, which could help to reduce the carbon footprint from urban feeding systems. Waste tomato plant leaves and stems from experimental crops were used in the present research. Tomato plants were cultivated using the same soil-less systems (with perlite substrate) conventionally used in Mediterranean areas. The i-RTG used for tomato cultivation is located on the top of the ICTA-ICP building of the Autonomous University of Barcelona campus (Bellaterra, Spain).

UA wastes have not yet been studied for economic valorisation. UA wastes are of great interest if are considered as local low-cost sources that may not require transportation. Moreover, the lack of waste management solutions, that could fix the C captured by UA crops, and the actual environmental concern about climate change (IPCC, 2013) make biochar production with UA feedstocks interesting from an environmental perspective.

[13] http://www.fertilecity.com

The present research mainly intends to elaborate a first approximation of the carbon footprint of a local pilot-scale biochar production system with UA feedstocks using LCA methodology. It aims to discuss how this strategy could help to reduce cities, urban agriculture and new products carbon footprint. Moreover, data collected for the study is used to simulate a larger scale scenario which is then compared with the urban pilot-scale scenario.

In addition the article does a basic assessment to determine the quality of tomato plant feedstocks from UA crops for biochar co-production. For that, the cellulose, hemicellulose and lignin contents of UA tomato plant feedstock were quantified. Furthermore, a thermogravimetric analysis (TGA) was developed to study the potential biochar yields and a metal content analysis was performed to determine if cities' air pollution influences the urban crop pollutant content and, consequently, biochar quality.

From an LCA perspective, it is expected that the low transportation requirements of UA feedstocks and biochar may contribute significantly to ensure that biochar production with UA feedstocks may result in a carbon sink strategy. It is also foreseen that UA tomato feedstocks may have a sufficient quality for biochar production; however, the metal content in the feedstock due to cities' air pollution may worsen its properties.

7.2. Materials & Methods

7.2.1. Samples obtaining and preparation.

Tomato plants used for the experiment were cropped between February and July 2015 in an i-RTG located in the ICTA-ICP building (Cerdanyola del Vallés, Barcelona). At the end of the crop, the plants were air dried at room temperature (as described for the LCA study – Figure 7.1) in the same i-RTG for 4 weeks. Later, the leaves and stems were manually separated and homogenised with an electric grinder (to a particle size of less than 0.2 mm) to prepare them for the TGA.

7.2.2. Cellulose, hemicellulose and lignin contents

The cellulose, hemicellulose and lignin contents were determined through a gravimetric method. To obtain the cellulose content, the sample was processed with basic and acidic digesters. For cellulose, the sample was submitted to a neutral digestion, and for lignin, the sample was administered sulfuric acid and dried (Kaloustian et al., 2001).

7.2.3. Thermogravimetric analysis of biochar feedstock

A pyrolysis test was conducted in a thermos-balance carrying out a simultaneous thermogravimetric analysis (TGA) and differential scanning calorimetry/differential thermal analysis (heat flow DSC/DTA) system NETZSCH -STA 449 F1 Jupiter (Puy et al., 2011). The sensitivity of the balance was 0.07 micrograms. The solid weight loss and heat flow, together with other process variables, such as temperature, were recorded. A heating rate of 10 $°C \cdot min^{-1}$ was applied from room temperature up to 800°C, placing 166 mg of biomass in the alumina crucible. The atmosphere of the analysis was N_2 (80%) and O_2 (20%) with a purge flow of 20 $ml \cdot min^{-1}$. The sample consisted of a mixture of tomato leaves (50%) and stem (50%).

7.2.4. Characterization of biochar feedstock quality

Currently, there are three main schemes available to assess biochar products. The IBI, the EBC and the BQM. The requirements are very strict to ensure that no contaminants are added to the soil, which could finally pollute and damage groundwater, plants, crops or animals. In this sense, limitations consist of establishing thresholds for the heavy metal content in biochar.

For the present study, tomato plant ashes (mixture of 50% leaves and 50% stem) from the TGA were analysed to determine their heavy metal contents (As, Cd, Cr, Cu, Pb, Hg, Mn, Mo, Ni, Se and Zn) for a subsequence comparison with the BQM, IBI and EBC thresholds. Moreover, results were contrasted to the metal content of other biochar materials found in the literature.

The metal content of ashes was determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). The equipment used was an Agilent ICP-MS 7500ce. The samples were microwave digested, with HNO_3 and HCl, and a semi quantitative estimation was carried out from the response curve vs molar atomic weight.

7.2.5. Biochar carbon footprint assessment

LCA methodology, according to ISO 14044 (ISO, 2006b), was used to calculate the potential carbon footprint of producing biochar with UA tomato plant feedstock. LCA is an accepted methodology that is used to approximately quantify the greenhouse gas emissions in equivalent CO_2 emissions from products, systems or processes from a life cycle approach (Berners-Lee et al., 2011; Pandey et al., 2011).

The scope of the analysis was (1) to quantify the carbon footprint of biochar production from UA tomato plant feedstocks at pilot and small-scale and (2) to determine whether CO_2 emissions from this biochar production were higher or lower than the CO_2 emissions that remained fixed as stable C within the biochar. The selected *functional unit for study is the production of 1 tonne of biochar with tomato plant feedstocks*. For the analysis, the Ecoinvent 3 database and Recipe (H) calculation method were used. SimaPro 8 was used as a support program. The impact category used to obtain the carbon footprint from biochar production was Climate Change (kg CO_2 eq.).

7.2.5.1. System boundaries and allocations

Describing the carbon flows (Figure 7.1) from biochar production with UA tomato plant feedstock was considered crucial for determining whether the final CO_2 fixed in the biochar was higher than the CO_2 emissions into air generated during the production stage. In our research, biochar samples were not elaborated because of the high level of ashes production (see Table 7.5) when tomato plant feedstocks undergo to thermal processes, which may damage the pyrolysis plant. This information is explained in more detail in section 7.3.1. from the discussion. Since the biochar was not produced, the final C within the biochar was neither quantified. For this reason, different scenarios considering different C contents assumed from the literature were analysed to determine the influence of this parameter on the LCA results.

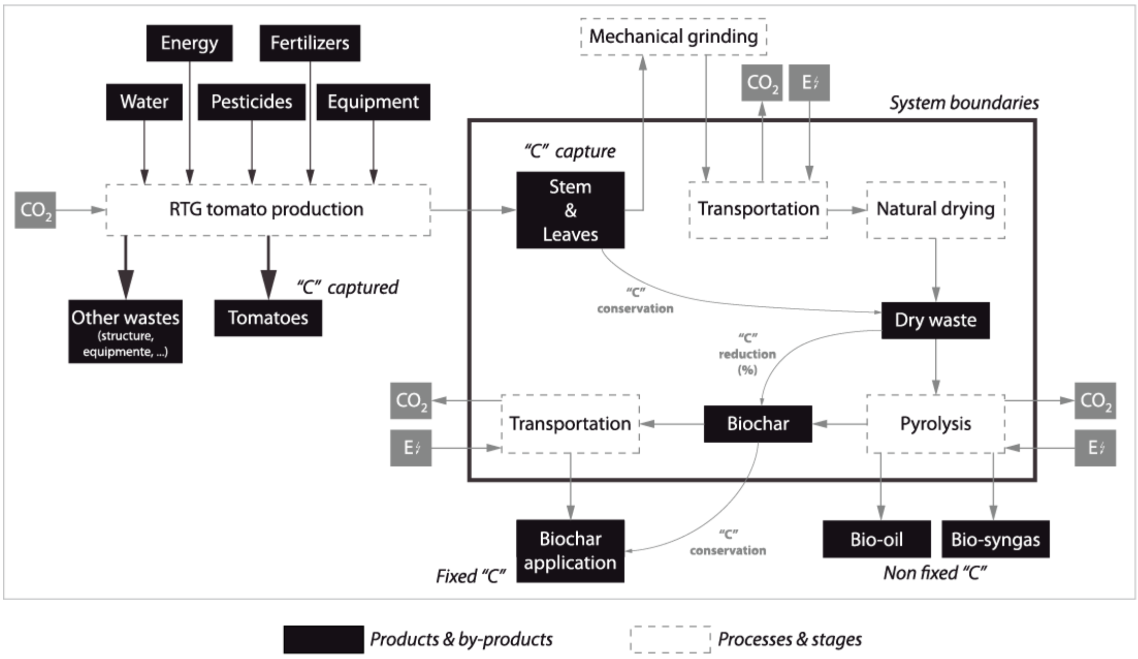


Figure 7.1. *Carbon flows from biochar production with tomato plant feedstocks and system boundaries under study*

As Figure 7.1 shows, the present study specifically analysed the production of biochar with tomato feedstocks. System boundaries (Figure 7.1) do not include tomato production or the related required inputs (i.e. water, fertilizers, and equipment). No environmental impact from tomato production is allocated to the waste stems and leaves and consequently to biochar. The environmental impact of the generation of stems and leaves, which do not have any economic value, was associated with tomato production, the main objective of the crop. The mechanical grinding of dry feedstocks is not considered within the system boundaries because it refers to a process required to reduce waste plant volume for its transportation, which is necessary in a conventional waste management solution as well. Therefore, the impact of this process is associated with tomato production and not with biochar. The system boundaries include the natural drying process of tomato plant waste (leaves and stems), the pyrolysis for biochar production and dry wastes and biochar transportation (see Figure 7.1).

Three different coproducts are produced during pyrolysis, see Figure 7.1. The main high-value coproducts that can be obtained from the pyrolysis process are solid (biochar), liquid (bio-oil) and gas (non-condensable gas) (Xiao et al., 2010). Depending on the temperature and length of the pyrolysis process, different percentages of solid, liquid or gas coproducts can be obtained (Bridgwater, 2003). The environmental impacts for each coproduct were allocated according to the percentage of product mass obtained from original green waste, parameter that is further discussed and described in the following section.

7.2.5.2. Inventory analysis & description of biochar production with UA feedstocks at urban pilot-scale

From waste stems and leaf generation, no CO_2 emissions were considered, as described in the previous section 7.2.5.1. The drying process, which consists of natural drying in or next to the same i-RTG where plants are cropped, see Figure 7.1, does not require any energy or specific equipment. Consequently, no CO_2 emissions were associated with this process. For the case of pyrolysis energy consumption, CO_2 emissions were associated with the Spanish medium-voltage energy mix from 2015.

Two transportations may be required during this process: (1) dry feedstock transportation to the pyrolysis plant and (2) biochar transportation to its final destination for soil amendment (see Figure 7.1). For the first transportation, it was assumed a distance of 25 km, which is the average distance between Bellaterra (where the plants used for the study were cropped) and the industrial areas of northern and southern of Barcelona. For the second transportation, a 10 km distance was selected. That is the extension between industrial areas of Barcelona and the peri-urban crops of the city. For such transportations, the use of lorries with EURO-6 engines with a maximum load between 3.5 and 7.5 metric tonnes was considered.

At the end of the tomato crop used for the study, the plant C content, which was 30.3% for leaves and 35.7% for stems of total dry weight, was analysed through an elemental analysis with a LECO elemental analyser. An average of both values was used for the study. However, not all of the C that is transformed into biochar remains as stable carbon ($\%_{Stable-C}$) (Mohan et al., 2006). Part of the C in the biochar is released as biogenic CO_2 into the atmosphere within the first years after the production of biochar (Mašek et al., 2013). The final $\%_{Stable-C}$ content in biochar produced with forest and agricultural biomasses is between 20% and 80%, of the C into the biochar, depending on the pyrolysis conditions (Mašek et al., 2013; McBeath et al., 2015). To study how the $\%_{Stable-C}$ influences LCA results and with the aim of covering the ranges of $\%_{Stable-C}$ found in the literature (from 20% to 80%) *3 scenarios assuming different percentages of* $\%_{Stable-C}$ *were studied: (SCENARIO A) 20%; (SCENARIO B) 50% and (SCENARIO C) 80%.*

A semi-industrial reactor pyrolysis plant developed by "Energies Tèrmiques Bàsiques SL" was the technology selected to produce biochar. It has a capacity of 100 $kg \cdot h^{-1}$ and scalable up to 1 $ton \cdot h^{-1}$. This plant consists of an intermediate pyrolysis process. It comprises eight main parts: a grinding module (obtaining a maximum particle size of 4 mm), the feeding system, a drying reactor, the pyrolysis reactor, a cooling screw, the vessel for solids collection, the cyclone and a condensing system. The process is carried out continuously, and temperature profiles along the reactor are measured using several thermocouples during the process.

This pyrolysis plant selected as a reference has an energy consumption of 12 kW per operation hour (including the energy consumption from the grinding process to homogenise biomass particles size) *when the pyrolysis is carried out at 400 ℃*. The optimum temperature to increase biochar yield during pyrolysis is from 350-400°C (Tripathi et al., 2016). For the present study, it will be considered that the pyrolysis process for all scenarios occurs at 400°C due to a lack of data about the energy consumption of the plant for other working temperatures. However, this limitation is not considered relevant because a working temperature of 400°C is a suitable temperature to obtain high biochar yields from agricultural feedstocks (Colantoni et al., 2016).

As mentioned before, many coproducts are obtained from pyrolysis. The percentage of solids liquids or gases varies depending on some parameters of pyrolysis, such as type of pyrolysis, type of reactor, volumetric flow rates, rotation speed of the screws in the reactor and the heat carrier inlet temperature (Brown and Brown, 2012). According to these parameters, the final ratio of total initial solid biomass that results in biochar (from now on referred to as biochar yield) after pyrolysis could be between 11% and 52% (Brown and Brown, 2012; McBeath et al., 2015; Sánchez et al., 2009).

Intermediate pyrolysis plants, which undergo pyrolysis with intermediate conditions between slow and fast pyrolysis (Tripathi et al., 2016), such as the semi-industrial reactor used as a reference for the study, achieve biochar yields between 35% and 45 % if the working temperatures are approximately between 350 or 450 °C (Mašek et al., 2013). This value depends on the C-H-O feedstock content (Shackley et al., 2016), data that was not analyses in the present research. For these reason it was decided to study three *scenarios with different biochar production yields, between 35% and 45%,* to determine how yields influence LCA results. *Concretely biochar yields of (SCENARIO 1) 35%, (SCENARIO 2) 40% and (SCENARIO 3) 45%* were analysed. Theerfore, if these scenarios are combined with the scenarios previously mentioned (A, B and C), 9 scenarios are studied as described in Table 7.2.

Table 7.2. *Description of the hypothetic scenarios under study. Scenarios A, B and C refer to the $\%_{stable\text{-}C}$, while scenarios 1, 2 and 3 refer to the biochar yield*

	Combination of scenario A, B and C with 1, 2 and 3								
	A-1	**A-2**	**A-3**	**B-1**	**B-2**	**B-3**	**C-1**	**C-2**	**C-3**
$\%_{Stable\text{-}C}$ assumed	20%	20%	20%	50%	50%	50%	80%	80%	80%
Biochar yield assumed	35%	40%	45%	35%	40%	45%	35%	40%	45%

Table 7.3 shows the different energy consumptions calculated for scenarios 1, 2 and 3 to produce 1 t of biochar. Depending on the yield of biochar obtained per unit of input dry feedstock, more or less feedstock will be required to produce 1 t of biochar. The lower percentage of biochar yield is, the more operation time and energy consumption are required per unit of biochar produced. The selected pyrolysis, a semi-industrial plant, has a biomass flowrate of up to 100 $kg{\cdot}h^{-1}$. For our study a biomass flowrate of 80 $kg{\cdot}h^{-1}$ was assumed, which is an efficient flow rate but not the maximum to ensure more fair scenarios.

Table 7.3. *Energy consumption for the production of 1 ton of biochar according to an input biomass flow rate of 80 $kg{\cdot}h^{-1}$ and a different percentage of biochar obtained per unit of input biomass*

Scenarios	**Biochar yield**	**Biochar production ($kg{\cdot}h^{-1}$)**	**Operation time (h)**	**Pyrolysis Energy consumption (kWh)**
A-1 / B-2 / C-3	35%	28	35.7	428.6
A-2 / B-2 / C-2	40%	32	31.3	375.0
A-3 / B-3 / C-3	45%	36	27.8	333.3

7.2.6. Inventory analysis & description of biochar production with agricultural feedstocks at large-scale in southern Spain

Southern Spain concentrates the largest areas of tomato production in the country. Almeria, is one of the provinces from the region, which concentrates more than 7,000 ha of greenhouses intended for the production of tomatoes (MAGRAMA, 2015). For this reason, Almeria province was selected to simulate the production of biochar with agricultural feedstocks at large-scale.

The following data from the pilot-scale scenario in cities was used to create the large-scale scenario:

- C content of tomato plants (30.3%).
- Lorries with EURO-6 engines with a maximum load between 3.5 and 7.5 metric tonnes for transportation.

Due to a lack of data in the literature of slow pyrolysis plant technologies, the pyrolysis plant applied for the present scenario is the same conceptual plant assumed in previous LCA studies of biochar production at larger scale (Roberts et al., 2010). The plant has a dry feedstock flow rate capacity of 10 $t{\cdot}h^{-1}$ and consists of an exothermic process, which needs 58 MJt^{-1} for the initial start-up of the process. The plant uses 11.1% of the gas coproducts (equivalent to 886 $MJ{\cdot}t^{-1}$) to produce energy for the drying and pyrolysis processes.

As for the pilot-scale biochar production in cities, two transportations are considered. The first one consists on the transportation of feedstock from the greenhouse to the pyrolysis plant. However, for the larger scale scenario it is considered that the feedstock is still wet. That means that the weight to be transported includes the 80% of water content in the tomato plant stems and leaves used for the study. The second transportation considers the shipping of biochar to the region where will be applied for soil amendment. The distance considered for both transportations was 20 km, which is approximately the average distance between the centre of Almeria province and its borders.

For the large-scale biochar production study only an intermediate scenario, such scenario B-2, assuming a biochar yield of 40% and a percentage of final carbon stable of 50% is studied. This is then compared with the production of biochar at pilot-scale in cities.

7.3. Results and discussion

7.3.1. Thermogravimetric analysis

As Table 7.4 shows, on the one hand, the tomato stem lignin content (19.7%) is similar to that of other crop feedstocks (i.e. cotton or olive) but lower than that of softwood (27-30%). This content lignin makes tomato plants interesting for biochar production because biomasses rich in lignin produce higher yields of biochar with higher $\%_{Stable\text{-}C}$ when are pyrolyzed at low temperatures (300-400°C) (Demirbas, 2006; Fushimi et al., 2003). On the other hand, stem's, hemicellulose and cellulose contents (8.2% and 28.8%) are significantly lower compared to the other biomasses in Table 7.4. In tomato leaf, the cellulose, hemicellulose and lignin contents are lower than the rest of the biomasses from Table 7.4, making the leaf less interesting for biochar production.

Table 7.4. *Cellulose, hemicellulose and lignin contents of different agricultural and forestry feedstocks*

	TOMATO PLANT		**FORESTRY BIOMASS**		**AGRICULTURAL BIOMASS**			**FRUIT PRODUCTION BIOMASS**	
	Tomato stem	**Tomato leaf**	**Softwood**	**Hardwood**	**Wheat straw**	**Switchgrass**	**Cotton stem**	**Olive (pruning)**	**Almond (pruning)**
Reference	*	*	(McKendry, 2002)	(McKendry, 2002)	(McKendry, 2002)	(McKendry, 2002)	(Ververis et al., 2004)	(Ververis et al., 2004)	(Ververis et al., 2004)
Cellulose (%)	28.8	13.7	35-40	45-50	33-40	30-50	40-44	38-42	36-41
Hemicellulose (%)	8.2	3.2	25-30	20-25	20-25	10-40	n/a	n/a	n/a
Lignin (%)	19.7	6.1	27-30	20-25	15-20	5-20	14-16	16-20	24-28

**Specifically analysed for the study from a solanum lycopersicum arawak (tomato) crop.*

According to the TGA results (Figure 7.2), the tomato stems and leaves start to devolatilize from 200°C to 500°C. First, hemicellulose decomposition occurs, followed by cellulose decomposition; finally, lignin decomposition starts and lasts until 410°C. As the TGA shows, a mass loss up to 47% is achieved at 300°C. It can be observed that at 500°C, the 83% of biomass conversion is ensured. Hence, the ideal maximum temperatures for tomato plant biochar production may be between 350 °C and 400 °C, resulting in a solid yield between 45% and 38%, respectively. These results agree with previous references that suggest low pyrolysis temperatures to increase biochar production (Tripathi et al., 2016) and are in harmony with the yields defined for the carbon footprint study of 35%, 40% and 45% for scenarios 1, 2 and 3, respectively.

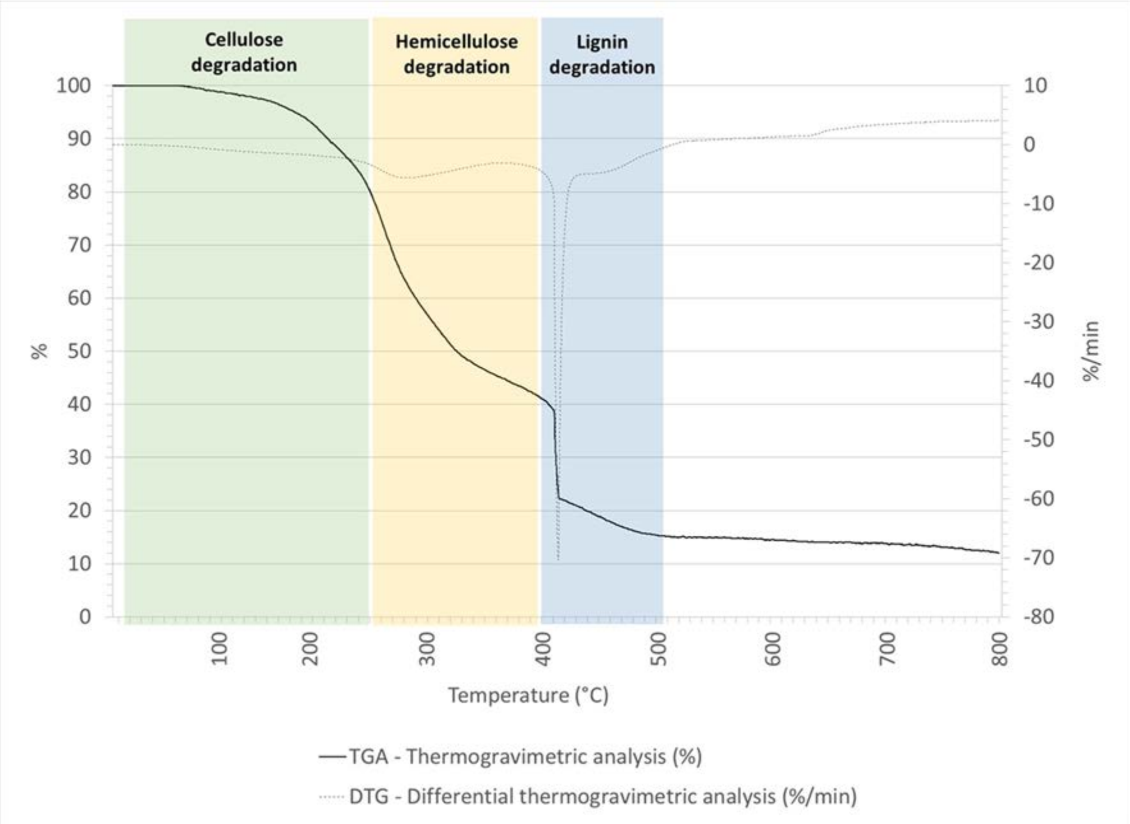


Figure 7.2. *TGA of Solanum lycopersicum arawak (tomato) stem mixed with leaves. The figure also shows the main compounds (cellulose, hemicellulose or lignin) that are degraded at certain temperatures*

It was also observed that tomato plant stem and leaves produce significant percentages of ashes, probably because of their high content of mineral salts. Respectively, from 8-15% and 18-23% of the initial mass results in ashes (Table 7.5). Other biomasses, such as wood or waste wheat biomass, produce less ash, 0.5% and 7% respectively (Table 7.5). The high ash production of tomato plant feedstock during the thermal processes could represent an important limitation for its use in conventional combustion due to corrosion processes. Additionally, the presence of inorganic compounds, such as metals, could affect the pyrolysis performance and equipment (see Table 7.5). Therefore, tomato plant feedstocks may be mixed with other biomasses to produce fewer ashes during thermal processes, such as forestry biomasses, which produce low amount of ashes (Table 7.5). For this reason, other strategies, such as using biochar as a soil amendment, must be addressed to add value to tomato plant feedstocks, which is further developed in the following section.

Table 7.5. *Percentage of ashes for different biomasses*

	AGRICULTURAL BIOMASS				FORESTRY BIOMASS		
	Tomato stem*	**Tomato leaf***	**Rice husk** (Yoon et al., 2012)	**Olive kernel** (Vamvuka, 2009)	**Pine woodchips** (Puy et al., 2011)	**Larch dust** (Yoon et al., 2012)	**Willow woodchips** (Ryu et al., 2006)
% ashes	8-15%	18-23%	16.3%	4.4%	0.39%	0.8%	1.0%

**Solanum lycopersicum arawak (tomato) variety*

7.3.2. Biochar quality and applications

Table 7.6 contrasts the heavy metal content of our tomato plant feedstock with that of some biochar samples from the literature and the IBI, BQM and EBC heavy metals thresholds. The results show that all of the biochars from the table and our tomato plant feedstock could obtain the IB and B QM certificates. In the case of the EBC certification, all of them could obtain the highest qualification. In general, all of the metals analyzed from our tomato plant feedstock were similar to the biochars from the literature. However, the manganese content (Mn), despite being under the thresholds from the certificates, is between 2 and 5 times higher than in the other biochars. This fact could be explained by the retention and accumulation of Mn provided through a micronutrient fertilizer with a 2.5% Mn content. However, it seems that air pollutants caused by traffic do not have a negative effect on these results.

According to the results in Table 7.6, tomato plant feedstock has a great potential to be used for the production of biochar for soil amendment. Moreover, other applications for biochar produced with tomato feedstock could be studied. Depending on the porosity, thermal conductivity, heating power, final nutrient content or mechanical properties of biochar obtained, it could be used to replace raw materials from products (i.e. insulation materials, mattresses, active carbon filters, paints, or cosmetics) and consequently reduce resource depletion while storing stable C.

7.3.3. Biochar carbon footprint

To calculate the final kg of CO_2 fixed by plants that remains as stable C ($\%_{Stable\text{-}C}$) within the biochar, formula 1 was used:

$$[1]\ CO_2\ eq. = (m_{dry\ biomass} \cdot y_s \cdot \%_{C-content} \cdot \%_{Stable-C}) + m_{oxygen}$$

where $m_{dry\ biomass}$ is the mass of dry biomass required to produce 1 tonne of biochar (according to functional unit); y_s is the biochar yield produced; $\%_{C\text{-}content}$ is the C content of tomato plant (*Solanum lycopersicum arawak* variety) biomass used for this study which was 30.3%; and the m_{oxygen} is the mass proportion of oxygen to produce one particle of CO_2 with each unit of mass of C fixed in the biochar.

As Figure 7.3 shows for scenarios A-1, A-2, A-3 and B-1, the C net emissions are positive. This means that more emissions are emitted during transportation steps and pyrolysis than are fixed as stable C within the biochar. For these scenarios, it cannot be considered that C is being fixed when biochar is produced. Nevertheless, in case biochar was used as a raw material to produce another product (i.e. insulation materials, mattresses, active carbon), instead of for soil amendment, environmental advantages could be obtained compared to the original raw material used in products. Depending on the final application, biochar could be considered a raw material with a low carbon footprint.

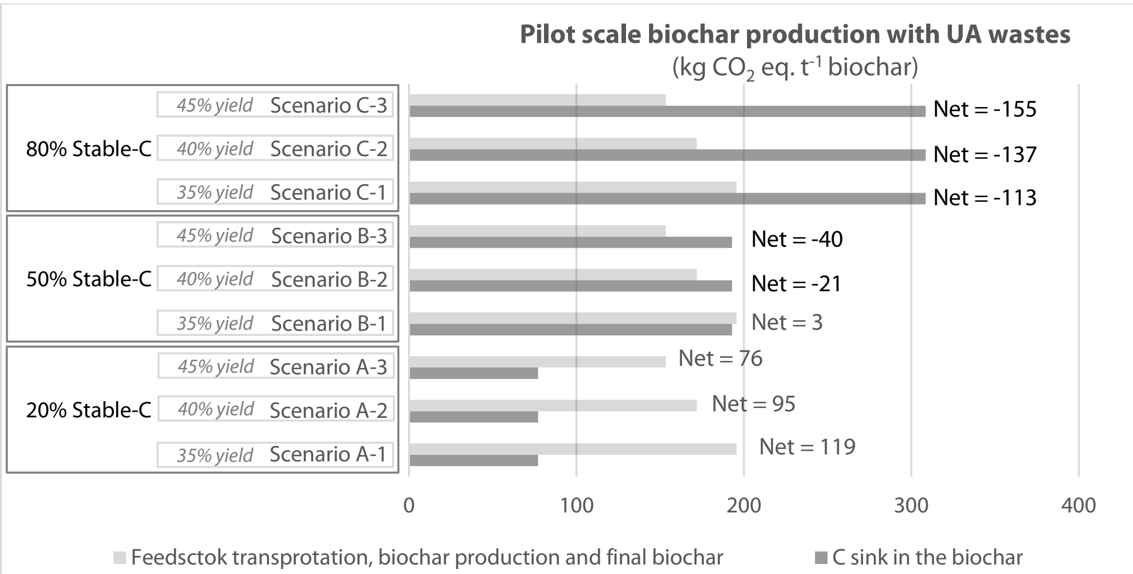


Figure 7.3. *CO_2 emissions from transportation and production for the production of one ton of biochar, carbon sink achieved and net carbon emissions for the multiple scenarios under study*

Table 7.6. *Metal content of tomato plant feedstock and different agricultural and forestry biochars compared to the IBI, BQM and EBC biochar certification thresholds*

			AGRICULTURAL BIOMASS			FORESTRY BIOMASS				*European Biochar Certificate* (EBC, 2012)		
		Units	**Dry tomato feedstock (ashes from TGA realized)**	**Corn (300°C -12 h and 600°C – 2.5 h)** (Freddo et al., 2012)	**Vine shoots (400°C-3 h)** (Venegas et al., 2015)	**Tree barks (400°C-3 h)** (Venegas et al., 2015)	**Bamboo (600°C-2.5 h)** (Freddo et al., 2012)	**IBI Guidelines thresholds** (IBI, 2015)	**BQM thresholds** (Hackley et al., 2014)	**Premium biochar thresholds**	**Basic biochar thresholds**	**High grade biochar thresholds**
Arsenic	**As**	$mg \cdot kg^{-1}$	**<0.81****	0.25	n/a	n/a	0.29	12-100	100	n/a	n/a	10
Cadmium	**Cd**	$mg \cdot kg^{-1}$	**<0.81****	0.03	0.6	1.2	0.03	1.4-39	39	1	1.5	3
Chromium	**Cr**	$mg \cdot kg^{-1}$	**5.07**	5.09	n/a	n/a	4.39	64-100	100	80	90	15
Copper	**Cu**	$mg \cdot kg^{-1}$	**20.27**	10.6	17	33	6.31	63-1500	1500	100	100	40
Lead	**Pb**	$mg \cdot kg^{-1}$	**1.27**	0.06	1.7	4.2	3.87	70-500	500	120	150	60
Mercury	**Hg**	$mg \cdot kg^{-1}$	**<0.81****	n/a	n/a	n/a	n/a	1-17	17	1	1	1
Manganese	**Mn**	$mg \cdot kg^{-1}$	**147.43**	n/a	56	27	n/a	n/a	n/a	n/a	n/a	3500
Molybdenum	**Mo**	$mg \cdot kg^{-1}$	**0.95**	n/a	n/a	n/a	n/a	5-75	75	n/a	n/a	10
Nickel	**Ni**	$mg \cdot kg^{-1}$	**1.55**	0.37	1.6	13	1.25	25	600	30	50	10
Selenium	**Se**	$mg \cdot kg^{-1}$	**<0.81****	n/a	n/a	n/a	n/a	1-100	100	n/a	n/a	5
Zinc	**Zn**	$mg \cdot kg^{-1}$	**49.2**	92	105	73	0.29	200-2800	2800	400	400	150

*Mix of stem (50%) and leaves (50%)   **Below detection levels

For the rest of scenarios (B-2; B-3; C-1; C-2 and C-3), the CO_2 emissions sunk within the biochar are higher than emissions emitted for its generation (see Figure 7.3). For these case studies, it can be assumed that there is a carbon sink between 21 and 155 kg of $CO_2 \cdot t^{-1}$ of biochar. For the scenario with better results, C-3, the CO_2 sink was 2 times higher than emissions from the pyrolysis process.

The distribution of carbon emissions for the different life cycle stages is very similar in all scenarios (+/- 1%): 18% transportation of feedstock to pyrolysis plant; 79% grinding and pyrolysis process and 3% transportation of biochar to the field for its application into soil. The low transportation distances of the feedstock and biochar helps significantly to avoid emissions during these stages; however, production stage penalizes seriously the final emissions balance. Reducing the energy losses of the pyrolysis process, which is a small-scale pilot plant, may result on a significant reduction of the emissions emitted during this stage.

7.3.4. Comparison between urban pilot-scale and large-scale biochar production

Figure 7.4 compares the carbon emissions between the biochar production at pilot-scale in urban areas with UA feedstocks and at large-scale with feedstocks from conventional crops. As can be observed, total and net emissions for the small-scale scenario are greater. It has the potential to sink carbon emissions; however, the large-scale scenario does not.

The large-scale scenario emits 33 kg CO_2 eq.$\cdot t^{-1}$ biochar less than the pilot-scale plant during the pyrolysis process. This could be explained by the optimization of heat loses of the pyrolysis plant of the large-scale scenario. Nevertheless, for the transportation stage of feedstocks to the plant, the large-scale scenario emits 92 kg CO_2 eq. t^{-1} biochar more because the feedstock is wet unlike the pilot-scale scenario. In addition, emissions from biochar transportation to field for soil amendment are the double (20 kg CO_2 eq.$\cdot t^{-1}$ biochar) than for the pilot-scale scenario, because the transportation distance for the large-scale scenario is the double too. According to results, the urban pilot-scale scenario is interesting from a logistics point of view, but it is penalized by the low efficiency of the pyrolysis plant. Moreover, if for the pilot scale feedstock was dry instead of wet for its transportation to the plant approximately 92 kg CO_2 eq.$\cdot t^{-1}$ biochar could be avoided and the final net emissions could be -42 kg CO_2 eq.$\cdot t^{-1}$ biochar.

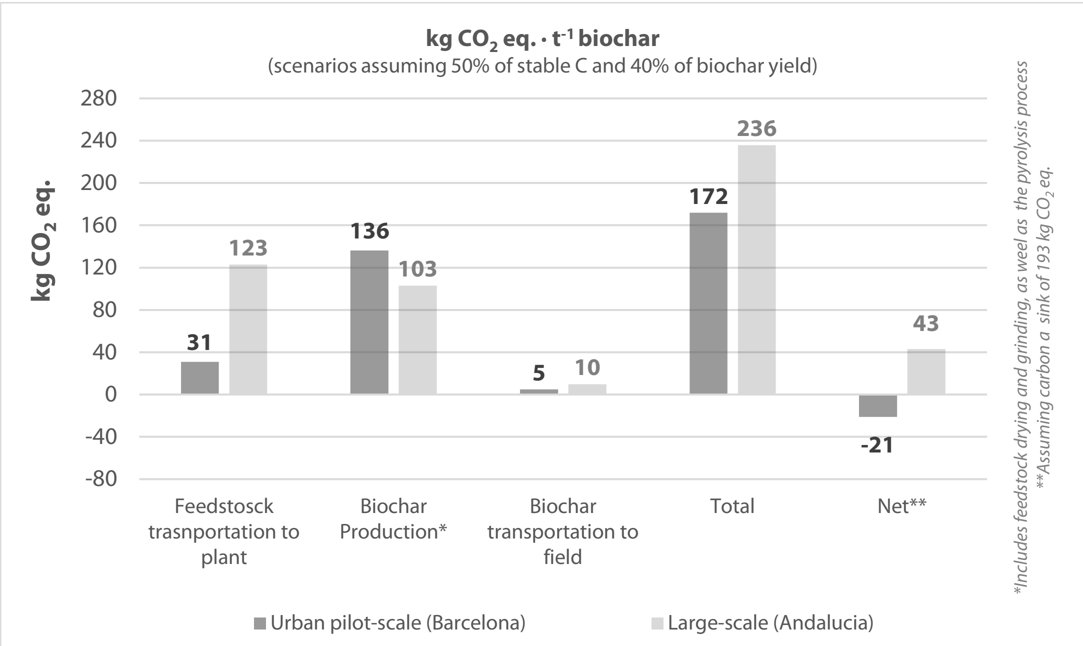


Figure 7.4. *Carbon emissions from biochar generation at pilot-scale in urban areas (Barcelona) with UA feedstocks and at large-scale (Andalucia) with agricultural feedstocks from conventional food production. (It was assumed a 50% of final stable C in biochar and a biochar yield from production process of 40%)*

7.4. Conclusions

- The cellulose, hemicellulose and lignin contents of *Solanum lycopersicum arawak* (tomato variety) stem were 28.8%, 8.2% and 19.7%, respectively. These results show that there is a great potential to valorise these residues by producing biochar. However, the results for leaves were not as positive. Their low lignin content (6.1%) does not make leaves very suitable for biochar production if not mixed with other biomasses with a high lignin content.

- According to the IBI, BQM and EBC certificates and to the low content of heavy metals in tomato plant biomass, the biochar produced with this feedstocks could be safely used for multiple applications, including soil amendment. Air pollution caused by traffic in urban areas does not seem to affect the results.

- The potential biochar yield production from tomato plant biomass can be between 38% and 45% according to TGA results. However, the $\%_{Stable\text{-}C}$ into the biochar needs to be quantified in future research. Percentages equal or higher than 50% may be required to ensure C sink with biochar production with UA feedstock with small-scale plants.

- The transportation of dry waste biomass for biochar production should be minimized to ensure the production of environmentally friendly biochar. The transportation of the final biochar produced should be minimized as well; nevertheless, its environmental impact per kilometre transported is lower than the transportation of the dry waste required to produce the biochar. Both biochar yield and $\%_{Stable\text{-}C}$ will determine the maximum transportation distances for each type of biochar to ensure that the biochar is fixing and not emitting CO_2 eq. emissions. The higher the biochar yield and $\%_{Stable\text{-}C}$ are, the greater the transportation distances that biochar could be transported.

- C fixed by UA tomato plant feedstock has the potential to reduce emissions to cities, urban agriculture and products. However, these results may be used carefully to avoid double accounting.

- Further research is required to determine how tomato plant biomass should be mixed with other biomasses, such as forestry biomasses, to reduce ash production during thermal processes.

- The thermal and mechanical properties of biochar may be determined for different biochar samples produced with tomato plant biomass to determine its potential application to produce new products, such as insulation material or mattresses.

Chapter 8

Environmental assessment of a renewable thermal insulation material produced with tomato plant stems derived from urban agriculture wastes

"Energy for mountaineering comes from food, which requires human and environmental efforts to be produced"

Southeast of Myanmar

CHAPTER 8 - Environmental assessment of a renewable thermal insulation material produced with tomato plant stems derived from urban agriculture wastes

From this chapter, a paper has been extracted and submitted in a peer-review indexed journal.

Abstract

Urban agriculture food production and subsequence waste generation are increasing worldwide. These wastes should be properly managed to minimize their environmental impacts. To avoid their impacts by-products could be produced with them, which fix the biogenic carbon captured by crops. This study aims (1) to determine the carbon footprint of a renewable thermal insulation material made with urban agriculture wastes from a tomato crop and (2) to determine the potential biogenic carbon that this by-product could fix. The carbon footprint of the insulation material analyzed was determined thought life cycle assessment (LCA) methodology according to ISO 14044. The inventory analysis was done with data collected from the production of the insulation material at laboratory scale.

The primary results indicate that if biogenic carbon fixed in agricultural wastes is considered, the insulation material studied has a negative carbon footprint of -0.2 kg CO_2 eq. but a high embodied energy of 3.63 MJ per kg of insulation material. Due to the negative carbon footprint of the material, it could be assumed from a cradle-to-gate perspective that the material fixes carbon emissions instead of emitting them. In addition, it was determined that if organic wastes from the specific crop used for this study were used to produce new products, approximately 0.42 kg CO_2 eq.·m^{-2}·$year^{-1}$ could be fixed. Producing by-products with agricultural wastes at local level could be a solution to store the carbon fixed by crops and reduce resources depletion. However, further discussion is required to determine to whom should be associated these stored emissions (i.e. crops, by-products, cities).

Keywords: renewable thermal insulation material; urban agriculture wastes; biogenic carbon; tomato plant stem; carbon footprint

8.1. Introduction

8.1.1. Thermal insulation of buildings

Buildings are designed, inter alia, to guarantee the thermal comfort of its occupants. Thermal comfort is commonly achieved using cooling or heating systems. Consequently, on average, energy consumption for heating spaces represents as much as 68% of the total energy composition in European households (European Environment Agency, 2009). Moreover, households are responsible for the 26.6% of the total energy consumption in Europe (European Environment Agency, 2010).

Existing energy policies promote energy efficiency and renewable energy use in buildings, such as in the European Energy Performance of Buildings Directive 2002/91/EC (EPBD) (European Comission, 2010). This directive introduces the concept of nearly zero-energy buildings (NZEB): buildings with very high energy performance where the nearly zero or very low amount of energy required should be extensively covered by renewable sources produced on site or nearby. The implementation of these regulations means less energy consumption during the use phase of the building; this energy is called the operating energy and is used to maintain the inside environment through heating and cooling, lighting and operating appliances. However, in addition to the operating energy, the total life cycle energy of a building also includes the embodied energy, which is the sequestered energy in building materials throughout all processes of production, on-site construction, final demolition and disposal. If all efforts focused on reducing operational energy, the relative importance of the embodied energy of materials would be more relevant with regard to the baseline situation (Pacheco-Torgal, 2014; Pacheco-Torgal et al., 2012; Thormark, 2002).

One of the most influential construction materials in the environmental performance of buildings is insulation material. This material plays an important role because, in addition to influencing the environmental impacts of construction, it influences the operation phase of the building. The contribution of insulation materials could reach 30% to 50% of the embodied energy in a building construction (Sierra-Pérez et al., 2016b). Insulation materials are commonly used in households' external walls as a relatively low-cost solution for heat conservation. The environmental and economic benefits of insulation materials for energy savings in buildings have already been extensively proven in the literature (Ardente et al., 2011; Dylewski and Adamczyk, 2011; Sartori and Hestnes, 2007). Currently, there are many different nonrenewable (e.g., expanded polystyrene, rock wool) and renewable (e.g., sheep wool, cotton) insulation materials on the market for use in offices buildings and households. Nonrenewable and synthetic materials generally have better insulation properties (0’02-0’04 $W \cdot m^{-1} \cdot K^{-1}$) than mineral (0’03-0’05 $W \cdot m^{-1} \cdot K^{-1}$) or renewable animal (0’035-0’05 $W \cdot m^{-1} \cdot K^{-1}$) materials. However, synthetic materials present some environmental limitations due to their (1) dependence on nonrenewable resources, (2) potential toxicity and (3) difficulties in recycling.

8.1.2. Agricultural wastes and renewable thermal insulation materials

Wastes from horticulture crops commonly have three possible waste management scenarios: deposition into landfills, composting and energy valorization (e.g., incineration). The mentioned waste management solutions do not allow crops to act as a carbon capture and storage system. These waste scenarios commonly return to the air the carbon captured by in a brief periods (less than 1-2 years) in forms (Maria et al., 2016) of CO, CO_2 or CH_4 emissions. Thus, these emissions can be considered part of a fast carbon cycle. According to the current concern regarding climate change (IPCC, 2014b), there is great interest in preventing these fast carbon emissions. Producing new insulation materials with valueless agricultural wastes, which can be considered feedstocks, would avoid the conventional waste management scenarios and create stable materials with long lifespans (20 years or more) that could store CO_2 emissions captured by crops by transforming them into biogenic carbon.

Multiple thermal insulation materials have been previously developed with agricultural wastes; such as, with hay (Maria et al., 2016), kenaf (Ardente et al., 2008), stalk (Zhou et al., 2010), jute, flax and hemp (Korjenic et al., 2011). Moreover, few case studies have quantified the CO_2 emissions that are fixed and stored within renewable insulation materials and later contrasted with emissions from the production or transportation stage (Sierra-Pérez et al., 2016a). Nevertheless, to the best of our knowledge, no study has analyzed the technical and environmental potential of producing insulation materials with tomato plant biomass, which is the type of waste crop analyzed in this study.

8.1.3. Renewable thermal insulation materials from urban agriculture feedstocks

The growing population is predicted to reach 9.550 million by 2050, and 70% of the population will live in urban areas (UN, 2012). Consequently, cities' food demand will increase in the near future. Urban agriculture (UA) is considered a potential solution to mitigate the negative effects from feeding such population concentrations in urban areas (Zezza and Tasciotti, 2010). Specifically, UA has a great potential to (1) reduce the pressure exerted on nature and its resources from actual cities' feeding systems (Sanyé-Mengual et al., 2015c; Tomlinson, 2011); (2) provide social relevant benefits such as job creation, social integration and poverty reduction (Orsini et al., 2013; Sanyé-Mengual et al., 2015a; Specht et al., 2013; Zezza and Tasciotti, 2010); (3) and improve cities' food self-sufficiency (Orsini et al., 2013; Sanyé-Mengual et al., 2015b; Specht et al., 2013).

As a consequence of the increased UA activity (Zezza and Tasciotti, 2010), agricultural waste production in cities is expected to grow. UA waste production could be considered difficult to manage in cities. Within the framework of a circular economy, in order to add value to UA wastes, minimize the environmental impact of waste management and close the loop, new local products and materials could be produced using these wastes. For example, local insulation materials produced with UA wastes could be used to construct new buildings in cities. Then, greenhouse gas (GHG) emissions from the transportation of wastes and insulation materials would be minimized. In addition, the depletion of other raw materials would be avoided.

This new scenario, for the production and application of insulation materials at the local scale, could help to ensure that CO_2 emissions fixed by renewable insulation materials are higher than emissions generated during their transportation and production stages. However, the proposed scenario has not been environmentally analyzed yet. Moreover, research has not paid much attention to the environmental assessment of *renewable* insulation materials. For these reasons, *the present work aims to determine the carbon footprint of the manufacture of a new renewable insulation material, produced with UA tomato waste plants, for its application in new buildings in the same city where wastes are generated. For this, we accounted for the CO_2 emissions that ultimately remain as biogenic carbon within the insulation material under study. Later, through Life Cycle Assessment (LCA) methodology, we proceeded to determine the carbon footprint and embodied energy of the thermal insulation material. Finally, we compared the environmental impact of other renewable thermal insulation materials and the new one based on tomato plant wastes.*

8.2. Materials & methods

8.2.1. Thermal insulation material under study

Waste tomato plants (*Solanum lycopersicum arawak* variety) that were used to generate the thermal insulation material under study came from an experimental UA crop developed in the i-RTG-Lab (Integrated Rooftop Greenhouse Laboratory, see Figure 8.1). One of the subcategories developed within the concept of UA is vertical farming, which consists of the development of agricultural crops in buildings (Pons et al., 2015). Rooftop greenhouses (RTGs) are a specific typology of vertical farming based on the installation of adapted greenhouses on the tops of buildings. The i-RTG-lab is an RTG situated on the top of the ICTA-ICP building (Figure 8.1) located in the Unviersitat Autònoma de Barcelona campus (Bellaterra, Spain). The i-RTG-Lab has been integrated with the infrastructure of a building since the building's construction. This integration allows an exchange of energy, water and CO_2 between the greenhouse and the building in order to increase the efficiency of both elements. Thus, rooftop greenhouses could conceptually provide sustainable food to cities as well as low-carbon-footprint raw materials that, in turn, could produce new products. This concept may reduce the carbon footprint of products, crops and buildings.

Figure 8.1. *Outside view of the ICT-ICP building (left); inside of the i-RTG-Lab and first experimental tomato crop (center and right)*

8.2.2. Carbon content of UA tomato waste plants

The C content of the dry tomato plant wastes used for the study, which were cropped in the i-RTG-Lab (Figure 8.1), was determined through elemental analysis using a LECO© analyzer [14] in an external laboratory. Then, equation 1 was used to determine the potential annual CO_2 emissions that the waste of the i-RTG could contain:

$$[1]\quad C_{fixation} = \frac{dW_{prod.}}{A_{i-RTG}} \cdot C_{\%} + O_{2\,eq.} = \frac{\text{kg}\,CO_2}{m^2 \cdot year}$$

where $dW_{prod.}$ is the annual dry waste production of the i-RTG obtained by weighing the waste of tomato plant stems and leaves at the end of the two crop cycles in 2015. A_{i-RTG} is the crop area of the i-RTG-Lab, which is 84.3 m^2; $C_{\%}$ is the percentage of carbon content in dry waste per unit of mass measured through an elemental analysis of the stems of four different plants; and $O_{2\,eq.}$ is the equivalent mass (kg) of the oxygen from the CO_2 emissions that were fixed as C within the dry waste.

8.2.3. Carbon footprint of the new insulation material

For the carbon footprint calculation of the thermal insulation material produced with UA wastes, LCA methodology according to ISO 14044 (ISO, 2006b) was applied.

8.2.3.1. Goal and scope definition

The present study aims to determine from a cradle-to-gate perspective the carbon footprint and energy embodied of a thermal insulation materials produced with tomato plant wastes generated from UA systems, according to the Environmental Product Declaration (EPD) for construction products (European Committee for Standardization, 2014). In this study, two samples elaborated with different proportions of tomato plant wastes and other materials (sand, water and lime) were analyzed. Sample properties are described in depth in section 8.2.3.4.

For this study, SimaPro 8© software was used in combination with the Ecoinvent 3 database. The selected calculation method for the study was Recipe midpoint (H) (Goedkoop et al., 2009). The specific objectives of the study were:

- To determine the biogenic carbon fixed in the insulation material.
- To assess the environmental impact distribution of the different stages under study.
- To compare the carbon footprint and embodied energy of other renewable insulation materials with ours.
- To analyse the influence of transportation to the installation point on the local insulation materials produced with UA wastes.
- To provide background and recommendations for the creation of more sustainable insulation materials produced with tomato waste plants.

[14] http://leco.com/

8.2.3.2. Functional unit

Similar to previous LCA studies of thermal insulation materials (Ardente et al., 2008; Pargana et al., 2014; Sierra-Pérez et al., 2016a), the selected functional unit (FU) for our study was *the mass (kg) of insulation material required to provide a thermal resistance R-value of 1 m^2 K·W^{-1} for a surface are of 1 m^2*. Equation 2 describes how the mass for each sample of the thermal insulation material under study was calculated:

$$[2] \quad FU = R\lambda\rho A$$

where R is the thermal insulance of the material measured with the R-value (m^2 K·W^{-1}). The higher the thermal insulance is, the better insulation properties the material provides. λ is the thermal conductivity of the material (W·m^{-1}·K^{-1}), ρ represents the density of the material (kg·m^{-3}), and *A* refers to the surface (m^2) of the sample under study.

8.2.3.3. Production process description and system boundaries

Figure 8.2 describes the hypothetical stages (raw materials, transportation and production) involved in the creation of the insulation material studied. This process is similar to that used by Benfratello et al. (2013) to produce a hemp-lime biocomposite insulation material. At the end of the tomato cropping period, plants are manually collected and placed next to the greenhouse, where they are naturally dried. Once the plants are dry, their stems can be easily manually separated from the leaves. Through these actions during the stem is prepared for further processing. Then, dry stems are transported to the production plant, where they are chopped to obtain fibers of 4 mm in length and later mixed with water, sand and lime. The resulting mixture is placed in a mold for 5 days. Later the mix is demolded and naturally dried. Once the mixture is dry, the insulation material is ready for transportation to the installation point.

As Figure 8.2 shows, system boundaries include the following stages: raw materials, transportation (from the i-RTG-Lab to the production plant) and production. The transportation of the insulation material to the installation point is not included in the system boundaries according to the EPD for construction products (European Committee for Standardization, 2014).

System boundaries do not include any impact related to the production of the tomato stem because the main objective of the crop is tomato production. Thus, environmental impacts are associated with the tomatoes and not to the stems. Nevertheless, the environmental impacts of tomato production may be reduced because stem waste management is avoided.

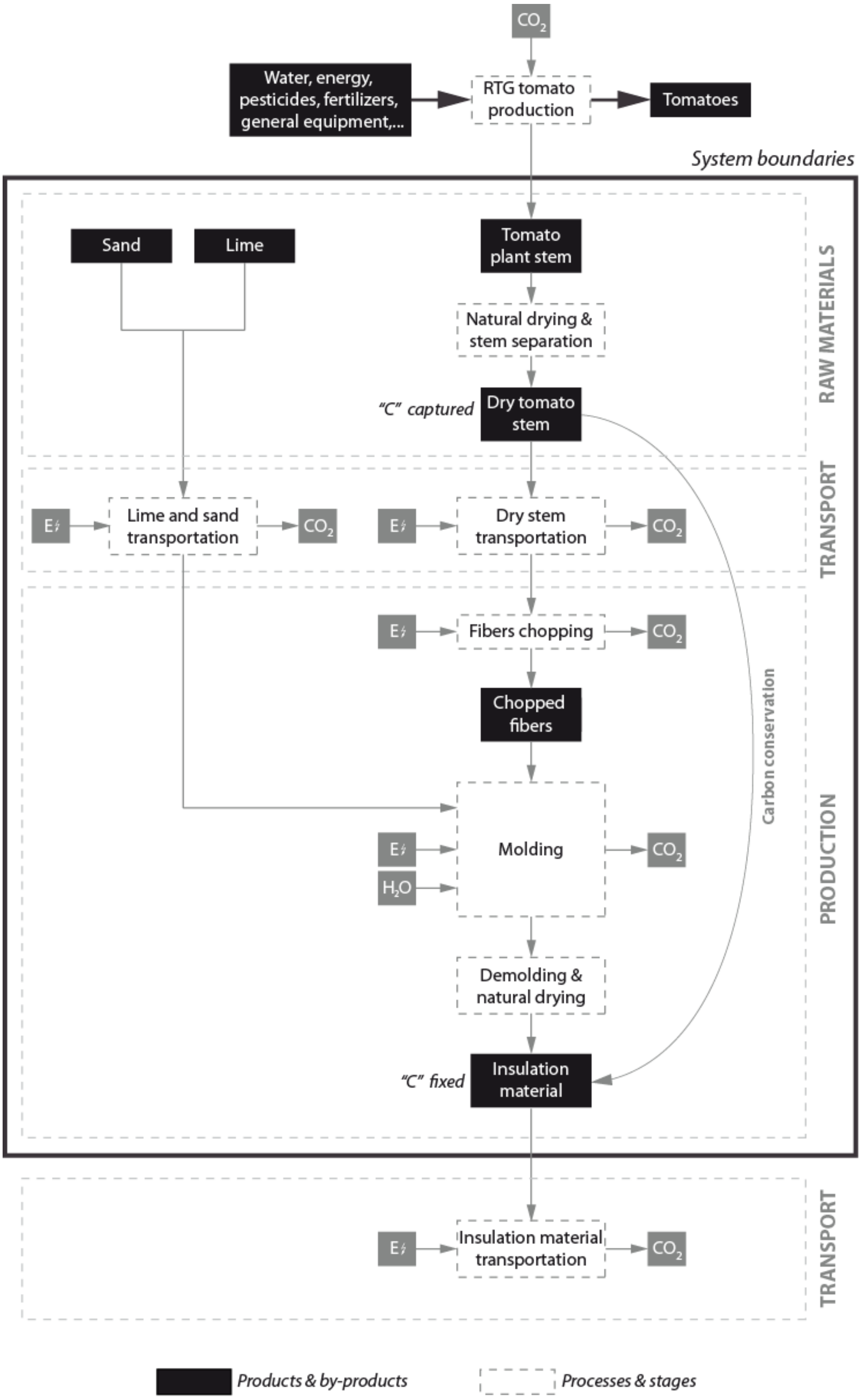


Figure 8.2. *Production process of the insulation material with waste tomato plant feedstock and system boundaries selected for the LCA study*

8.2.3.4. Inventory assessment & assumptions

The two insulation material samples analyzed in this LCA were produced (see Figure 8.3) through the production process described in Figure 8.2. For each sample, different tomato stem and raw material proportions were used, thereby obtaining samples with different thermal properties and densities. Consequently, the total mass to achieve the FU varied for each sample. The sample composition and properties are provided in Table 8.1. The percentages of materials were selected according to the study done by S. Benfratello et al. of a hemp-lime biocomposite insulation material (Benfratello et al., 2013).

Figure 8.3. *Pictures of the tomato plant stems used in the study (left), the production process of the insulation material (center) and the final insulation material (right)*

This research consists of a theoretical study of producing local insulation materials using UA wastes in Barcelona. To the best of our knowledge, no production plant produces such thermal insulation materials in the metropolitan area of Barcelona. Nevertheless, it was assumed that a production plant could be located in northern or southern Barcelona, where different industrial areas can be found. The distance from Bellaterra, where the plants were cropped, to the industrial areas was 25 km on average. This is the assumed distance that dry stems were transported from the i-RTG-Lab to the production plant with Euro 6 lorries with a load capacity of between 3.5 and 7.5 tons. Lime and sand could be provided from a local quarry located in Garraf, 35 km from Barcelona, by means of Euro 6 lorries with a load capacity of between 7.5 and 16 tons.

Table 8.1. *Sample properties for the selected FU*

			Sample	
			A	**B**
Composition	*Stem fiber content*	%	20%	30%
	Lime content	%	32%	28%
	Sand content (carbonate calcium)	%	32%	28%
	Water content	%	16%	14%
Properties	*Weight to produce the FU*	kg	75.7	51.3
	Density	$Kg{\cdot}m^{-3}$	733.7	788.9
	Thermal conductivity	$W{\cdot}K^{-1}{\cdot}m^{-1}$	0.103	0.065

The energy required to chop the fibers and to perform the molding process (Figure 8.2) was considered when producing the samples at lab scale. The power of the equipment used (kW) and the operation time (h) required to produce one unit of mass (kg) of insulation material were registered. These data were collected for each sample under study. The energy consumptions from the production process are provided in Table 8.2.

Table 8.2. *Energy consumption generated from production processes according to the FU of the samples under study*

		Sample	
		A	**B**
Fibers chopping	kWh	14.9	14.3
Molding	kWh	2.5	2.4

8.3. Results & discussion

8.3.1. Carbon contents of UA tomato plant stems

The i-RTG-Lab, with a crop area of 84.3 m^2, produces 27.4 kg of dry waste tomato stem annually, equivalent to 0.33 kg·m^{-2}·year^{-1}, as shown in Table 8.3. The C content in waste stems was 35.7% of the total dry mass, and according to equation 1, the tomato crop from the i-RTG-Lab had the potential to capture 0.42 kg CO_2 eq.·m^{-2}·year^{-1}. These emissions could be fixed once waste stems were used to produce new products, as this study proposed.

Table 8.3. *Waste dry stem's C content, production and CO_2 fixation from tomato plants (Solanum lycopersicum arawak variety) cropped in the i-RTG-Lab*

C content in tomato stems*	*%*	35,7%
Waste stem production	*Kg·m^{-2}·year^{-1}*	0.33
CO_2 fixed in the stem	*kg CO_2 eq.·m^{-2}·year^{-1}*	0.42

**Solanum lycopersicum arawak variety*

If stems are used to produce new products, two possible scenarios could be obtained. On the one hand, if the emissions captured by the stem are higher than the emissions from producing and transporting the new products, it could be assumed that these products fix carbon instead of emitting carbon. On the other hand, if the emissions from production and transportation are higher than the emissions captured by the stem, it could not be assumed that products fix C emissions. However, new materials with a lower carbon footprint that avoid the depletion of other raw materials could be created.

8.3.2. Potential insulation material production from the i-RTG

Aside from the C emissions that could be fixed if waste stems were used to produce insulation materials, it is also important to determine the amount of insulation material that could be generated per area of crop. This information could be essential to study in the future if UA waste production could supply enough waste to produce the insulation materials that a city may demand for producing new buildings or restoring old ones. The potential annual production of the i-RTG-Lab is 1.6 and 1.1 kg·m^{-2}·year^{-1} of insulation material for samples A and sample B, respectively. The higher value for sample A is explained by the fact that the tomato fiber content in this case is fewer (20%, see Table 8.1) than for sample B (30%, see Table 8.1).

The required crop are to produce a functional unit was 47.3 and 46.6 m^2 for samples A and B, respectively. These values were calculated by dividing the mass of insulation material needed to produce the FU (see Table 8.1) by the potential annual production of insulation material of the i-RTG-Lab. The annual wastes of more than the half of the i-RTG-Lab surface (total surface of 84.3 m^2) are required to produce 1 m^2 of insulation material. This required crop area could significantly decrease if the density of the material was lower.

Approximately 210 m^2 of tomato stem insulation material could be produced per hectare of a crop, such as by the i-RTG-Lab. So, for example, for a 4-floor building 20 m wide, 20 m deep and 15 m high with an external surface of 1,600 m^2 (without discounting empty surfaces for windows) would require an annual waste production of 7.6 hectares of tomato crop to insulate its external walls. Therefore, the dimensions of UA may limit the production of insulation materials, such as those proposed in the present research. However, in cities such as Barcelona, which has a consolidated peri-urban agriculture, waste could be obtained from this type of agriculture if required.

8.3.3. Carbon footprint and embodied energy of the new insulation material

Table 8.4 shows the carbon footprint and embodied energy of the samples studied. The net carbon footprint refers to the difference between emissions generated during the raw materials, transportation and production stages minus the C emissions fixed by the stem used to produce the sample. As can be observed, for both samples the net carbon footprint is negative, meaning that the biogenic carbon fixed within the material is higher than the emissions resulting from the production of the material. On average, fixed biogenic carbon reduces the carbon footprint by 212.3%.

The sample with the lower carbon footprint and the lower embodied energy is sample B (Table 8.4). This can be explained in three ways. Sample B has a fewer thermal conductivity (0.065 $W{\cdot}K^{-1}{\cdot}m^{-1}$) than sample A (0.103 $W{\cdot}K^{-1}{\cdot}m^{-1}$); therefore, less insulation material is required to produce the FU. Moreover, sample B contains a higher percentage of tomato stems (30%, see Table 8.1). Therefore, less other raw materials (lime, sand and water) are required and a higher percentage (224.5%, see Table 8.4) of CO_2 is fixed per unit of insulation material mass. A higher stem content within the material may be recommended; however, it could worsen the mechanical properties of the material.

Table 8.4. *Carbon footprint and embodied energy of the thermal insulation material samples under study according to the defined FU*

	Raw Materials, Transportation & Production emissions	Biogenic carbon content	Ratio CO_2 fixed/emitted	Net carbon footprint*	Embodied energy
	Kg CO_2 eq.	Kg CO_2 eq.	%	Kg CO_2 eq.	MJ
Sample A	9.9	19.8	200.1%	-9.9	202.9
Sample B	9.0	20.1	224.5%	-11.2	186.4

**Emissions from raw materials, transportation and production stages minus the C emissions fixed with the stem used*

The carbon footprint and embodied energy contribution at each life cycle stage were similar in the two samples, as shown in Figure 8.4 (this figure does not include samples' biogenic carbon content). The production stage was the main contributor to both of the impact categories studied. The stem chopping process, due to the required energy (see Table 8.2), produced more than 80% of this impact. It should be considered that the environmental impacts in the present study were calculated according to the production of samples at the lab scale. The industrialization of this process may reduce the environmental impacts of the production stage.

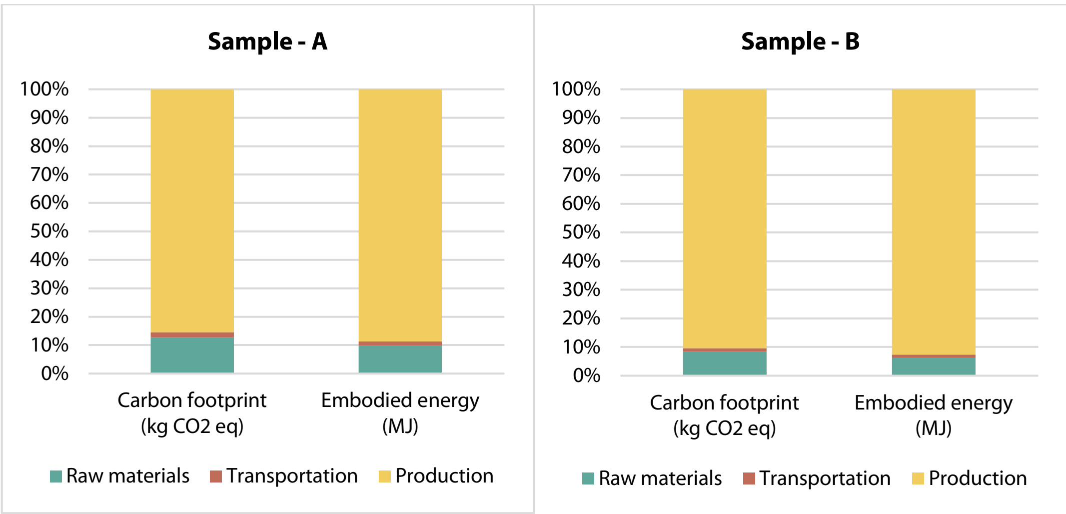


Figure 8.4. *Carbon footprint and embodied energy contributions for each life cycle stage analyzed (raw materials, transportations and production) without considering the biogenic carbon*

The raw materials stage is responsible for fewer than 15% of the environmental impacts of the samples. The environmental impact is approximately equally caused by the lime and sand used to produce the samples. The environmental impact of lime is probably caused by the calcination of stones extracted from mines at 1,000°C. The environmental impact of sand could be associated with its grinding to obtain sand powder. Water contributes to 0.25% or less of the impact.

The transportation of raw materials to the production plant has a low carbon footprint and an embodied energy fewer than 2%. The use of local materials seems to notably reduce the environmental impacts from the transportation phase in comparison with other studies for which this stage represents more than the 30% of the carbon footprint and embodied energy (Sierra-Pérez et al., 2016a).

8.3.4. Comparison with other thermal insulation materials

Comparisons in this section were done exclusively with sample B as having better thermal conductivity (Table 8.1), requiring less material to produce the FU (Table 8.1) and having fewer environmental impacts (Table 8.4). As shown in Table 8.5, the thermal conductivity and density of sample B were between 1.5-2.7 and 4.6-52.6 times higher than other conventional non-renewable and renewable insulation materials, respectively. The lofty thermal conductivity and density suggest that an elevated mass is required to produce the FU; consequently, the building structure might need to be reinforced for the installation of our insulation material, which would increase the environmental impact.

Table 8.5. *Comparison of sample B properties, carbon footprint and embodied energy with those of the most common insulation materials and other renewable insulation materials according to the defined FU*

		Thermal conductivity	Density	Weight per FU	Cradle to gate perspective	
					Carbon footprint	Energy embodied
		$W·K^{-1}·m^{-1}$	$Kg·m^{-3}$	kg	kg CO_2 eq.	MJ
Tomato stem (Sample B) *	-	0.065	789	51.3	9.0	186.4
Tomato stem (Sample B) **	-	0.065	789	51.3	-11.2	186.4
Cork*	(Sierra-Pérez et al., 2016a)	0.042	171	7.2	12.2	211.0
Cork**	(Sierra-Pérez et al., 2016a)	0.042	171	7.2	-2.9	211.0
Kenaf*	(Ardente et al., 2008)	0.038	40	1.5	3.2	59.4
Mineral wool	(Ardente et al., 2008)	0.04	40	1.6	1.7	57.6
Polyurethane (PU)	(Ardente et al., 2008; Pargana et al., 2014; Zabalza Bribián et al., 2011)	0.024	35	0.8	3.2-6.5	25.2-99
Expanded polystyrene (EPS)	(Pargana et al., 2014; Zabalza Bribián et al., 2011)	0.0396	15	0.6	3.2-8.2	74.4-118
Extruded polystyrene (XPS)	(Pargana et al., 2014)	0.035	30	1.1	5.2	98.1

** Not including biogenic carbon   **Including biogenic carbon*

Despite the limitations of the insulation material under study, its carbon footprint from a cradle-to-gate perspective was significantly better than all of the other renewable and non-renewable materials when considering the fixed biogenic carbon (see Table 8.5). In comparison with cork, the carbon footprint of sample B could be better since cork material needs to be transported far to the production plant (Sierra-Pérez et al., 2016a). The low raw materials transportation for sample B may compensate the environmental impact of the large amount of raw materials required to produce the FU. By comparing the carbon footprint of sample B (not including biogenic carbon) with that of kenaf, it seems that kenaf has a lower environmental impact. Nevertheless, for the production of insulation material, 70% of the required kenaf is converted into a residue that is used for energy valorization (Ardente et al., 2008). So, only the 30% of the impact of kenaf is associated with the insulation material.

Sample B had the second highest embodied energy value after cork but a significantly higher embodied energy in comparison with that of kenaf and other non-renewable materials, even when biogenic carbon was considered. If biogenic carbon was considered, despite the high embodied energy of sample B and cork, the real environmental impact in terms of CO_2 eq. emissions would be lower. Therefore, if biogenic carbon is included when computing the CO_2 emissions, embodied energy should not be used as the main indicator for decision-making purposes when selecting more environmentally friendly thermal insulation materials.

8.3.5. Sensitivity analysis: increasing tomato plant stem transportation distances.

As quantified in section 8.3.2, the tomato crop area required to produce enough insulation material to produce the FU is quite high, meaning that provable UA does not generate enough wastes to satisfy cities' demand for insulation materials. Consequently, waste stems may be obtained from non-UA crops, meaning that the transportation distances of stems could increase. For example, if required, waste stems could be transported from southern Spain (the region with the largest tomato production in Spain) to Barcelona. This solution may increase the transportation distance of waste stems by 770 km.

This section aims to discuss how transportation affects the carbon footprint and embodied energy of the material and how it draws concern regarding the maximum distance that the waste stems are transported. Figure 8.5 shows the increased carbon footprint (considering the fixed biogenic carbon) and embodied energy of sample B caused by the increased transportation distances of waste stem from generation point to the production plant. A carbon footprint of 0 kg CO_2 eq. (for the defined FU) was achieved at a transportation distance of 2,976 km. Therefore, the material may be transported fewer than 2,976 km to ensure that the material fixes CO_2 emissions instead of emitting them. With this result, the transportation of stems from southern Spain to Barcelona seems feasible, as the carbon footprint after transporting the stems 770 km is still negative (-8.3 kg CO_2 eq.). The embodied energy increases from 186.4 to 360 MJ when the stem is transported 2,976 km, confirming the results and suggesting that it may not be taking into account for decision-making.

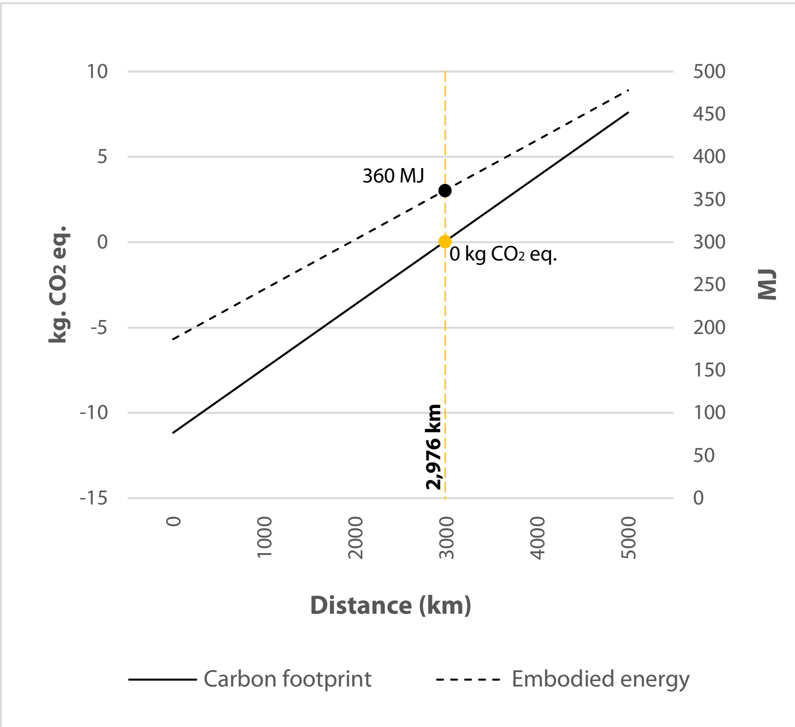


Figure 8.5. *Carbon footprint (considering the fixed biogenic carbon) and embodied energy increase for sample B caused by the increased transportation distance of waste stems from where the crop is produced to the production plant (according to the defined FU)*

8.4. Conclusions

- The i-RTG-Lab tomato crop (*Solanum lycopersicum arawak* variety) has the potential to fix 0.42 kg CO_2 eq.·m^{-2}·$year^{-1}$ if its wastes are used to produce insulation materials.

- Compared with other insulation renewable and non-renewable materials, the insulation material studied here has a higher embodied energy (between 150 and 740% higher) but the lowest net carbon emissions if biogenic carbon is considered (12.9-19.4 kg CO_2 eq. lower per FU).

- The higher the percentage of tomato plant stem in the insulation material is, the lower is the carbon footprint of the material due to the biogenic carbon content.

- Insulation materials made with UA wastes have the potential to fix CO_2 emissions from urban crops (between -9.9 and -11.2 kg CO_2 eq. according to the defined FU).

- These results allow high transportation distances of the material from the production plant to the installation point; distances that are recommended not to exceed 900 km.

- The production of insulation materials with UA wastes may not satisfy the demand of growing regions, such as Barcelona, because annual waste from more than 45 m^2 of crop is required to produce 1 m^2 of insulation material. Other crops with higher waste production could be of interest for further study.

- The density of the material obtained is high; thus, a high mass of material is required to produce the FU, which would require the building structure to be reinforced. Further research is required to identify other complementary materials that could reduce the density of insulation materials made with tomato plant stems.

PART V

Conclusions & furthers research

Chapter 9

Conclusions

"At summit there is a perfect view to analyze everything with perspective"
Catalan Pyrenees, from the submit of La Sarrera (Andorra)

CHAPTER 9 - General conclusions

This chapter aims to discuss the main results of this dissertation and highlight its contributions by answering the three question set out in the objectives proposed in chapter 1.

9.1. Contributions of the dissertation

Table 9.1 reflects the CO_2 eq. emissions that could be avoided if i-RTGs applied the strategies laid out in the dissertation. The range of values provided for Chapter 3 and 4 represent the carbon footprint savings that PCM could obtain when used to increase the efficiency of root heating systems with three different boilers: gas (intermediate value of 1440 kg CO_2 eq.), oil (highest value of 1,800 kg CO_2 eq.) and biomass (lowest value of 90 kg CO_2 eq.).

Part III of the dissertation will help to improve precision in LCA studies of the i-RTG-Lab. The carbon footprint of the i-RTG-Lab could have been overestimated by 12,500 kg CO_2 eq. per hectare of crop. The interest of this result resides in its influence on the decision making process when selecting more environmentally friendly UA systems.

Finally, potential CO_2 eq. emissions savings that Table 9.1 shows for Chapter 7 and 8 (Part IV) of the dissertation, represent the carbon sink that producing by-products (biochar or insulation materials) with tomato plant feedstock could generate.

Table 9.1. *Potential CO_2 eq. emissions that each specific study of the dissertation could save from RTGs. Results provided refer to annual savings of one hectare of tomato crop with an assumed productivity of 25 kg·m^{-2} (chapter 5 is not included as a LCA was not conducted in that chapter)*

		Description	Potential carbon mitigation (kg CO_2 eq.) per hectare and year (*Productivity = 25 kg·m^{-2}*)
PART II	Chapter 3	Passive PCM heating system	90-1,800*
	Chapter 4		
PART III	Chapter 6	N_2O emission factor for hydroponic crops grown in i-RTGs	12,500**
PART IV	Chapter 7	Biochar as a by-product from UA feedstocks	122,000
	Chapter 8	Insulation material as a by-product from UA feedstocks	132,000

**Assuming that 60 days per year temperatures will be low enough to require the use of heating systems*
***This value was calculated for a lettuce crop; so, values for this chapter are illustrative. It refers to carbon emissions overestimated until today when measuring the carbon footprint of tomato crops grown in the i-RTG-Lab.*

The present dissertation provides different strategies to reduce the carbon footprint of i-RTGs and facilitates quantitative results which describe their carbon footprint reduction potential. From Table 9.1 it can be concluded that there is potential to reduce the carbon footprint from i-RTGs. From the strategies studied, the elaboration of by-products with tomato plant wastes is the strategy with a higher carbon footprint mitigation potential. These solutions allow storage of CO_2 emissions captured by crops and avoid the management (i.e. composting or incineration) of agricultural wastes.

9.2. Addressing research questions

This section addresses the four questions set out in this dissertation:

Question 1*: Can passive systems made with phase change materials (PCMs) replace conventional heating in greenhouses and reduce the carbon footprint of i-RTGs?*

- A passive system with PCM could provide the perlite bag with 86.7% of the total heat required to maintain the root zone of plants at 15 °C in Mediterranean greenhouses.
- The melting of PCM during day time is not guaranteed on cloudy days. Therefore, the accumulation of heat during day may not take place and, consequently, no heat would be released during night.
- As the melting of PCM is not guaranteed on cloudy days, which means that crop may not be heated at night, PCM cannot completely replace conventional root zone heating systems but can be combined with these heating systems to reduce their carbon footprint and costs.
- 93% of the environmental impact of the tested PCM system is generated by the extraction and transformation of paraffin to produce the PCM.
- PCM represent the 97% of total costs of the proposed passive system. PCM prices may reduce to achieve make this system interesting for farmers from an economic point of view.
- PCM has a low environmental impact and maintenance costs associated to use stage because no energy consumption is required for its use.
- The environmental and economic payback of a passive system with PCM for greenhouses or i-RTGs depends on the number of cool nights during which the PCMs provide energy savings. The higher the number of cool nights, the faster the environmental payback.
- If PCM are combined with a gas or oil heating systems 32 and 43 cold nights per year, respectively, are required to ensure that PCM provide a carbon footprint reduction.
- The installation of a root zone passive system based on PCM in an i-RTG is technically feasible as it does not hinder crop maintenance and is compatible with the hydroponic system used in i-RTGs.
- The i-RTG-Lab has the potential to keep crops warmer during night than a conventional greenhouse by taking advantage of the building it is placed on, without using heating systems. Therefore, PCMs' may not be required or their phase change temperature may be higher.

Question 2: *Can the residual air of a building be used for CO_2 enrichment in i-RTGs?*

- The CO_2 concentration in the i-RTG-Lab in hours of high solar radiation is near 350 ppm, which is the same CO_2 concentration as air. So, CO_2 enrichment could be of interest to increase crop productivity and efficiency.
- The CO_2 concentration of the residual air from the labs of the ICTA-ICP building, which is between 400 and 500 ppm, is not high enough to ensure the carbon enrichment of the i-RTG-Lab. It could be interesting to look for new sources in the ICTA-ICP building which could provide clean air with CO_2 concentrations over 500 ppm to the i-RTG-Lab.
- The indoor air concentration in households and office buildings can reach 2,500 ppm because of human respiration. Therefore, the residual air from such buildings could be used for the carbon enrichment of i-RTGs.

Question 3: *Could the GHG emissions of i-RTGs be calculated with more accuracy?*

- The real direct N_2O emissions of fertilized crops may differ from the emissions that can be calculated by using generic emission factors, as the IPCC.
- The carbon footprint of fertilized crops could be overestimate or underestimated if generic N_2O emission factors are used to determine their direct N_2O emissions.
- The emission factor calculated (0.0072-0.0084 ±8% kg N_2O^{-1} per kg N^{-1}), for lettuce crops developed in the i-RTG-Lab, suggest that the carbon footprint calculated in previous research for tomato crops grown in the i-RTG-Lab may be overestimated by 7.5%.
- The use of more specific N_2O emission factors will improve the accuracy of fertilized crop carbon footprint calculation grown in the i-RTG-Lab. This fact could affect the decision making process of both LCA makers and politicians.

Question 4: *Is the creation of new by-products, with UA wastes, a strategy to sink the CO_2 emissions captured by crops grown in i-RTGs?*

- The production of by-products with UA wastes is a feasible strategy that can help to sink the carbon of CO_2 emissions captured by plants.
- If a ton of waste is used to produce biochar, only 0.4 t of by-product is obtained (Table 9.2) because part of the waste is degraded during the pyrolysis process.
- If one ton of waste is used to produce an insulation material, 3.3 t of by-product are obtained (Table 9.2) because there are not mass losses during the production process. Moreover, once crushed, tomato plants are mixed with other raw materials: sand and lime. So, tomato plant represents the 30% of the total mass of the insulation material.
- The production of biochar and insulation materials with residual tomato plants from UA crop produce -487 and -529 net kg of CO_2 emissions per ton of dry tomato plant residue (Table 9.2), respectively.
- Net emissions are 8% lower for the insulation material than for biochar (see Table 9.2). Therefore, the insulation material has a higher capacity to store carbon for long periods.
- The carbon sink for the biochar is lower than for the insulation material (see Table 9.2) because part of the carbon in the biochar (the 50%) is not considered stable, which means that is emitted into the air if it is used for soil amendment.

Table 9.2. *Carbon footprint balance of biochar and insulation materials production with 1 ton of dry tomato plant residue*

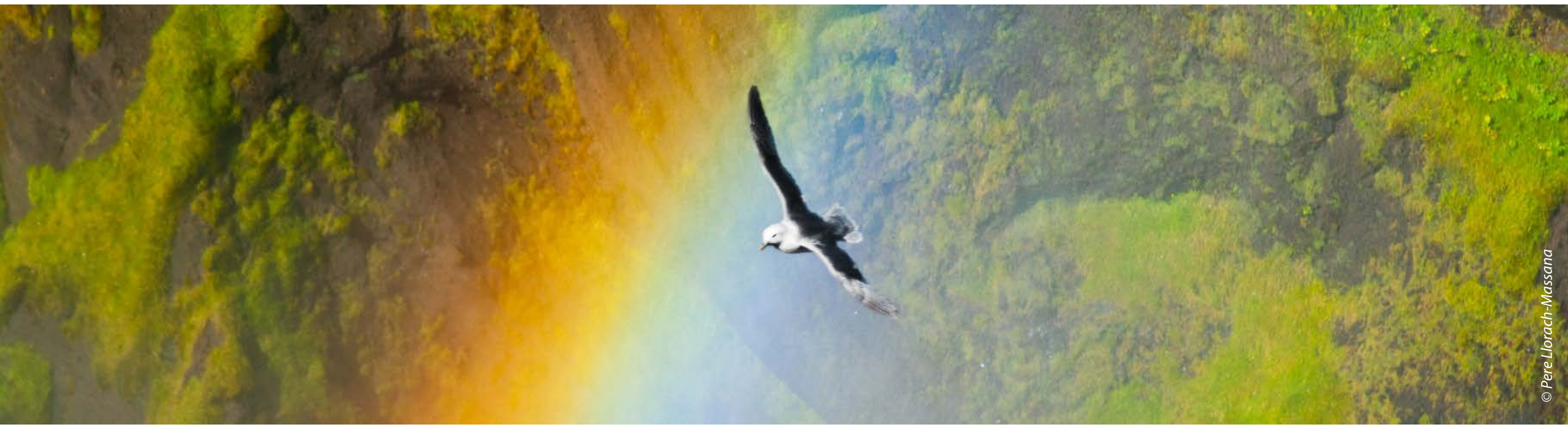
	1 ton of dry tomato plant residue			
	Amount of by-product production	**Carbon sink in the by-product**	**C emissions** (raw materials, transportation and production stages)	**Net emissions**
	t	kg $CO_2 \cdot t^{-1}$ of tomato plant residue	kg $CO_2 \cdot t^{-1}$ of dry tomato plant residue	kg $CO_2 \cdot t^{-1}$ of dry tomato plant residue
Insulation material*	3,3	1111	582	-529
Biochar**	0,4	556	69	-487

**Sample B developed in chapter 8 of the dissertation*

*** Assuming scenario 2-B from chapter 7 of the dissertation with a 40% of biochar yield and 50% of final carbon stable in the biochar*

Chapter 10

Suggestions for further research



"Life give us opportunities to enjoy new experiences"
Seagull (Iceland)

CHAPTER 10 - Suggestions for further research

This section groups aspects that were detected during the development period of the dissertation, which could be of interest for future researchers. The section is divided into two parts: methodological recommendations and future actions.

10.1. Methodological recommendations

This section provides methodological recommendations which could help to improve the environmental impact calculation of UA and i-RTGs.

10.1.1. Provide more precise direct N_2O emission factors to LCA makers

Nowadays, LCA practitioners use the IPCC emission factor to estimate the direct emission derived from N fertilization of crops, which could lead to a significant error in the calculation of urban and conventional agriculture's carbon footprint. In terms of cost and time it might not be feasible to measure the emission factor of each crop that is analyzed with LCA methodology. For that reason, it is important to develop a methodology which provide LCA makers a broader number emission factors for crops with different characteristics. This methodology could focus on:

- Develop a standard method, such as the open chamber method, to measure the direct N_2O emissions in different types of crop under different environmental conditions.
- Create a table that provides different emission factors to LCA makers. To classify emission factors different characteristics of crops, with significant influence on crop direct N_2O emissions (i.e. type of soil, avg. solar radiation, avg. humidity), that are of easy access to LCA makers should be used.

10.1.2. Further discussion when comparing conventional greenhouses with i-RTGs

For the case of the i-RTG-Lab it was detected that using a specific emission factor, instead of the general one from the IPCC, could improve the calculation of its carbon footprint by reducing the final value by 7.5%. Therefore, using a specific emission factor to quantify the carbon footprint of conventional greenhouses could modify the final results calculated until today. For that reason:

- In future LCA studies, if the i-RTG-Lab is compared with a conventional greenhouse, how the direct N_2O emissions were accounted for each systems should be better discussed.

In addition, when the i-RTG-Lab is compared with conventional greenhouses it is not taken into account that land occupied by the i-RTG-Lab is shared with a building. The land use impact category describes the damage caused to natural resources and ecosystems due to the transformation of natural land to other uses (Goedkoop et al., 2009). The land that i-RTGs occupy is part of the land transformed to build the building they are place on. Accordingly, the following aspects may be addressed:

- How should the impact on land use be allocated to i-RTGs?
- Would i-RTGs have a lower effect on the natural carbon cycles than greenhouses located on the ground, because they reduce the alteration of soil changes respiration?
- What are the environmental advantages of i-RTGs caused by the reduction of land use alterations in comparison with ground-based agriculture?

10.2. Future actions

In this part of the dissertation different suggestions for future research lines are provided.

10.2.1. Further research on PCM for its application in i-RTGs

Night temperatures in the i-RTG-Lab are higher than in conventional greenhouses because of the high thermal inertia of the ICTA-ICP building. It allows to storage large amounts of heat during day, which is provided to the crop at night. Moreover, PCMs were not tested in i-RTGs. Consequently, following actions may be of interest in future research:

- To determine the adequate phase change temperature of PCMs for its installation in i-RTGs.
- To test PCM functionality in i-RTGs, such as in the i-RTG-Lab.
- To determine the environmental and economic impacts of applying PCMs in i-RTGs.
- To study the effect of PCMs in crop productivities of i-RTGs and conventional greenhouses.
- To look for other PCMs applications in the i-RTG-Lab and the ICTA-ICP building to increase the efficiency of both systems.

10.2.2. Look for CO_2 sources for the carbon enrichment of i-RTGs

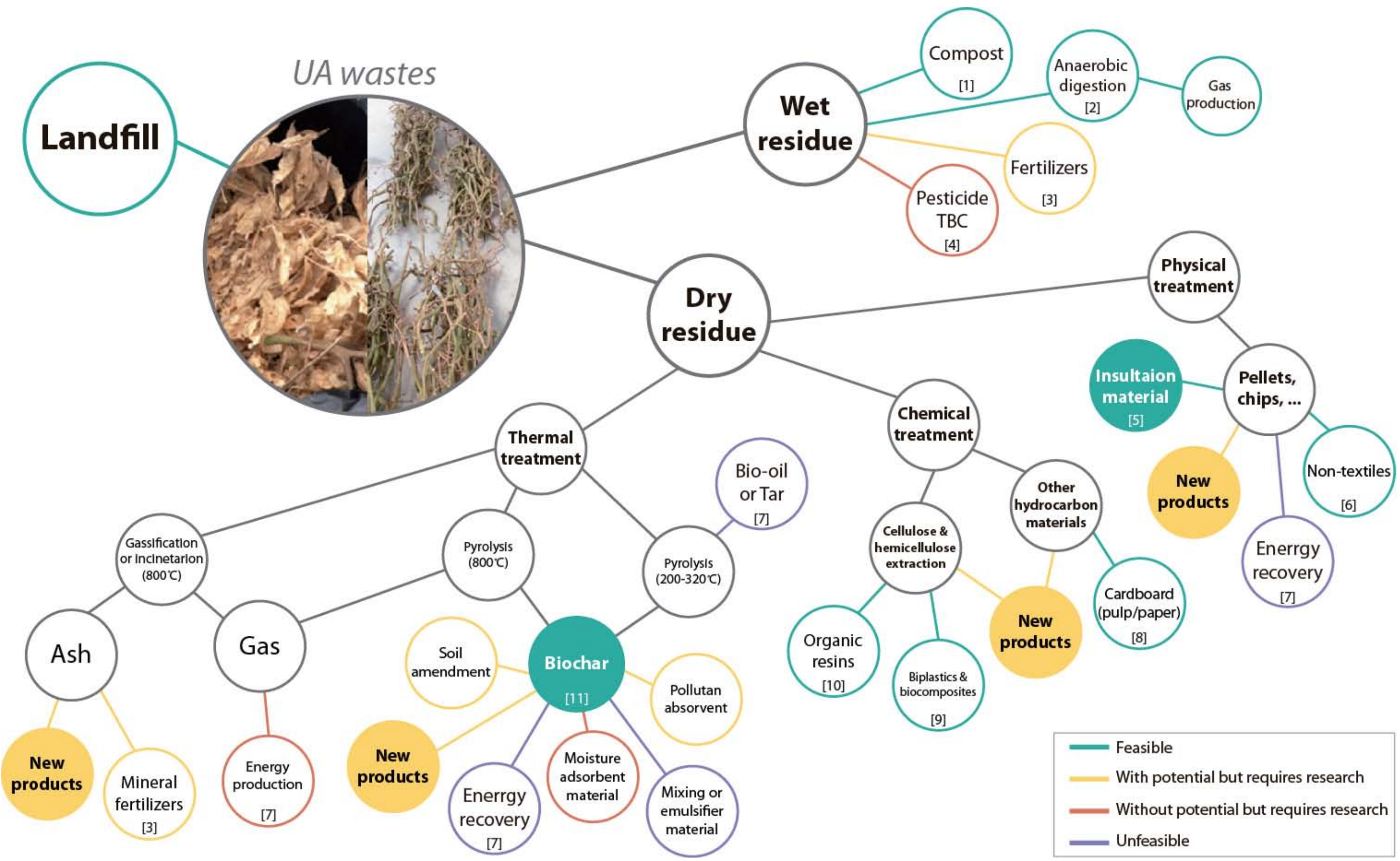
As observed throughout the dissertation, the low CO_2 concentration in the i-RTG-Lab may limit crop growth and productivity. Therefore, the following strategies should be considered in future research:

- To look for new CO_2 sources in the ICTA-ICP building which could provide enough CO_2 to the i-RTG-Lab for its carbon enrichment.
- To study the CO_2 concentrations of the residual air in different types of buildings (i.e. households, offices, industries) to determine its potential for the carbon enrichment of i-RTGs. Later, inject into the i-RTG-Lab the equivalent CO_2 detected in such residual airs, to determine its influence on productivity and consequently on the environmental and economic performance of food production.
- In new constructions, which include i-RTGs on the tops of buildings, previous studies may be required to analyse the potential CO_2 sources of buildings that could be used for the carbon enrichment of i-RTGs.

10.2.3. New by-products with waste from food production systems

Apart from products developed in the present dissertation, other potential materials and by-products could be created with tomato plant waste biomass (see Figure 10.1). Moreover, tomato crops generate multiple wastes which have not been studied in the present dissertation. The following actions could be developed, within the framework of the circular economy, to reuse or recycle wastes form crops:

- To detect, quantify and characterize all wastes derived from food production in i-RTGs that have not been studied yet.
- To study the technical and environmental potential of developing more new materials and products with wastes produced in i-RTGs crops, such perlite substrates.
- To determine how these potential new materials could be integrated into our waste management systems at their end of life.
- To organize innovation workshops with multidisciplinary groups to generate new ideas on how wastes from i-RTGs crops could be exploited to produce new products with low environmental impacts.



[1] (Alkoaik and Ghaly, 2006, 2005); **[2]** (D.J. and D.W., 1982; Hills and Nakano, 1984; Trujillo et al., 1993); **[3]** (Achmon et al., 2015); **[4]** (Achmon et al., 2015); **[5]** (Khedari et al., 2003; Luamkanchanaphan et al., 2012; Sampathrajan et al., 1992); **[6]** (Aitex, 2015); **[7]** (Bensaid et al., 2012; Callejón-Ferre et al., 2011); **[8]** (Wageningen UR, 2014); **[9]** (Ford Motor Company, 2014); **[10]** (Biocopac Project, 2013); **[11]** (GenXing et al., 2010; McHenry, 2009)

***Figure 10.1.** Scheme of the main waste tomato plant management solutions detected with special attention on those which have potential to create new materials and products*

In addition further research on the by-products studied in the dissertation could be of interest:

- To study how the density of thermal insulation materials made with residual tomato plants could be reduced.

- To determine the stability over time of thermal insulation materials made with residual tomato plants to define their lifespan

- To study in greater depth if tomato plant residues can be mixed with other forestry or agricultural wastes, to reduce its ash generation when is subjected to thermal processes and allow its processing in pyrolysis plants.

- To discuss to whom the carbon sank by by-products should be allocated: the by-products themselves, crops or cities.

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Appendix

Supporting information

Appendix 1. Supporting information for chapter 3

LCA & LCCA of a PCM application to control root zone temperatures of hydroponic protected crops in comparison with conventional root zone heating systems, which use natural gas, oil or biomass boilers.

Content:

- **Supporting Information 1.1:** Selected processes from the ecoinvent database for scenarios A, B, C and D
- **Supporting Information 1.2:** Environmental Impact distribution of scenario A: Root zone heating system with gas.
- **Supporting Information 1.3:** Environmental Impact distribution of scenario B: Root zone heating system with oil.
- **Supporting Information 1.4:** Environmental Impact distribution of scenario C: Root zone heating system with biomass.
- **Supporting information 1.5:** Detailed costs per year for scenarios A, B, C and D.

Supporting Information 1.1: Selected processes from the ecoinvent database for scenarios A, B, C and D

The following table indicates the ecoinvent database processes selected for each component of the inventory used to realize the life cycle assessment of scenarios A,B, C and D.

Common inventory for scenarios A, B and C for a root heating system with Gas, Oil and Biomass	
Product	**Process used in the EcoInvent Database**
HDPE tubes 6 atm (D90mm)	Polyethylene, HDPE, granulate, at plant/RER [Kg] Extrusion, plastic pipes/RER [Kg]
HDPE tubes 2'5 atm (D19mm)	Polyethylene, HDPE, granulate, at plant/RER [Kg] Extrusion, plastic pipes/RER [Kg]
Water pump (Q>19'84L/s -71'4L/h)	Steel, converter, chromium steel 18/8, at plant/RER [Kg] 25% Milling, steel, average/RER [Kg] 25% Steel, low-alloyed, at plant/RER [Kg] 75% Milling, cast iron, average/RER [Kg] 75%
Energy water pump	Electricity, medium voltage, at grid/ES 2013
Water	Tap water, at user/RER S
Disposal HDPE tubes 6 atm (D90mm)	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH [Kg]
Disposal HDPE tubes 2'5 atm (D3/4")	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH [Kg]
Water pump waste treatment	Recycling steel and iron/RER [Kg]

Specific inventory for scenario A for a root heating system with Gas	
Product	**Process used in the EcoInvent Database**
Gas boiler 300 kwh	Gas Boiler 300KW/RER/ [u] (calc)*
Heat generation with gas boiler	Heat, natural gas, at boiler modulating >100kW/RER [Kwh]
Gas boiler waste management	Recycling steel and iron/RER [Kg] 75% Disposal, steel, 0% water, to inert material landfill/CH [Kg] 25%

Specific inventory for scenario B for a root heating system with Oil	
Product	**Process used in the EcoInvent Database**
Oil tank	Oil storage 3000l/CH/I [u]
Oil boiler 300 kwh	Oil boiler300kW/CH/I [u] (calc)**
Oil for heating	Heat, light fuel oil, at boiler 300kW/RER [Kwh] (calc)***
Oil boiler waste management	Recycling steel and iron/RER [Kg] 75% Disposal, steel, 0% water, to inert material landfill/CH [Kg] 25%
Oil tank waste management	Recycling steel and iron/RER [Kg] 75% Disposal, steel, 0% water, to inert material landfill/CH [Kg] 25%

Specific inventory for scenario C for a root heating system with Biomass	
Product	**Process used in the EcoInvent Database**
Pellets tank 10'2 m3	Tower silo, plastic/CH/I [m3]
Biomass boiler 300 kwh	Furnace, wood chips, softwood, 300kW/CH/I S
Heat from biomass	Heat, softwood chips from industry, at furnace 300kW/CH [Kwh]
Biomass boiler waste management	Recycling steel and iron/RER [Kg] 75% Disposal, steel, 0% water, to inert material landfill/CH [Kg] 25%
Pellets Tank waste management	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH [Kg] 37,5% Recycling steel and iron/RER [Kg] 62,5%

Specific inventory for scenario D for a passive solar energy storage to control root zone temperatures with PCM	
Product	**Process used in the EcoInvent Database**
PCM	Paraffin, at plant/RER [Kg]
LDPE tube bags	Polyethylene, LDPE, granulate, at plant/RER [Kg] Extrusion, plastic film/RER [kg]
Disposal PCM (RT18HC - Rubitherm)	Recycling paraffin /RER [kg] (calc)
Disposal LDPE tube bags	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH S [kg]

*Gas Boiler 300KW/RER/I = ([[Gas boiler/RER/I]*30]+[[Industrial furnace, natural gas/RER/I]*0,3])/2
**Oil boiler300kW/CH/I= ([[Oil boiler 100kW/CH/I]*3]+[[Industrial furnace 1MW, oil/CH/I]*0,3])/2
***Heat, light fuel oil, at boiler 300kW/RER = ([Heat, light fuel oil, at boiler 100kW, non-modulating/CH] + [Heat, light fuel oil, at industrial furnace 1MW/RER]) / 2

Supporting Information 1.2: Environmental Impact distribution of scenario A: Root zone heating system with gas

Scenario A: Root zone heating system with gas														
Impact categories	Units	Gas boiler	HDPE tubes (D-19mm)	HDPE tubes (D-90mm)	Heat generation with gas boiler	Water	Water pump	Water pump energy	Disposal gas boiler	Disposal tubes HDPE (D-19mm)	Disposal tubes HDPE (D-90mm)	Disposal water pump	Total environmental impact per year	Per Kg Tomato
Climate change	kg CO_2 eq.	2,89E+02	1,78E+02	3,85E+01	2,13E+05	1,54E-01	8,71E+00	2,35E+02	1,58E-01	8,67E+00	1,88E+00	2,75E-03	2,40E+05	6,23E-01
Photochemical oxidant formation	kg NMVOC	1,03E+00	7,32E-01	1,59E-01	2,07E+02	4,13E-04	2,66E-02	8,35E-01	1,75E-03	1,23E-02	2,67E-03	3,04E-05	3,14E+02	8,16E-04
Terrestrial acidification	kg SO_2 eq.	1,52E+00	5,84E-01	1,27E-01	1,53E+02	6,11E-04	3,16E-02	1,52E+00	9,81E-04	5,74E-03	1,24E-03	1,71E-05	2,66E+02	6,90E-04
Freshwater eutrophication	kg P eq.	3,59E-01	2,34E-02	5,08E-03	3,19E+00	1,22E-04	4,57E-03	7,95E-02	1,25E-05	9,68E-05	2,10E-05	2,17E-07	1,13E+01	2,94E-05
Water depletion	m^3	2,94E+00	4,45E-01	9,64E-02	4,96E+01	5,51E-01	1,62E-01	1,97E+00	3,81E-03	2,22E-02	4,82E-03	6,63E-05	2,30E+02	5,97E-04
Fossil depletion	kg oil eq.	9,46E+01	1,40E+02	3,04E+01	8,83E+04	4,11E-02	2,62E+00	7,10E+01	1,01E-01	5,44E-01	1,18E-01	1,75E-03	9,98E+04	2,59E-01
CED	**MJ**	**5,34E+03**	**6,69E+03**	**1,45E+03**	**3,93E+06**	**3,03E+00**	**1,38E+02**	**2,40E+04**	**4,44E+00**	**2,53E+01**	**5,48E+00**	**7,72E-02**	**4,55E+06**	**1,18E+01**

Supporting Information 1.3: Environmental Impact distribution of scenario B: Root zone heating system with oil

Scenario B: Root zone heating system with oil																
Impact categories	Units	Oil boiler	HDPE tubes (D-19mm)	HDPE tubes (D-90mm)	Heat generation with oil boiler	Oil tank	Water	Water pump	Water pump energy	Disposal oil boiler	Disposal oil tank	Disposal tubes HDPE (D-19mm)	Disposal tubes HDPE (D-90mm)	Disposal water pump	Total environmental impact per year	Per Kg Tomato
Climate change	kg CO_2 eq.	1,86E+02	1,78E+02	3,85E+01	2,70E+05	4,87E+01	1,54E-01	8,71E+00	2,35E+02	7,37E-02	3,11E-02	8,67E+00	1,88E+00	2,75E-03	2,96E+05	7,70E-01
Photochemical oxidant formation	kg NMVOC	6,46E-01	7,32E-01	1,59E-01	4,36E+02	2,06E-01	4,13E-04	2,66E-02	8,35E-01	8,14E-04	3,43E-04	1,23E-02	2,67E-03	3,04E-05	5,43E+02	1,41E-03
Terrestrial acidification	kg SO_2 eq.	8,92E-01	5,84E-01	1,27E-01	6,00E+02	2,98E-01	6,11E-04	3,16E-02	1,52E+00	4,57E-04	1,93E-04	5,74E-03	1,24E-03	1,71E-05	7,12E+02	1,85E-03
Freshwater eutrophication	kg P eq.	2,02E-01	2,34E-02	5,08E-03	8,69E+00	8,20E-02	1,22E-04	4,57E-03	7,95E-02	5,82E-06	2,46E-06	9,68E-05	2,10E-05	2,17E-07	1,67E+01	4,35E-05
Water depletion	m^3	1,76E+00	4,45E-01	9,64E-02	3,48E+02	5,52E-01	5,51E-01	1,62E-01	1,97E+00	1,77E-03	7,48E-04	2,22E-02	4,82E-03	6,63E-05	5,27E+02	1,37E-03
Fossil depletion	kg oil eq.	6,26E+01	1,40E+02	3,04E+01	9,37E+04	1,55E+01	4,11E-02	2,62E+00	7,10E+01	4,69E-02	1,98E-02	5,44E-01	1,18E-01	1,75E-03	1,05E+05	2,73E-01
CED	**MJ**	**3,49E+03**	**6,69E+03**	**1,45E+03**	**4,04E+06**	**7,87E+02**	**3,03E+00**	**1,38E+02**	**2,40E+04**	**2,07E+00**	**8,72E-01**	**2,53E+01**	**5,48E+00**	**7,72E-02**	**4,67E+06**	**1,21E+01**

Supporting Information 1.4: Environmental Impact distribution of scenario C: Root zone heating system with biomass.

Scenario C: Root zone heating system with biomass.																
Impact categories	Units	Biomass boiler	Biomass tank	HDPE tubes (D-19mm)	HDPE tubes (D-90mm)	Heat generation with biomass boiler	Water	Water pump	Water pump energy	Disposal biomass boiler	Disposal biomass tank	Total environmental impact per year	Disposal tubes HDPE (D-90mm)	Disposal water pump	Total environmental impact per year	Per Kg Tomato
Climate change	kg CO_2 eq.	1,34E+03	7,44E+01	1,78E+02	3,85E+01	7,99E+03	1,54E-01	8,71E+00	2,35E+02	7,01E-02	3,38E-01	8,67E+00	1,88E+00	2,75E-03	3,58E+04	9,31E-02
Photochemical oxidant formation	kg NMVOC	4,16E+00	2,16E-01	7,32E-01	1,59E-01	4,21E+02	4,13E-04	2,66E-02	8,35E-01	7,75E-04	4,80E-04	1,23E-02	2,67E-03	3,04E-05	5,31E+02	1,38E-03
Terrestrial acidification	kg SO_2 eq.	3,42E+00	2,40E-01	5,84E-01	1,27E-01	2,61E+02	6,11E-04	3,16E-02	1,52E+00	4,35E-04	2,24E-04	5,74E-03	1,24E-03	1,71E-05	3,77E+02	9,79E-04
Freshwater eutrophication	kg P eq.	2,64E-01	1,74E-02	2,34E-02	5,08E-03	7,39E+00	1,22E-04	4,57E-03	7,95E-02	5,54E-06	3,77E-06	9,68E-05	2,10E-05	2,17E-07	1,54E+01	4,01E-05
Water depletion	m^3	1,79E+01	6,59E-01	4,45E-01	9,64E-02	1,11E+02	5,51E-01	1,62E-01	1,97E+00	1,69E-03	8,65E-04	2,22E-02	4,82E-03	6,63E-05	3,07E+02	7,98E-04
Fossil depletion	kg oil eq.	2,41E+02	1,81E+01	1,40E+02	3,04E+01	1,41E+03	4,11E-02	2,62E+00	7,10E+01	4,47E-02	2,12E-02	5,44E-01	1,18E-01	1,75E-03	1,31E+04	3,41E-02
CED	**MJ**	**1,30E+04**	**9,39E+02**	**6,69E+03**	**1,45E+03**	**2,08E+05**	**3,03E+00**	**1,38E+02**	**2,40E+04**	**1,97E+00**	**4,92E-01**	**2,53E+01**	**5,48E+00**	**7,72E-02**	**8,43E+05**	**2,19E+00**

Supporting Information 1.5: Detailed costs per year for scenarios A, B and C and D

Following tables show the distribution of annual costs for producing 1 kg of tomato in a multitunel greenhouse in Almeria of the case of all studied scenarios: A, B, C and D.

	SCENARIO A: GAS HEATING SYSTEM	
	Annual costs	€/kg tomato
Required infrastructure and inputs for a conventional crop in a multitunel greenhouse (EUPHOROS project)	175.154,40 €	0,46 €
Gas Boiler 300 kwh	728,90 €	0,00 €
Gas	42.071,13 €	0,11 €
HDPE tubes 6 atm (D90mm)	100,80 €	0,00 €
HDPE tubes 2'5 atm (D3/4")	287,67 €	0,00 €
Water pump (Q>19'84L/s -71'4L/h)	319,70 €	0,00 €
Water	0,57 €	0,00 €
Installation Costs	7.113,75 €	0,02 €
Maintenance	1.370,80 €	0,00 €
	227.147,72 €	**0,59 €**

	SCENARIO B: OIL HEATING SYSTEM	
	Annual costs	€/kg tomato
Required infrastructure and inputs for a conventional crop in a multitunel greenhouse (EUPHOROS project)	175.154,40 €	0,46 €
Oil Tank 3000L	368,40 €	0,00 €
Oil Boiler 300Kw	460,70 €	0,00 €
Oil	60.775,51 €	0,16 €
HDPE tubes 6 atm (D90mm)	100,80 €	0,00 €
HDPE tubes 2'5 atm (D3/4")	287,67 €	0,00 €
Water pump (Q>19'84L/s -71'4L/h)	319,70 €	0,00 €
Water	0,57 €	0,00 €
Installation Costs	7.113,75 €	0,02 €
Maintenance	1.370,80 €	0,00 €
	245.952,31 €	**0,64 €**

	SCENARIO C: BIOMASS HEATING SYSTEM	
	Annual costs	€/kg tomato
Required infrastructure and inputs for a conventional crop in a multitunel greenhouse (EUPHOROS project)	175.154,40 €	0,46 €
Biomass Boiler 300 kwh	1.443,75 €	0,00 €
Wood biomass	42.918,52 €	0,11 €
HDPE tubes 6 atm (D90mm)	100,80 €	0,00 €
HDPE tubes 2'5 atm (D3/4")	287,67 €	0,00 €
Water pump (Q>19'84L/s -71'4L/h)	319,70 €	0,00 €
Water	0,57 €	0,00 €
Installation Costs	7.113,75 €	0,02 €
Maintenance	1.370,80 €	0,00 €
	228.709,96 €	**0,59 €**

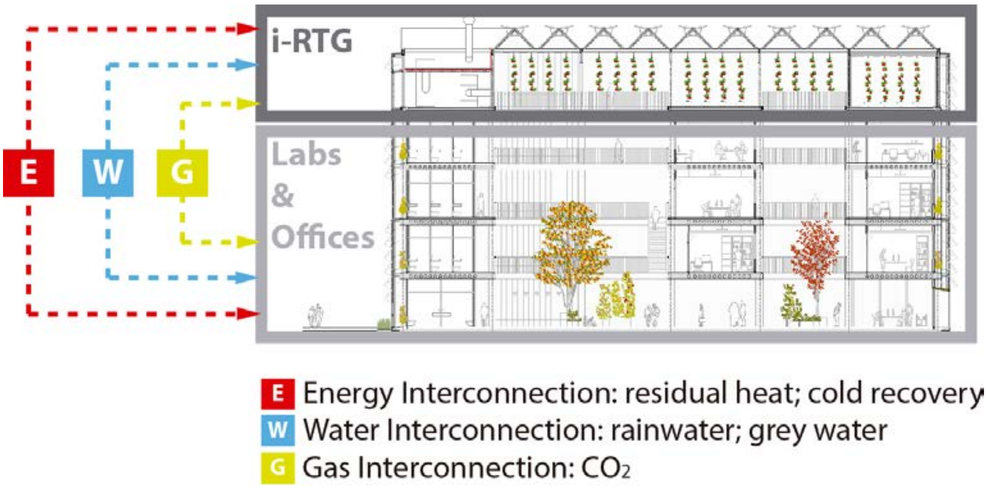
	SCENARIO D: PCM ROOT ZONE TEMEPRATURE CONTROL	
	Annual costs	**€/kg tomato**
Required infrastructure and inputs for a conventional crop in a multitunel greenhouse (EUPHOROS project)	175.154,40 €	0,46 €
PCM - RT18HC	15.917,29 €	0,04 €
LDPE tube bags	487,15 €	0,00 €
Disposal PCM (RT18HC - Rubitherm)	0,00 €	0,00 €
Disposal LDPE tube bags	0,00 €	0,00 €
Installation PCM encapsulated in LDPE tube bags	16.787,69 €	0,04 €
Maintenance PCM encapsulated in LDEP tube bags	342,70 €	0,00 €
	208.689,23 €	**0,54 €**

Appendix 2. Supporting information for chapter 6

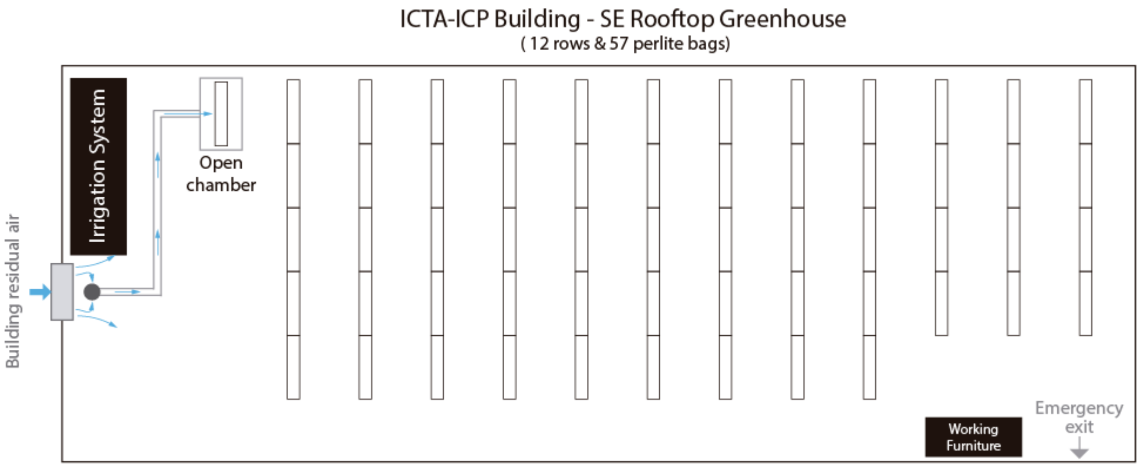
N_2O emissions from protected soil-less crops for more precise food and urban agriculture life cycle assessments

Content:

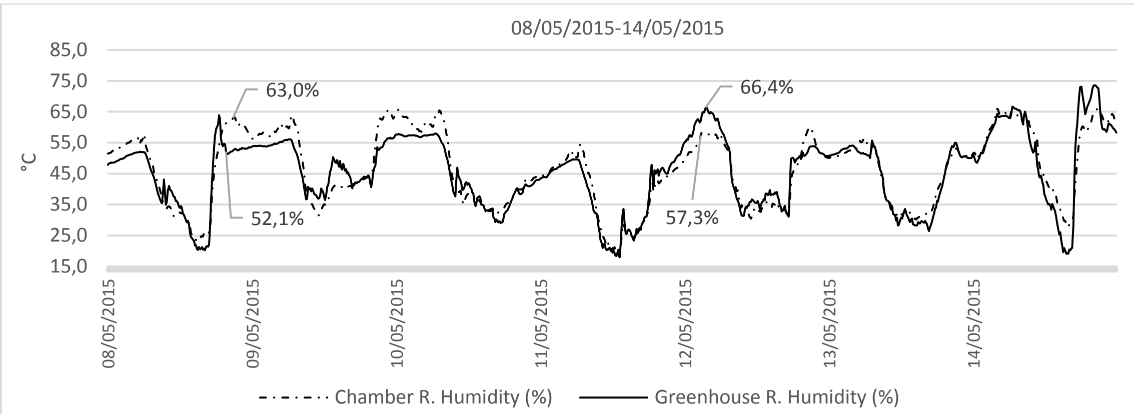
- **Supporting Information 2.1:** Exchange of flows between the new ICTA-ICP building and the i-RTG
- **Supporting Information 2.2:** Location of the open chamber used for the experiment in the ICTA-ICP building SE rooftop greenhouse
- **Supporting Information 2.3:** Relative humidity in the greenhouse and open chamber during a representative week of the experiment
- **Supporting Information 2.4:** Greenhouse and open chamber temperatures during a representative week of the experiment
- **Supporting Information 2.5:** Left: Hourly average temperatures inside the open chamber and the greenhouse during experiment 2. Right: Hourly average humidity inside the open chamber and the greenhouse during experiment 2
- **Supporting Information 2.6:** Irrigation and leachate composition for experiment 2.
- **Supporting Information 2.7:** Left: Hourly average temperatures inside the open chamber and the greenhouse during experiment 3. Right: Hourly average humidity inside the open chamber and the greenhouse during experiment 3
- **Supporting Information 2.8:** Irrigation and leachate composition for experiment 3.
- **Supporting Information 2.9:** Open chamber N_2O concentrations, humidity and temperature during experiment 3 between 21/09/2015 and 22/09/2015
- **Supporting Information 2.10:** Open chamber N_2O concentrations, humidity and temperature during experiment 3 between 09/10/2015 and 10/10/2015



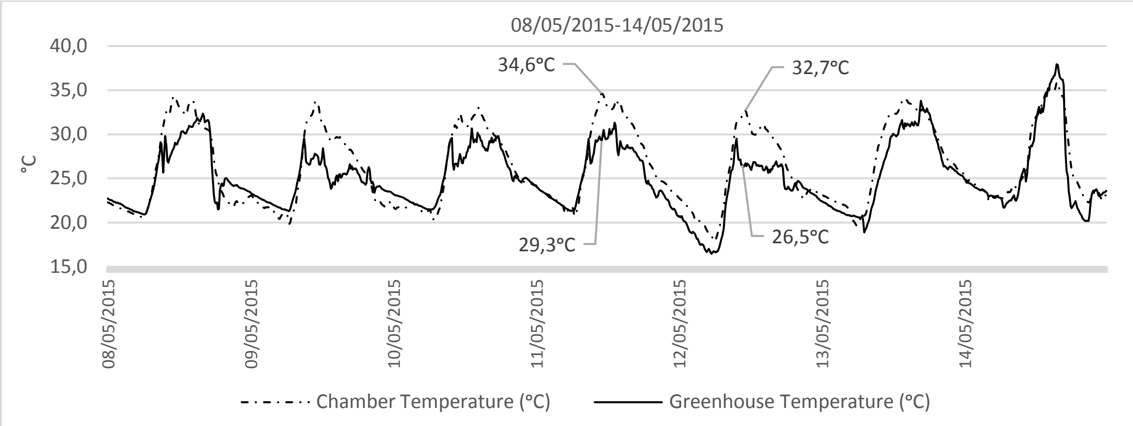
Supporting Information 2.1: Exchange of flows between the new ICTA-ICP building and the i-RTG



Supporting Information 2.2: Location of the open chamber used for the experiment in the ICTA-ICP building SE rooftop greenhouse.

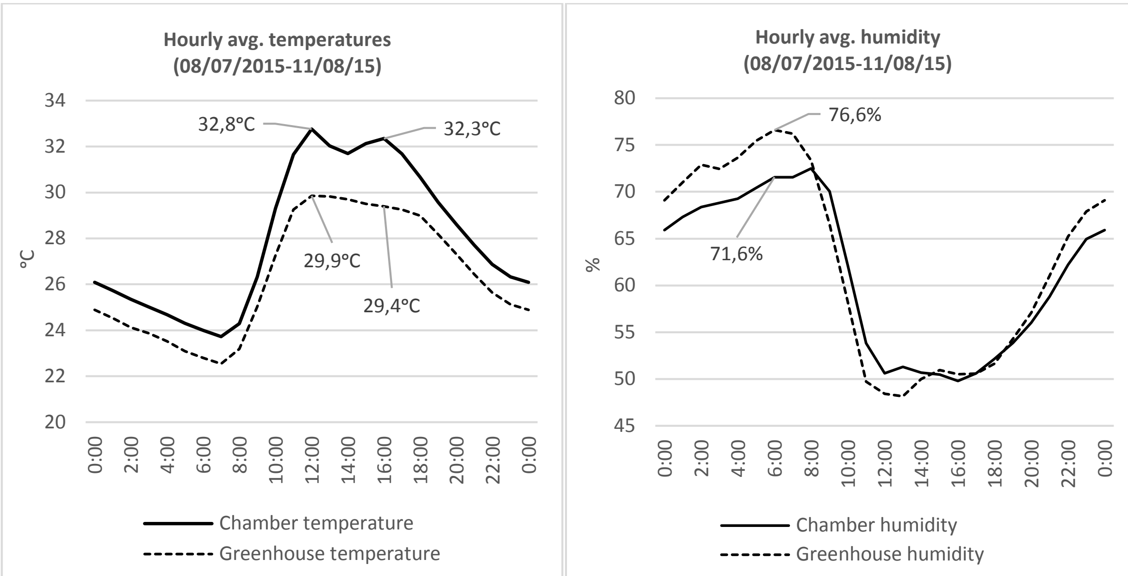


Supporting Information 2.3: Relative humidity of the greenhouse and open chamber during a representative week of the experiment



Supporting Information 2.4: Greenhouse and open chamber temperatures during a representative week of the experiment

As supporting information 2.5 shows, the average temperature of the open chamber was approximately 3°C higher than the greenhouse. Humidity in the greenhouse and the chamber were similar during the day, but during the night, the humidity was 3-5% higher in the greenhouse. Nevertheless, these values were considered low enough to ensure that the chamber was not significantly affecting the crop as the data from experiment 1 demonstrated.

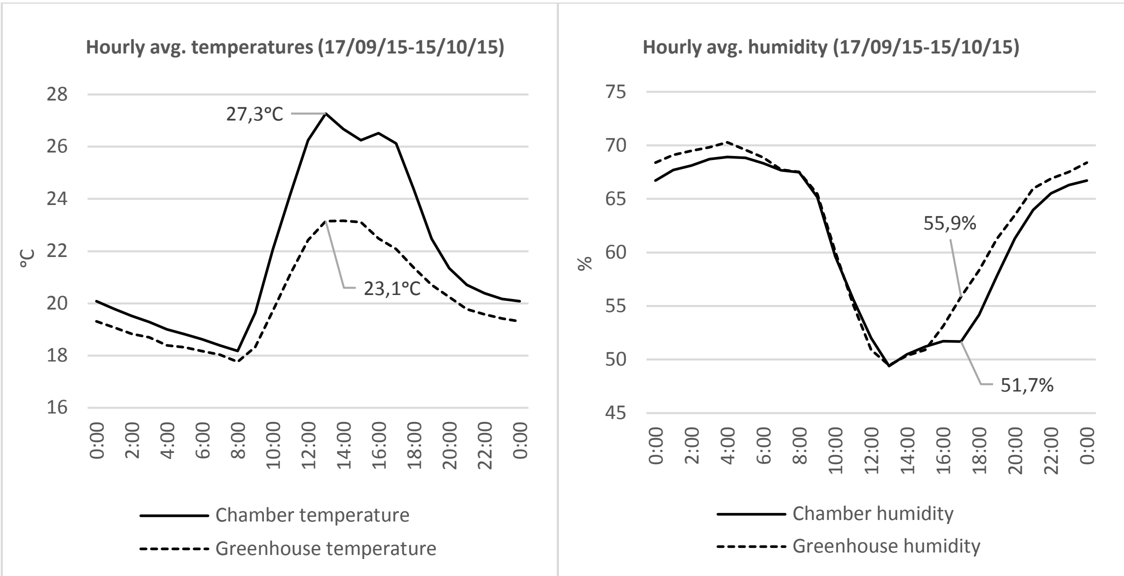


Supporting Information 2.5: Left: Hourly average temperatures inside the open chamber and the greenhouse during experiment 2. Right: Hourly average humidity inside the open chamber and the greenhouse during experiment 2

Supporting Information 2.6: Irrigation and leachate composition for experiment 2

		Total (l)	Avg. NO_2^- (mg/l)	Avg. NO_3^- (mg/l)	Total N (g)
Experiment 2 (07/07/2015-14/08/2015)	**Irrigation**	349.9	0.0	507.4	40.1
	Leachates	180.1	0.1	478.9	23.6

In supporting information 2.7., can be observed that, during the day, the average difference in temperature between the open chamber and the greenhouse was 4°C. Humidity values for this experiment were similar for both systems with lower differences than those recorded for experiment 2. In this case, growth rates for lettuces cropped inside and outside were 6.44 ± 0.38 g/day and 6.67 ± 0.39 g/day, respectively. Growth rates were lower than those measured in the 1st experiment, probably because the temperature and solar radiation in the middle of September, when the 3rd experiment was conducted, were lower than in May, when the 1st experiment was conducted.

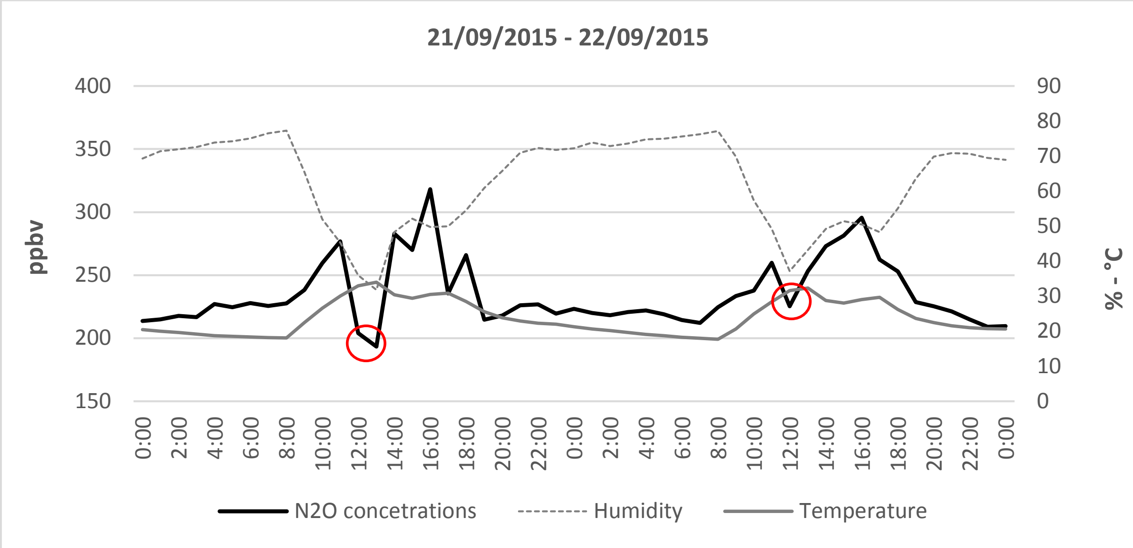


Supporting Information 2.7: Left: Hourly average temperatures inside the open chamber and the greenhouse during experiment 3. Right: Hourly average humidity inside the open chamber and the greenhouse during experiment 3.

Supporting Information 2.8: Irrigation and leachate composition for experiment 3.

		Total (l)	Avg. NO_2^- (mg/l)	Avg. NO_3^- (mg/l)	Total N (g)
Experiment 3 (17/09/2015-15/10/2015)	**Irrigation**	139.4	0.1	465.6	17.9
	Leachates	80.5	0.1	439.6	11.4

Supporting Information 2.9: Open chamber N_2O concentrations, humidity and temperature during experiment 3 between 21/09/2015 and 22/09/2015



Supporting Information 2.10: Open chamber N_2O concentrations, humidity and temperature during experiment 3 between 09/10/2015 and 10/10/2015