Universitat Autònoma de Barcelona

Environmental assessment of water supply: cities and vertical farming buildings

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Doctoral thesis

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

Sostenipra research group
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By

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«We are just and advanced breed of monkeys on a minor planet of a very average star. But we can understand the Universe. That makes us something very special»

Stephen Hawkins

The present thesis entitled *Environmental assessment of water supply: cities and vertical farming buildings* by David Sanjuan Delmás has been carried out at the Institute of Environmental Science and Technology (ICTA) at Universitat Autònoma de Barcelona (UAB)

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Joan Rieradevall Pons	Xavier Gabarrell Durany	Alejandro Josa García-Tornel

Bellaterra (Cerdanyola del Vallès), June 9, 2017

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List of acronyms and abbreviations

1.4 DB eq	1,4 dichlorobenzene equivalent emissions
ADP	Abiotic Depletion Potential
AP	Acidification Potential
CAATEEB	Col·legi d'Aparelladors, Arquitectes Tècnics i Enginyers d'Edificació de Barcelona
$CaCl_2 \cdot 2\ H_2O$	Calcium chloride dihydrate
$Ca(NO_3)_2$	Calcium nitrate
CC	Climate Change
CED	Cumulative Energy Demand
CEDEX	Centro de Estudios y Experimentación de Obras Públicas
CFC-11 eq	Trichlorofluoromethane equivalent emissions
C_2H_4 eq	Ethylene equivalent emissions
CO_2 eq	Carbon dioxide equivalent emissions
DI	Ductile Iron
DU	Declared Unit
DWTDN	Drinking Water Transport and Distribution Network
DWTP	Drinking Water Treatment Plant
EC	European Council
EC-JRC	European Comission – Joint Research Centre
EP	Eutrophication Potential
EPA US	Environmental Protection Agency's
EPD	Environmental Product Declaration
EPS	Expanded Polystyrene
ET	Ecotoxicity
FAO	Food and Agriculture Organization of the United Nations
FC	Fibre Cement
FE	Freshwater Eutrophication
FU	Functional Units
GFRP	Glass Fibre Reinforced Polyester
GHG	Greenhouse Gases
GIS	Geographical Information System
GWP	Global Warming Potential
HDPE	High Density Polyethylene
IC	Ion Chromatography
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
ICS	Ion Chromatography System
ICTA-ICP	Institute of Environmental Science and Technology-Insitute of ICTA–Catalan Institute of Palaeontology Miquel Crusafont
IDESCAT	Institut d'Estadística de Catalunya
INE	Instituto Nacional De Estadística
IRTA	Agrifood Research and Technology Institute

i-RTG	Integrated Rooftop Greenhouse
ISO	International Standard Association
ITEC	Institute of Technology of Catalonia
IWA	International Water Association
KCl	Potassium chloride
KH_2PO_4	Potassium dihydrogen phosphate
KNO_3	Potassium nitrate
KPO_4H_2	Monopotassium phosphate
K_2SO_4	Potassium sulfate
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LDPE	Low Density Polyethylene
$MgCl_2 \cdot 6\ H_2O$	Magnesium dichloride hexahydrate
$Mg(NO_3)_2$	Magnesium nitrate
MMA	Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente
N eq	Nitrate equivalent emissions
NaCl	Sodium chloride
Na_2CO_3	Sodium carbonate
$NaNO_2$	Sodium nitrite
$NaNO_3$	Sodium nitrate
Na_2SO_4	Sodium sulfate
NO^{2-}	Nitrite ion
NO^{3-}	Nitrate ion
oil eq	Oil equivalent
OLDP	Ozone layer depletion
P eq	Phosphorus equivalent emissions
PE	Polyethylene
POCP	Photochemical Oxidation Potential
PO^{4-}	Phosphate
PO_4^{3-} eq	Phosphate equivalent emissions
PVC	Poly Vinyl Chloride
PVC-O P	VC with Molecular Orientation
PVC-U	Polyvinyl Chloride Unplasticised
PWTP	Potable Water Treatment Plant
RTG	Rooftop Greenhouse
Sb eq	Antimony equivalent emissions
SO_2 eq	Sulphur dioxide equivalent emissions
SO^{4-}	Sulphate
Sostenipra	Sustainability and Environmental Prevention research group
TA	Terrestrial Acidification
UAB	Universitat Autònoma de Barcelona

UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNU-INWEH	United Nations University – Institute for Water, Environment and Health
UPC	Universitat Politècnica de Catalunya
UWC	Urban water cycle
WBCSD	World Business Council for Sustainable Development
WUE	Water Use Efficiency
WWAP	World Water Assessment Programme
WWF	World Wildlife Found

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Summary

The sustainability of water supply networks is expected to be a major issue in the near future due to the lack of access to water in specific areas, the growth of cities and the refurbishment of old networks. In this sense, analysing the environmental performance of this system is key to planning future networks—this can prevent significant environmental impacts. Moreover, water use efficiency in cities is another important issue and new urban uses for water, such as agriculture, need to be analysed. This is the case for vertical farming, which consists of the integration of agricultural systems in buildings. Although these urban food production systems can increase the demand for water in cities, they represent an opportunity to reduce the water consumption and transport related to agriculture at the regional level.

Previous research on water supply networks focus on analysing specific case studies at municipal or regional level, showing very different results. Thus, a comprehensive assessment of the system from a general perspective is required to understand which are the key factors affecting its environmental impacts. At the building scale, improving water efficiency can prevent significant environmental impacts along the urban water cycle, especially for new water uses such as vertical farming. In this context, previous studies have discussed the potential of these systems or implemented analysis based on theoretical data. However, the assessment of crops conducted in a real case study is still lacking.

This dissertation aims at contributing to understand more deeply these research fields, analysing urban areas from the city level to specific alternatives at the building level, and seeks to answer the following questions:

- **(i)** What are the main factors affecting the environmental impacts of water supply networks in cities and which improvements should be implemented? – *city scale*
- **(ii)** How effective are water-saving technologies used at the building level in urban areas? – *building scale*
- **(iii)** Are integrated rooftop greenhouses an efficient and sustainable alternative for food production in cities? – *Specific alternative*

The main study systems considered and the methodologies implemented in the dissertation are summarised in Figure 1 and are detailed below.

The construction of the water supply network was analysed using the life cycle assessment (LCA) methodology, considering different constructive solutions including the pipe, trench and the necessary appurtenances. The results showed the importance of the trench for pipe installation, especially for small pipe diameters—the trench can account for more than 40% of the impact. For larger pipe diameters, the material of the pipe has the most impact. Selecting the less impacting materials will prevent significant environmental impacts. The comparison of the different pipe materials showed that pipes made of poly vinyl chloride (PVC) or polyethylene (PE) generate the least impacts. For instance, the installation of one meter of network with a PVC pipe with 200 mm of diameter

generates 37 kg of CO_2 eq emissions, whereas the same case with a glass fibre reinforced polyester pipe generates 73 kg.

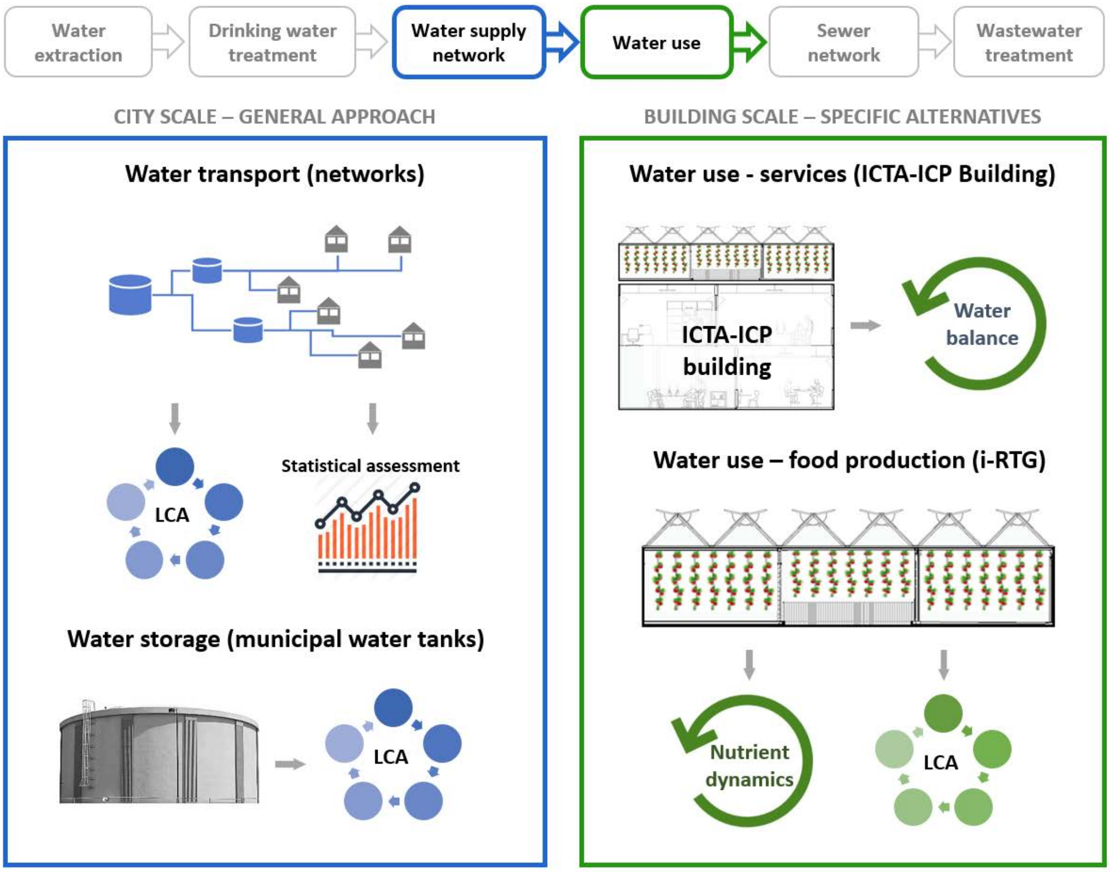

Figure X 1 Diagram of the studies conducted in the dissertation and methodologies applied.

Within the water supply network, municipal water storage tanks are essential for a proper functioning of the system. The construction of municipal water storage tanks was also assessed using the LCA methodology to optimise the dimensions of the water storage tank from an environmental perspective. The results reveal that taller water tanks are the less impactful (60 to 70% fewer impact for a 10.000 m^3 tank). Regarding the position, superficial water tanks have shown to have between 15 and 35% less impacts than buried ones. The environmentally preferred water storage capacity is between 1,000 and 2,500 m^3, being between 20 and 40% less impacting. For instance, an 8,000 m^3 tank would emit 1,040 t of CO_2 eq. Applying the environmental standards to this case 170.5 t of CO_2 eq could be saved (16% of the total amount).

The operation of the water supply network was analysed separately, implementing a statistical assessment with data from a sample of small to medium Spanish municipalities. The study provided data regarding the variables related to the environmental impacts of the operation of water supply networks. The results show that the number of inhabitants and the population density are the variables that influence more clearly the electricity consumption of networks. Moreover, small municipalities have up to 14 times higher relative electricity consumption compared with medium-sized municipalities (1.15E-2 as opposed to 8.3E-4 kWh/m^3 registered water·km of network) due to case-specific factors such as a strong gradient between a water tank and the consumption point.

The use of water in cities was analysed at the building scale, balancing the water flows of an innovative building with water-saving technologies such as rainwater harvesting and greywater reclamation. The results show that the water used for flushing toilets represents the largest demand, accounting for 90% of the total. A proposal is presented for the redesign of the system, which consists of reducing the water discharge in toilets and using rainwater directly to flush toilets (redesign of the network). This proposal has the potential to save 75% of the current external water demand of the building.

Within the ICTA-ICP building, the integrated rooftop greenhouse (i-RTG) was analysed from an agronomical and environmental perspective, using LCA. The study proves the feasibility of the system, which produced 30.2 kg/m^2 of tomato over 15.5 months of assessment (1,650 kg in total). Moreover, the symbiosis with the building was effective and between 80 and 90% of the water used in the crops was rainwater. The environmental impacts were between 50 and 75% lower than conventional production in five out of six impact categories due to the lack of packaging and transportation.

The efficiency in the use of nutrients was analysed applying the methodology of nutrient dynamics to hydroponic crops in the i-RTG. The most significant finding is that part of the nutrients are retained in the substrate (perlite), which is a factor that was usually ignored in previous studies, in particular for nitrogen (in average, 6% of the incoming nutrient), phosphorus (7%) and calcium (5%). The study provided interesting and new insights on the functioning of hydroponic crops.

This dissertation contributes to understand the main factors influencing the impacts of water supply networks and provides useful tools for the environmental analysis of these systems. The results can be used by urban planners and network managers to planning sustainable networks. Moreover, the experimental research conducted in innovative buildings with water-saving technologies and vertical farming proves the feasibility of these advanced systems and highlights the importance of optimising the use of resources. Future research on the fields assessed might focus on the following areas:

- Evaluating the ecoefficiency of the construction of water supply networks.
- Implementing further statistical studies of the operation of water supply networks.
- To implement the water-energy-food nexus to develop new urban systems that integrate food production and water use efficiency issues.
- Exploring the full potential of i-RTGs and analyse the system growing different crops.

Resumen

Se espera que la sostenibilidad de las redes de suministro de agua sea un tema importante en un futuro próximo debido a la falta de acceso al agua en áreas específicas, al crecimiento de las ciudades y a la renovación de viejas redes. En este sentido, analizar a nivel ambiental este sistema es clave para planificar futuras redes, lo cual puede prevenir impactos ambientales significativos. Además, la eficiencia en el uso del agua en las ciudades es otra cuestión importante y es necesario analizar los nuevos usos urbanos del agua, como la agricultura. Este es el caso de la agricultura vertical, que consiste en la integración de sistemas agrícolas en edificios. Aunque estos sistemas de producción de alimentos urbanos pueden aumentar la demanda de agua en las ciudades, representan una oportunidad para reducir el consumo y el transporte de agua relacionados con la agricultura a nivel regional.

Investigaciones previas sobre redes de abastecimiento de agua se centran en analizar estudios de casos específicos a nivel municipal o regional, mostrando resultados muy diferentes. Por lo tanto, se requiere una evaluación integral del sistema desde una perspectiva general para entender cuáles son los factores clave que afectan a los impactos ambientales de las redes. A escala edificio, la mejora de la eficiencia en el uso del agua puede prevenir impactos ambientales significativos a lo largo del ciclo urbano del agua, especialmente para nuevos usos del agua como la agricultura vertical. En este contexto, estudios anteriores han discutido el potencial de estos sistemas o implementado análisis basados en datos teóricos. Sin embargo, todavía falta una evaluación de cultivos realizados en un caso de estudio real.

Esta tesis tiene como objetivo profundizar en estas áreas de conocimiento analizando el sistema urbano desde la escala ciudad a alternativas locales específicas y busca responder a las siguientes preguntas:

- **(i)** ¿Cuáles son los principales factores que afectan a los impactos ambientales de las redes de abastecimiento de agua en las ciudades y qué mejoras deben implementarse? - *Escala ciudad*
- **(ii)** ¿Cómo de eficaces son las tecnologías para el ahorro del agua utilizadas a nivel de edificios en las zonas urbanas? - *Escala edificio*
- **(iii)** ¿Los invernaderos integrados en cubierta son una alternativa eficiente y sostenible para la producción de alimentos en las ciudades? – *Alternativa específica*

Los principales sistemas de estudio considerados y las metodologías implementadas en la disertación se resumen en la Figura 1 y se detallan a continuación.

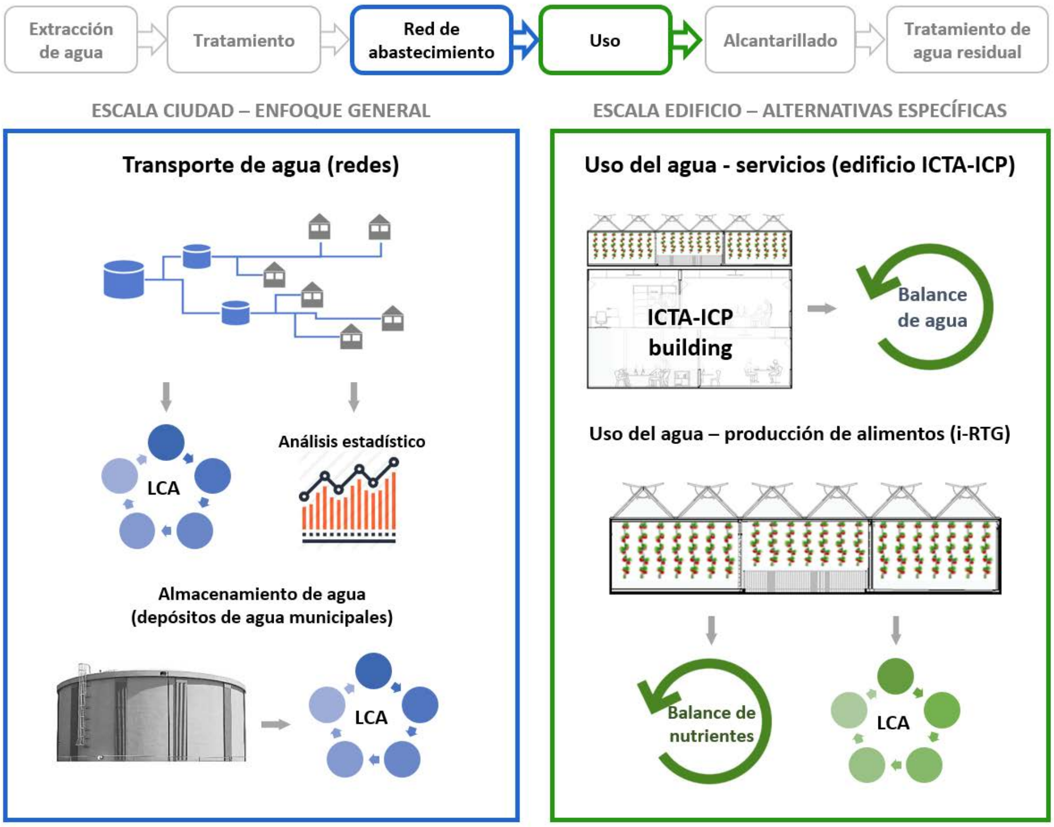

Figure X 2 Diagrama de los estudios realizados en la disertación i metodologias aplicadas.

La construcción de la red de abastecimiento de agua se analizó utilizando la metodología de análisis del ciclo de vida (ACV), considerando diferentes soluciones constructivas incluyendo la tubería, la zanja y los complementos necesarios. Los resultados mostraron la importancia de la zanja para la instalación de tuberías, especialmente para pequeños diámetros de tubería, en los que la zanja puede representar más del 40% del impacto. Para diámetros de tubería más grandes, el material de la tubería tiene mayor impacto. De este modo, seleccionar los materiales menos impactantes puede evitar impactos ambientales significativos. La comparación de diferentes materiales de tuberías mostró que las tuberías de cloruro de polivinilo (PVC) y polietileno (PE) son las que generan menores impactos. Por ejemplo, la instalación de un metro de red con una tubería de PVC de 200 mm de diámetro genera 37 kg de emisiones de CO_2 eq, mientras que el mismo caso con un tubo de poliéster reforzado con fibra de vidrio genera 73 kg.

En el marco de la red de abastecimiento de agua, los depósitos municipales de almacenamiento de agua son esenciales para el buen funcionamiento del sistema. La construcción de depósitos municipales de almacenamiento de agua también fue evaluada utilizando la metodología de ACV para optimizar las dimensiones del depósito desde una perspectiva ambiental. Los resultados revelan que los depósitos más altos son menos impactantes (entres un 60 y un 70% menos de impacto que uno de 10,000 m^3). En cuanto a la posición, los depósitos superficiales han demostrado tener entre un 15 y un 35% menos impactos que los enterrados. La capacidad de almacenamiento de agua preferible a nivel ambiental es de entre 1,000 y 2,500 m^3, siendo entre un 20 y un 40% menos impactante. Por ejemplo, la construcción de un tanque de 8,000 m^3 generará 1,040 t de CO_2 eq. Aplicando las normas medioambientales recomendadas a este caso se podrían ahorrar 170,5 t de CO_2 eq (16% del total).

La fase de uso de la red de abastecimiento de agua se analizó por separado, incluyendo una evaluación estadística con datos de una muestra de pequeños y medianos municipios españoles. El estudio proporcionó datos sobre las variables relacionadas con los impactos ambientales de la operación de las redes de abastecimiento de agua. Los resultados muestran que el número de habitantes y la densidad de población son las variables que influyen más claramente en el consumo de electricidad de las redes. Además, los municipios pequeños tienen un consumo relativo de electricidad hasta 14 veces superior al de los municipios medianos (1.15E-2 frente a 8.3E-4 kWh / m^3 de agua registrada · km de red) debido a factores específicos de cada caso, como una fuerte pendiente entre un depósito de agua y el punto de consumo.

El uso del agua en las ciudades se analizó a escala edificio, realizando un balance de los flujos en un edificio innovador con tecnologías para el ahorro del agua como el uso de aguas pluviales y la reutilización de aguas grises. Los resultados muestran que el agua utilizada para las descargas en los baños es la mayor demanda, representando el 90% del total de agua consumida. Se presenta una propuesta para el rediseño del sistema que consiste en reducir el volumen por descarga de agua en los baños y utilizar el agua de lluvia directamente para las descargas (rediseño de la red). Esta propuesta tiene el potencial de ahorrar el 75% de la demanda externa de agua actual en el edificio.

En el contexto del edificio ICTA-ICP, el invernadero integrado en cubierta (i-RTG) fue analizado desde una perspectiva agronómica y ambiental, utilizando el ACV. El estudio demuestra la viabilidad del sistema, que produjo 30.2 kg/m^2 de tomate durante 15.5 meses de evaluación (1,650 kg en total). Además, la simbiosis con el edificio fue eficaz y entre el 80 y el 90% del agua utilizada en los cultivos fue agua de lluvia. Los impactos ambientales fueron entre un 50 y un 75% inferiores a la producción convencional en cinco de seis categorías ambientales debido a la ausencia de envase y transporte.

La eficiencia en el uso de nutrientes se analizó aplicando la metodología de dinámica de nutrientes a cultivos hidropónicos en el invernadero. El hallazgo más significativo es que parte de los nutrientes son retenidos en el sustrato (perlita) durante el cultivo, un factor que ha sido por lo general ignorado en estudios previos. En particular, un 6% del nitrógeno es retenido en promedio, un 7% del fósforo y un 5% del calcio. El estudio proporcionó información interesante sobre el funcionamiento de los cultivos hidropónicos.

Esta tesis contribuye a un major entendimiento de los principales factores que influyen en los impactos de las redes de abastecimiento de agua y aporta herramientas útiles para el análisis ambiental de estos sistemas. Los planificadores urbanos y los administradores de redes pueden utilizar los resultados para planificar redes sostenibles. Además, la investigación experimental realizada en edificios innovadores con tecnologías de ahorro de agua y agricultura vertical demuestra la viabilidad de estos sistemas avanzados y destaca la importancia de optimizar el uso de los recursos. Investigaciones futuras en estas áreas de conocimiento podrían centrarse en los siguientes temas:

- Evaluar la ecoeficiencia de la construcción de redes de abastecimiento de agua.
- Implementación de estudios estadísticos adicionales sobre el funcionamiento de las redes de abastecimiento de agua.
- Desarrollar nuevos sistemas urbanos que implementen el nexo agua-energía-alimento para integrar la producción de alimentos y los problemas de eficiencia en el uso del agua.
- Explorar todo el potencial de los i-RTGs y analizar el sistema que cultiva diferentes cultivos.

Resum

S'espera que la sostenibilitat de les xarxes de subministrament d'aigua sigui un tema important en un futur pròxim a causa de la falta d'accés a l'aigua en àrees específiques, al creixement de les ciutats i a la renovació de xarxes velles. En aquest sentit, analitzar a nivell ambiental aquest sistema és clau per planificar futures xarxes, la qual cosa pot prevenir impactes ambientals significatius. A més, l'eficiència en l'ús de l'aigua a les ciutats és una altra qüestió important i cal analitzar els nous usos urbans de l'aigua, com l'agricultura. Aquest és el cas de l'agricultura vertical, que consisteix en la integració de sistemes agrícoles en edificis. Tot i que aquests sistemes de producció d'aliments urbans poden augmentar la demanda d'aigua a les ciutats, representen una oportunitat per reduir el consum i el transport d'aigua relacionats amb l'agricultura a nivell regional.

Investigacions prèvies sobre xarxes d'abastament d'aigua es centren en analitzar estudis de casos específics a nivell municipal o regional, mostrant resultats molt diferents. Per tant, es requereix una avaluació integral del sistema des d'una perspectiva general per entendre quins són els factors clau que afecten els impactes ambientals de les xarxes. A escala edifici, la millora de l'eficiència en l'ús de l'aigua pot prevenir impactes ambientals significatius al llarg del cicle urbà de l'aigua, especialment per a nous usos de l'aigua com l'agricultura vertical. En aquest context, estudis anteriors han discutit el potencial d'aquests sistemes o implementat anàlisis basades en dades teòriques. No obstant això, encara falta manca avaluar cultius realitzats en un casos d'estudi reals.

Aquesta tesi té com a objectiu aprofundir en aquestes àrees de coneixement analitzant el sistema urbà des de l'escala ciutat a alternatives locals específiques i busca respondre a les següents preguntes:

- **(i)** Quins són els principals factors que afecten els impactes ambientals de les xarxes d'abastament d'aigua a les ciutats i quines millores s'han d'implementar? - *Escala ciutat*
- **(ii)** Com d'eficaces són les tecnologies per a l'estalvi de l'aigua utilitzades a nivell d'edifici en les zones urbanes? - *Escala edifici*
- **(iii)** Els hivernacles integrats en coberta són una alternativa eficient i sostenible per a la producció d'aliments a les ciutats? - *Alternativa específica*

Els principals sistemes d'estudi considerats i les metodologies implementades en la dissertació es resumeixen a la Figura 1 i es detallen a continuació.

La construcció de la xarxa de proveïment d'aigua es va analitzar utilitzant la metodologia de l'anàlisi del cicle de vida (ACV), considerant diferents solucions constructives incloent la canonada, la rasa i els complements necessaris. Els resultats van mostrar la importància de la rasa per a la instal·lació de canonades, especialment per a petits diàmetres de canonada, en els quals la rasa pot representar més del 40% de l'impacte. Per a diàmetres de canonada més grans, el material de la canonada té major impacte. D'aquesta manera, seleccionar els materials menys impactants pot evitar impactes ambientals significatius. La comparació de diferents materials de canonades va mostrar que les canonades de

clorur de polivinil (PVC) i polietilè (PE) són les que generen menors impactes. Per exemple, la instal·lació d'un metre de xarxa amb una canonada de PVC de 200 mm de diàmetre genera 37 kg d'emissions de CO_2 eq, mentre que el mateix cas amb un tub de polièster reforçat amb fibra de vidre genera 73 kg.

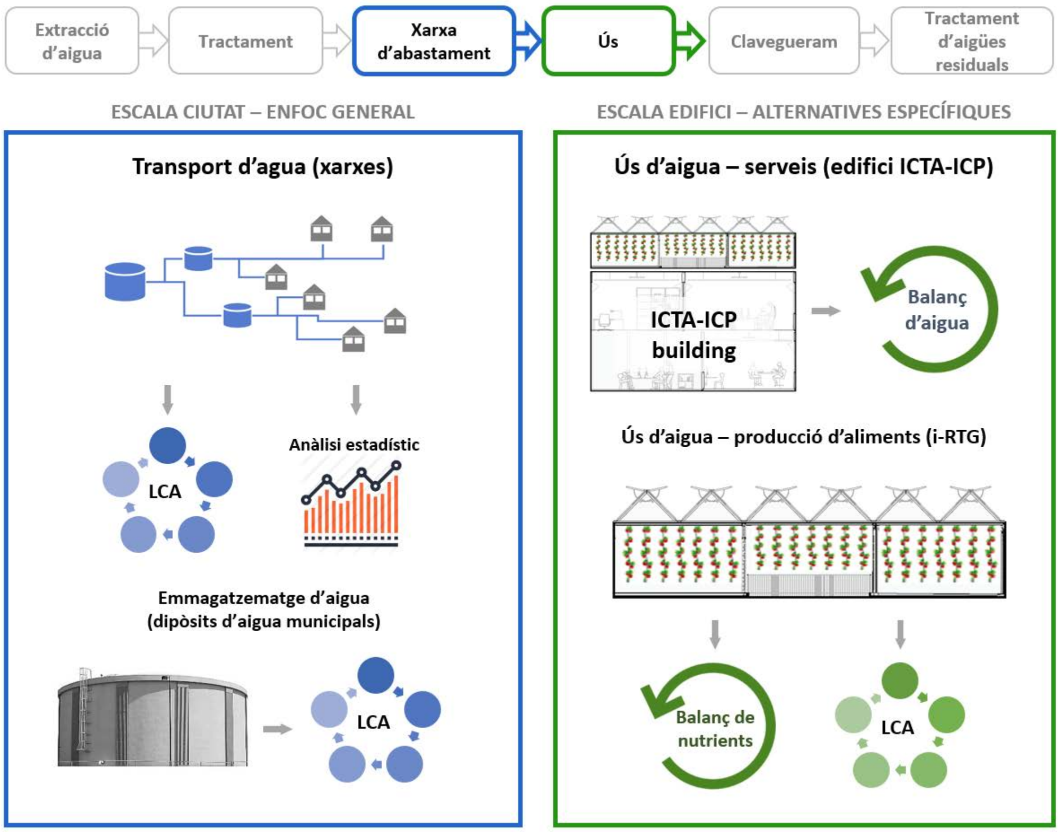

Figure X 3 Diagrama dels estudis realizats en la dissertació i metodologies aplicades.

En el marc de la xarxa de proveïment d'aigua, els dipòsits municipals d'emmagatzematge d'aigua són essencials per al bon funcionament del sistema. La construcció de dipòsits municipals d'emmagatzematge d'aigua també va ser avaluada utilitzant la metodologia d'ACV per optimitzar les dimensions del dipòsit des d'una perspectiva ambiental. Els resultats revelen que els dipòsits més alts són menys impactants (entre un 60 i un 70% menys d'impacte que un de 10,000 m^3). Pel que fa a la posició, els dipòsits superficials han demostrat tenir entre un 15 i un 35% menys impactes que els enterrats. La capacitat d'emmagatzematge d'aigua preferible a nivell ambiental és d'entre 1,000 i 2,500 m^3, sent entre un 20 i un 40% menys impactant. Per exemple, la construcció d'un tanc de 8,000 m^3 generarà 1,040 t de CO_2 eq. Aplicar les normes mediambientals recomanades a aquest cas podria estalviar 170,5 t de CO_2 eq (16% del total).

La fase d'ús de la xarxa de proveïment d'aigua es va analitzar per separat, incloent una avaluació estadística amb dades d'una mostra de petits i mitjans municipis espanyols. L'estudi va proporcionar dades sobre les variables relacionades amb els impactes ambientals de l'operació de les xarxes d'abastament d'aigua. Els resultats mostren que el nombre d'habitants i la densitat de població són les variables que influeixen més clarament en el consum d'electricitat de les xarxes. A més, els municipis petits tenen un consum relatiu d'electricitat fins a 14 vegades superior al dels municipis mitjans (1.15E-2 contra 8.3E-4 kWh / m^3 d'aigua registrada · km de xarxa) a causa de factors específics de cada cas, com una forta pendent entre un dipòsit d'aigua i el punt de consum.

L'ús de l'aigua a les ciutats es va analitzar a escala edifici, realitzant un balanç dels fluxos en un edifici innovador amb tecnologies per a l'estalvi de l'aigua com l'ús d'aigües pluvials i la reutilització d'aigües grises. Els resultats mostren que l'aigua utilitzada per a les descàrregues als lavabos és la major demanda, representant el 90% del total d'aigua consumida. Es presenta una proposta per al redisseny del sistema que consisteix a reduir el volum d'aigua per descàrrega als lavabos i utilitzar l'aigua de pluja directament per a les descàrregues (redisseny de la xarxa). Aquesta proposta té el potencial d'estalviar el 75% de la demanda externa d'aigua actual a l'edifici.

En el context de l'edifici ICTA-ICP, l'hivernacle integrat en coberta (i-RTG) va ser analitzat des d'una perspectiva agronòmica i ambiental, utilitzant l'ACV. L'estudi demostra la viabilitat del sistema, que va produir 30.2 kg/m^2 de tomàquet durant els 15.5 mesos d'avaluació (1,650 kg en total). A més, la simbiosi amb l'edifici va ser eficaç i entre el 80 i el 90% de l'aigua utilitzada en els cultius va ser aigua de pluja. Els impactes ambientals van ser entre un 50 i un 75% inferiors a la producció convencional en cinc de sis categories ambientals com a conseqüència de l'absència d'envàs i transport.

L'eficiència en l'ús de nutrients es va analitzar aplicant la metodologia de dinàmica de nutrients a cultius hidropònics a l'hivernacle. La troballa més significativa és que part dels nutrients són retinguts en el substrat (perlita) durant el cultiu, un factor que ha estat en general ignorat en estudis previs. En particular, un 6% del nitrogen és retingut de mitjana, un 7% del fòsfor i un 5% del calci. L'estudi va proporcionar informació interessant sobre el funcionament dels cultius hidropònics.

Aquesta tesi contribueix a un major enteniment dels principals factors que influeixen en els impactes de les xarxes d'abastament d'aigua i aporta eines útils per a l'anàlisi ambiental d'aquests sistemes. Els planificadors urbans i els gestors de xarxes poden utilitzar els resultats per planificar xarxes sostenibles. A més, la investigació experimental realitzada en edificis innovadors amb tecnologies d'estalvi d'aigua i agricultura vertical demostra la viabilitat d'aquests sistemes avançats i destaca la importància d'optimitzar l'ús dels recursos. Investigacions futures en aquestes àrees de coneixement podrien centrar-se en els següents temes:

- Avaluar l'ecoeficiència de la construcció de xarxes d'abastament d'aigua.
- Implementació d'estudis estadístics addicionals sobre el funcionament de les xarxes d'abastament d'aigua.
- Desenvolupar nous sistemes urbans que implementin el nexe aigua-energia-aliments per integrar la producció d'aliments i els problemes d'eficiència en l'ús de l'aigua.
- Explorar tot el potencial dels i-RTGs i analitzar el sistema que conrea diferents cultius.

Presentation of the dissertation

The present doctoral thesis was developed in compliance with the PhD program in Environmental Science and Technology of the Universitat Autònoma de Barcelona. Its development took place within the Sostenipra research group (2014 SGR 1412) at the Institute of Environmental Science and Technology (ICTA) in the Universitat Autònoma de Barcelona, from October 2013 to March 2017, including teaching assistance at the Department of Chemical, Biological and Environmental Engineering. In addition, the Universitat Politècnica de Catalunya (UPC) was involved through the supervision of the thesis by professor Alejandro Josa and the collaboration in the studies conducted. The thesis was supported by a pre-doctoral fellowship awarded by the Generalitat de Catalunya (FI-DGR 2014) from March 2014 to February 2017. Moreover, the research was conducted in a "María de Maeztu" Unit of Excellence in R&D (MDM-2015-0552), thanks to the support of the Spanish Ministry of Economy and Competitiveness.

This dissertation analyses water supply networks at the city scale and vertical farming systems in water-efficient buildings from a multidisciplinary approach. In respect of the water supply networks, the novelty of the dissertation relies on the general approach adopted for the assessment. This approach allowed obtaining comprehensive results about the factors influencing the environmental impacts of water supply networks and providing useful data regarding their management. Moreover, in the field of vertical farming, the dissertation presents a pilot system for food production made up of a rooftop greenhouse integrated with the building in terms of water, air, energy and food.

Previous studies in the Sostenipra research group addressed the sustainability of rainwater and greywater utilisation in the framework of the PLUVISOST national project (PLUVISOST.CTM2010-17365). The results of this research were the background of the present thesis, which started from these results and took advantage of the expertise in the group.

The research on water supply networks presented in this doctoral thesis was developed in the framework of the AQUAENVEC project "Assessment and improvement of the urban water cycle eco-efficiency use LCA and LCC" funded by the European LIFE+ programme (LIFE10 ENV/ES/000520). The project was coordinated by Cetaqua (Water Technology Center), with the participation of the Universitat Autònoma de Barcelona (UAB), the Universidade de Santiago de Compostela (USC) and the Universitat Politècnica de València (UPV), with the collaboration of the Universitat Politècnica de Catalunya (UPC). The main result of this project was the Aquaenvec tool (http://tool.life-aquaenvec.eu/en), an open online application for the calculation of the environmental impacts of the urban water cycle. The section of the tool for the assessment of water supply networks was developed in this thesis, and the student contributed to elaborate the databases for the tool. Moreover, the analysis of sewer networks in the project was conducted by the fellow PhD student Anna Petit, which allowed the student to have a complete vision of the urban water cycle.

The assessment of water efficiency in buildings and Vertical Farming was developed in the framework of the Fertilecity project "Agrourban sustainability through rooftop greenhouses. Ecoinnovation on residual flows of energy, water and CO_2 for food production" (CTM2013-47067-C2-1-R) and the Fertilecity II project "Invernaderos integrados en azoteas: simbiosis de energía, agua y emisiones de CO_2 con el edificio - Hacia la seguridad alimentaria urbana en una economía circular" (CTM2016-75772-C3-1-2-3-R) both funded by the Spanish Ministerio de Economía y Competitividad (MINECO). These projects are coordinated by the Institute of Environmental Science and Technology (ICTA), with the participation of the Universitat Politècnica de Catalunya (UPC) and the Institute of Agriculture and Food Research and Technology (IRTA).

Figure 1 illustrates the structure of the dissertation, which is composed of four parts, each made up of a group of chapters addressing specific issues related with the topic of the dissertation.

Part I. Introduction, objectives and methodological framework

[Chapter 1]

Introduction and objectives

[Chapter 2]

Methodological framework

Part II. Environmental assessment of urban water supply networks

[Chapter 3]

Environmental assessment of different pipelines for drinking water transport and distribution network in small to medium cities: a case from Betanzos, Spain

[Chapter 4]

Environmental assessment of drinking water transport and distribution network use phase for small to medium-sized municipalities in Spain

[Chapter 5]

Environmental and geometric optimization of cylindrical drinking water storage tanks

Part III. Water flows and vertical farming in buildings

[Chapter 6]

Analysing water use efficiency in a building with rainwater harvesting and greywater reclamation in a Mediterranean climate

[Chapter 7]

Applying the nutrient dynamics methodology to close the nutrient and water balance in hydroponic crops

[Chapter 8]

Water, energy, CO_2 and food symbiosis between crops and buildings. Environmental assessment of an integrated rooftop greenhouse

Part IV. Final remarks and future research

[Chapter 9]

General discussion and main contributions

[Chapter 10]

General conclusions

[Chapter 11]

Future research lines

Figure X 4 Structure of the dissertation.

Part I. Introduction, objectives and methodological framework

Part I has two chapters. **Chapter 1** [*Introduction and objectives*] outlines the general background of the thesis, explaining basic information and previous literature regarding water supply networks and vertical farming systems. It also includes the motivations of the dissertation, as well as the definition of the research questions and the objectives. **Chapter 2** [*Methodological framework*] describes the materials and methods used in the dissertation, explaining with further detail the elements that could not be developed in the chapters.

Part II. Environmental assessment of urban water supply networks

Part II includes the environmental analysis of urban water supply networks. **Chapter 3** [*Environmental assessment of different pipelines for drinking water transport and distribution network in small to medium cities: a case from Betanzos, Spain*] assesses the installation of the network using the life cycle assessment (LCA) methodology. **Chapter 4** [*Environmental assessment of drinking water transport and distribution network use phase for small to medium-sized municipalities in Spain*] focuses on the assessment of the use phase of water supply networks, conducting a statistical analysis of data from a representative sample of Spanish municipalities. **Chapter 5** [*Environmental and geometric optimisation of cylindrical drinking water storage tanks*] analyses the installation of water storage tanks, a specific element of the water supply network, using the LCA methodology.

Part III. Water flows and vertical farming in buildings

Part III addresses the assessment of water flows at building scale and the implementation of vertical farming systems. **Chapter 6** [*Analysing the nutrient and water dynamics in hydroponic crops: closing the research gap*] analyses the water flows in the ICTA-ICP building, which includes water-saving elements such as rainwater harvesting and greywater reclamation. **Chapter 7** [*Analysing water use efficiency in a building with rainwater harvesting and greywater reclamation in a Mediterranean climate*] implements the nutrient budget methodology to study the flows of water and nutrients in an integrated rooftop greenhouse (i-RTG) located in the ICTA-ICP building. **Chapter 8** [*Water, energy, CO_2 and food symbiosis between crops and buildings. Environmental assessment of an integrated rooftop greenhouse*] conducts an environmental assessment of tomato production in the i-RTG using the LCA methodology, comparing the environmental performance of the system with conventional tomato production.

Part IV. Final remarks and future research

Part IV includes three chapters. The final discussion of the dissertation is explained in **Chapter 9** [*Discussion of the main contributions*]. **Chapter 10** [*General conclusions*] answers the research questions stated at the beginning of the dissertation, including the main conclusions reached along the research conducted. Finally, **Chapter 11** [*Future research*] states potential research lines that future studies might cover.

Dissemination and training

The dissertation is based on the following articles either published or under review in peer-reviewed indexed journals:

- **Sanjuan-Delmás, D.,** Petit-Boix, A., Gasol, C. M., Villalba, G., Suárez-Ojeda, M. E., Gabarrell, X., Josa, A., Rieradevall, J. (2014). Environmental assessment of different pipelines for drinking water transport and distribution network in small to medium cities: a case from Betanzos, Spain. Journal of Cleaner Production. Journal of Cleaner Production 66:588–598. doi: 10.1016/j.jclepro.2013.10.055

- **Sanjuan-Delmás, D.,** Petit-Boix, A., Gasol, C. M., Farreny, R., Villalba, G., Suárez-Ojeda, M. E., Gabarrell, X., Josa, A., Rieradevall, J. (2015). Environmental assessment of drinking water transport and distribution network use phase for small to medium-sized municipalities in Spain. Journal of Cleaner Production 87:573–582. doi: 10.1016/j.jclepro.2014.09.042

- **Sanjuan-Delmás, D.,** Hernando-Canovas, E., Pujadas, P., de la Fuente, A., Gabarrell, X., Rieradevall, J., Josa, A. (2015). Environmental and geometric optimisation of cylindrical drinking water storage tanks. The International Journal of Life Cycle Assessment, 20:1612–1624. doi: 10.1007/s11367-015-0963-y

- **Sanjuan-Delmás, D.,** Josa, A., Muñoz, P., Rieradevall, J., Gabarrell, X. (2017). Analysing the nutrient and water dynamics in hydroponic crops: closing the research gap. – Submited to Agricultural Water Management

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

Moreover, preliminary results were presented as poster and oral communications in international congresses and conferences:

Water supply networks

- **Sanjuan-Delmás, D.,** Petit-Boix, A., Gasol, C. M., Villalba, G., Suárez-Ojeda, M. E., Gabarrell, X., Josa, A., Rieradevall, J. (2014). LCA of PVC and HDPE pipes for drinking water distribution networks in cities. Poster. IWA World Water Congress & Exibition. September 2014, Lisbon (Portugal).

- Petit-Boix, A., **Sanjuan-Delmás, D.,** Arnal, C., Marín, D., Amores, M. J., Rieradevall, J., Josa, A., Gabarrell, X. (2015). Eco-efficiency assessment of water supply and sewer networks using LCA and LCC. Oral presentation. SETAC Europe 25th Annual Meeting. May 2015, Barcelona (Spain).

- **Sanjuan-Delmás, D.,** Arnal, C., Petit-Boix, A., Marín, D., Gabarrell, X., Josa, A., Rieradevall, J. (2015). Comparison of HDPE and ductile iron pipes for drinking water supply networks in future smart cities through LCA and LCC.

Poster. CILCA 2015. VI Conferencia Internacional de Análisis de Ciclo de Vida en Latinoamérica. July 2015, Lima (Perú).

- **Sanjuan-Delmás, D.,** Petit-Boix, A., Marín, D., Gabarrell, X., Josa, A., Rieradevall, J. (2015). Environmental assessment of drinking water supply and sewer networks for small to medium cities. Poster. LCM 2015. Mainstreaming Life Cycle Management for sustainable value creation. September-October 2015, Bordeaux (France).

- **Sanjuan-Delmás, D.,** Arnal, C., Petit-Boix, A., Marín, D., Gabarrell, X., Josa, A., Rieradevall, J. (2015). Ecoefficiency assessment of the drinking water distribution network of Calafell (Spain). Poster. GCPC 2015. Global Cleaner Production and Sustainable Consumption Conference 2015. November 2015, Sitges (Spain).

- **Sanjuan-Delmás, D.,** Petit-Boix, A., Marín, D., Josa, A., Rieradevall, J., Gabarrell, X. (2016). Drinking water and sewer networks in Spanish medium-sized cities: an environmental assessment from an industrial ecology perspective. Oral presentation. ISIE Americas 2016 Meeting. May 2016, Bogotá (Colombia).

Water efficiency in buildings and vertical farming

- **Sanjuan-Delmás, D.,** Sanyé-Mengual, E., Montero, J. I., Gabarrell, X., Alejandro Josa, Rieradevall, J. (2014). Application of rainwater harvesting to rooftop greenhouse, a case study from Barcelona. Poster. International Conference on Vertical Farming and Urban Agriculture 2014. September 2014, The University of Nottingham (United Kingdom).

- **Sanjuan-Delmás, D.,** Muñoz, P., Gabarrell, X., Josa, A., Rieradevall, J. (2015). Environmental assessment of adapting the nutritious solution for rainwater use in the irrigation of hydroponic crops. Poster. LCM 2015. Mainstreaming Life Cycle Management for sustainable value creation. September-October 2015, Bordeaux (France).

- **Sanjuan-Delmás, D.,** Josa, A., Rieradevall, J., Gabarrell, X. (2015). Rainwater harvesting and integration of water flows for reducing water consumption in buildings: a real case study from Barcelona. Poster. GCPC 2015. Global Cleaner Production and Sustainable Consumption Conference 2015. November 2015, Sitges (Spain).

- **Sanjuan-Delmás, D.,** Llorach-Masana, P., Sanyé-Mengual, E., Josa, A., Montero, J. I., Rieradevall, J., Gabarrell, X., Ercilla-Montserrat, M., Nadal, A., Muñoz, P., Rovira, M. R., Cuerva, E., Pons, O. (2016). The FertileCityProject: improving local food production in cities from an industrial ecology approach. Oral presentation. ISIE Americas 2016. May 2016, Bogotá (Colombia).

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

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

In addition, during the development of the dissertation the opportunity was given to work in other studies, which are related with the goals of the dissertation:

Participation in articles and book chapters

- **Sanjuan-Delmàs, D.,** Llorach-Massana, P., Nadal, A., Sanyé-Mengual, E., Petit-Boix, A., Ercilla-Montserrat, M., Cuerva, E., Rovira, M. R., Josa, A., Muñoz, P., Montero, J. I., Gabarrell, X., Rieradevall, J., Pons, O. (2017). Improving the metabolism and sustainability of buildings and cities through integrated rooftop greenhouses (i-RTG). In: Urban Horticulture: Sustainability for the Future. – Pending to be published.

- Petit-Boix, A., **Sanjuan-Delmás, D.,** Gasol, C. M., Villalba, G., Suárez-Ojeda, M. E., Gabarrell, X., Josa, A., Rieradevall, J. (2014). Environmental Assessment of Sewer Construction in Small to Medium Sized Cities Using Life Cycle Assessment. Water Resources Management 28, 979–997. doi: 10.1007/s11269-014-0528-z

- Petit-Boix, A., **Sanjuan-Delmás, D.,** Gasol, C. M., Farreny, R., Villalba, G., Suárez-Ojeda, M. E., Gabarrell, X., Josa, A., Rieradevall, J. (2015). Assessing the energetic and environmental impacts of the operation and maintenance of Spanish sewer networks from a life-cycle perspective. Water resources management 29, 2581-2597. doi: 10.1007/s11269-015-0958-2

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- Petit-Boix, A., Sanyé-Mengual, E., Llorach-Massana, P., **Sanjuan-Delmás, D.,** Sierra-Pérez, J., Vinyes, E., Gabarrell, X., Rieradevall, J. (2017). Research on strategies towards sustainable cities from a life cycle perspective: a review. Accepted with major revisions in the Journal of Cleaner Production.

- Sanyé-Mengual, E., Llorach-Masana, P., **Sanjuan-Delmás, D.,** Oliver-Solà, J., Josa, A., Montero, J. I., Rieradevall, J. (2014). The ICTA-ICP Rooftop Greenhouse Lab (RTG-Lab): closing metabolic flows (energy, water, CO_2) through integrated Rooftop Greenhouses. VHL University of Applied

Sciences. Proceedings of the 6th AESOP Sustainable Food Planning Conference 693–701. doi:10.13140/RG.2.1.5016.7206

- **Sanjuan-Delmás, D.,** Petit-Boix, A., Martínez-Blanco, J., Rieradevall, J. (2016). Environmental metabolism of educational services. Case study of nursery schools in the city of Barcelona. Energy Efficiency 9, 981-992. doi: 10.1007/s12053-015-9403-x

Participation in conferences

- Sanyé-Mengual, E., Llorach-Massana, P., **Sanjuan-Delmás, D.,** Rieradevall, J. Montero, J. I., Oliver-Solà, J. (2014). The Rooftop Greenhouse Lab: optimising food production on buildings through integrated Rooftop Greenhouses in Barcelona, Spain. Poster. International Conference on Vertical Farming and Urban Agriculture 2014. September 2014, The University of Nottingham (United Kingdom).

- Marín, D., Amores, M. J., Lorenzo-Toja, Y., **Sanjuan-Delmás, D.,** Petit-Boix, A., Arnal, C., Feijóo, G., Rieradevall, J., Termes-Rifé, M., Hernandez-Sancho, F. (2015). Eco-efficiency indicators for decision-making support in the urban water sector. Oral presentation. SETAC Europe 25th Annual Meeting. May 2015, Barcelona (Spain).

- Sanyé-Mengual, E., Llorach-Massana, P., **Sanjuan-Delmás, D.** Nadal, A., Oliver-Solà, J., Josa, A., Montero, J. I., Gabarrell, X., Rieradevall, J. (2015). The ICTA-ICP Rooftop Greenhouse Lab: coupling industrial ecology and life cycle thinking to assess innovative urban agricultura. Poster. CILCA 2015. VI Conferencia Internacional de Análisis de Ciclo de Vida en Latinoamérica. July 2015, Lima (Perú).

- Petit-Boix, A., **Sanjuan-Delmás, D.,** Arnal, C., Marín, D., Gabarrell, X., Josa, A., Rieradevall, J. (2015). LCA and LCC Integration for Supporting Decisions in the Design and Construction of Sewer Networks in Future Smart Cities. Poster. CILCA2015. VI Conferencia Internacional de Análisis de Ciclo de Vida en Latinoamérica. July 2015, Lima (Perú). – Third place at poster awards

- Llorach-Massana, P., Sanyé-Mengual, E., **Sanjuan-Delmàs, D.,** Gabarrell, X., Rieradevall, J., Gasol, C., Farreny, R., Garcia-Lozano, R. (2015). edTOOL: new free qualitative Ecodesign Tool to promote SCP policies. Poster. LCM 2015. Life Cycle Management Conference 2015. August-September 2015, Bordeaux (France).

- Arnal, C., Marín, D., Termes, M., Planas, M., Petit-Boix, A., **Sanjuan-Delmás, D.,** Amores, M. J., Prieto, M., Aldea, X. (2015). Life Cycle Costing assessment of water supply and sewer networks in small-medium cities. Poster. LCM 2015. Mainstreaming Life Cycle Management for sustainable value creation. August–September 2015, Bordeaux (France).

- Nadal, A., Llorach-Massana, P., **Sanjuan-Delmàs, D.,** Sanyé-Mengual, E., Cuerva, E., Cerón, I., Josa, A., Rieradevall, J. (2015). Ecoinnovación en flujos residuales de energía, agua y CO_2 de edificios. Poster. 1er foro internacional Innovación social hacia la sustentabilidad. October 2015, Chiapas (Mexico).

Participation in journals

The student contributed with the Journal of Industrial Ecology translating abstracts into Spanish from November 2015 until present.


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Introduction, objectives and methodological framework

Part I

Chapter 1

Introduction and objectives

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Chapter 1 Introduction and objectives

This chapter introduces the background of the urban water supply and vertical farming. First, the state of the water supply in the world is discussed as well as its importance for cities. Secondly, the urban water cycle and water supply networks are described and the main elements for their analysis are stated. Thirdly, different systems for water efficiency in buildings are presented along with the water-food-energy nexus. Finally, the concepts of urban agriculture and vertical farming are explained as well as their main typologies. At the end of the chapter, the motivation and the objectives of the dissertation are stated.

1.1 Water supply in cities

Water is an essential element for the development of any society. Having access to sufficient good-quality freshwater is necessary to cover the basic needs of people and to promote the development of any kind (WWAP 2016). Since drinking water is a scarce resource in the world, its availability has always been decisive for determining the location and the activities of human settlements.

Water security is defined as "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable water quality for sustaining livelihoods, human well-being, and socio-economic development" (UNU-INWEH 2013). Unfortunately, water security is far from being guaranteed in a large part of the world, as shown in Figure 1.1. The reason for water scarcity can be either physical or economic, which is the lack of economic resources to develop water supply infrastructures.

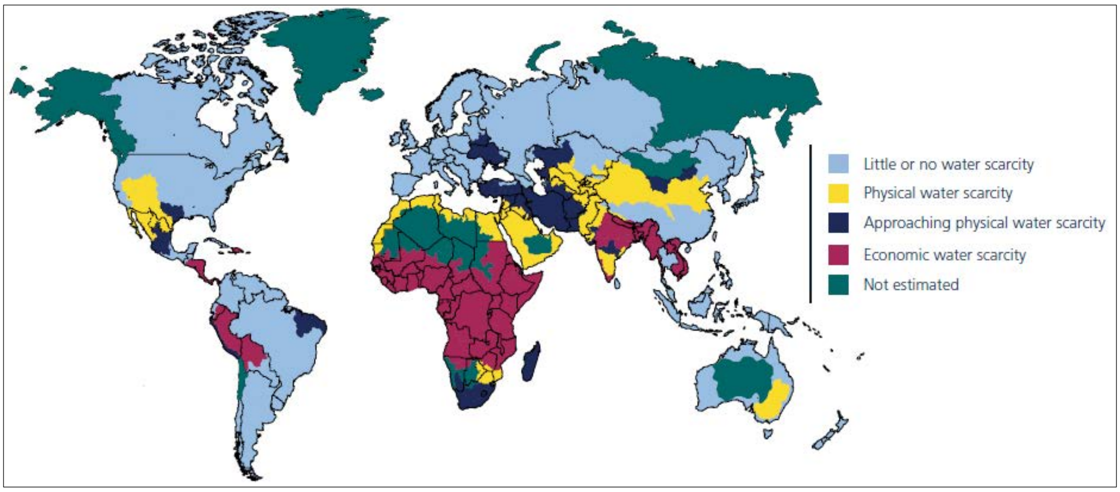


Figure 1.1Global physical and economic water scarcity
Source: (WWAP 2016)

Climate change is a major concern related to water security worldwide. The increasing concentration of anthropogenic greenhouse gases in the atmosphere is altering the world climate with severe consequences. The effects on ecosystems and economies will increase both physical and economic water scarcity. Perturbations in the global water cycle are expected to increase the occurrence of drought in some areas as well as floods in some others, with significant consequences for ecosystems and economies (Milly et al. 2002, 2005). The rising of temperatures on a global scale will reduce rainfall, and at the same time, snow will melt earlier in Spring. Both of these effects will reduce the availability of freshwater affecting one-sixth of the Earth's population using glaciers and seasonal snow for their water supply (Barnett et al. 2005).

Another menace to the water supply is the pollution of freshwater from different sources. This pollution affects the ecosystems, but it particularly constitutes a risk for human health. Both superficial and groundwater can be polluted because many pollutants leach into aquifers. One example is the discharge of untreated domestic wastewater into freshwater and coastal areas, which generates microbial pollution. This problem is a consequence of inadequate sanitation, especially in some developing countries where only 10% of wastewater treatment plants are working properly, and only 10% of wastewater is collected for treatment (UNEP 2007). Another major source of pollution comes from pesticides and nutrients from agriculture runoff. A high concentration of waste nutrients in water can result in eutrophication, which is a major threat to the environment (Andersen 2006).

Finally, agriculture accumulates 70% of the global water demand, contributing to the overexploitation of water resources (FAO 2011). Leaky irrigation systems often cause excessive water demand for farming, as well as wasteful field application methods and cultivation of crops not suited to the environment (WWF 2017). This bad practice entails multiple problems such as drying up lakes and rivers and damaging ecosystems.

One of the main issues threatening water security is the increment in the world's population. In the last 50 years, the world's population has more than doubled and is expected to maintain this trend reaching 9.7 billion by 2050 (UN 2015). Moreover, the percentage of the population living in urban areas at the present time is 54% and rising (The World Bank 2017a).

Population growth represents a challenge for the supply of water to new cities in expanding towns and new settlements, which will imply the construction of new water supply networks around the world. The study of water supply networks can help to prevent environmental impacts in the life cycle of these networks. The priority should be providing the necessary infrastructure to the 10% of the world population that do not have access to water supply (The World Bank 2017b). The replacement and refurbishment of old supply networks is also an important factor to consider in developed countries. Furthermore, there is an increment in the demand for water due to the greater use of water for basic needs such as food, energy or sanitary purposes, and the provision of certain goods such as clothes or technology contributes to aggravating the problem. The more resources used, the more pressure on freshwater (greater consumption) and the transformation of ecosystems due to the direct impacts of abstraction and transport of water and wastewater (Giljum et al. 2009). The higher demand for commodities and energy increases the burdens on the environment and affects the quality of the water.

As stated above, the population is increasingly concentrating in urban areas around the world, and in Europe 73% of citizens live in cities (Eurostat 2015). These cities are a large focus of resource consumption and therefore generate significant environmental impacts. As a consequence, attention towards its sustainability is growing, becoming a centrepiece of European action for the environment (European Comission 2010). Water is at the core of city sustainability due to its essential role supporting life and development, for this reason legislation is being defined for water management from an ecosystem-based approach (Kallis 2001). As this is gaining recognition, more research is being conducted in the field, analysing the urban water cycle as a part of the urban system (AQUAENVEC 2016; SWSS 2017; TRUST 2017).

1.2 Water supply in urban areas

As discussed in the previous section, the study of the urban water cycle is key to improving the sustainability of cities. This section introduces the urban water cycle and the water supply network, which are two of the main elements analysed in the dissertation.

1.2.1 Urban water cycle

In nature, water circulates around the hydrosphere, the lithosphere, the atmosphere and the biosphere driven by processes such as evaporation, precipitation, runoff and condensation. This constant movement of water is called the hydrological cycle or water cycle.

In urban areas, the hydrological cycle is severely modified by the impacts of urbanisation on the environment and by the use of water to provide services to the population. Although its main structure remains intact, the complexity of the water cycle becomes greater as a result of these influences (UNESCO 2006). The urban water cycle (UWC) is the fruit of this "urbanisation" of the natural water cycle. As observed in Figure 1.2, the system becomes more complex and the driving processes making water circulate are not only natural but also anthropogenic.

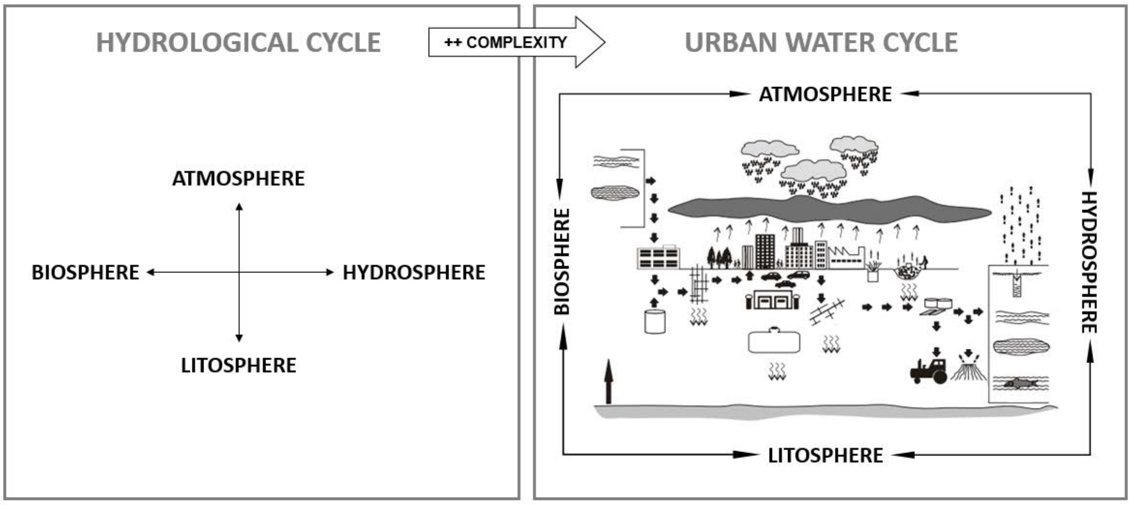


Figure 1.2 Schema of the hydrological cycle and the urban water cycle.

Source: Adapted from (UNESCO 2006)

The UWC includes all the processes from the extraction of water from the environment to the discharge after wastewater treatment. As shown in Figure 1.3, there are five main stages: water extraction and drinking water treatment, water transport and distribution, use, wastewater transport (sewers) and wastewater treatment and discharge. These phases might be located far away from the urban area being supplied, and water must be carried to the consumption point and the treatment plants.

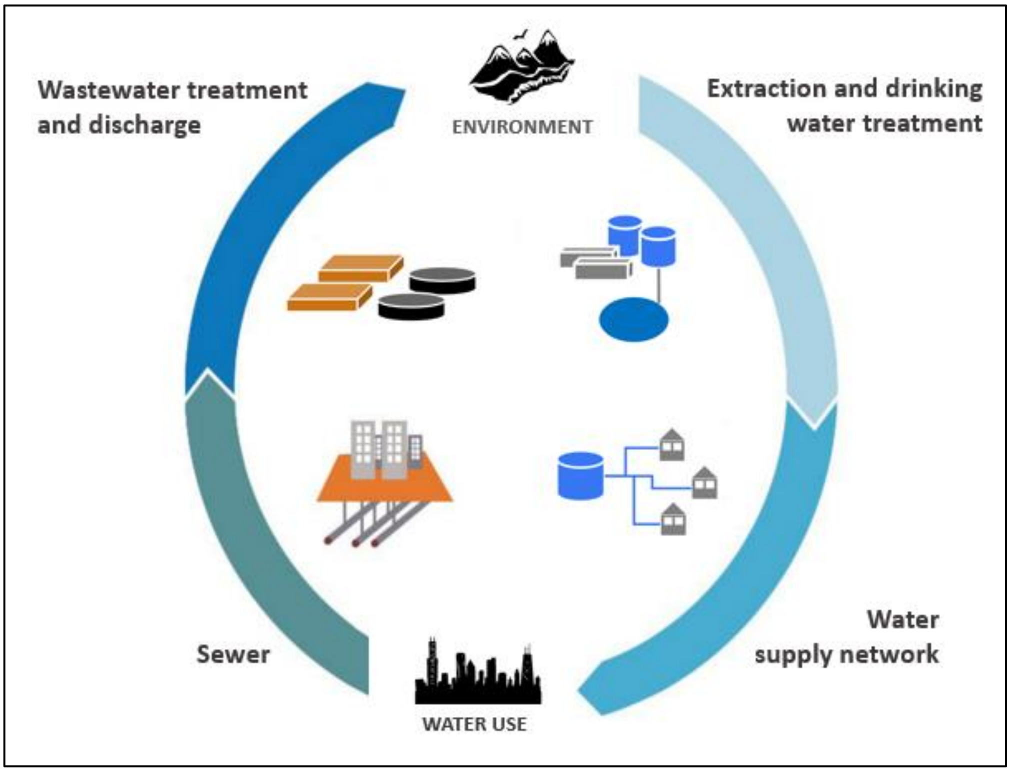


Figure 1.3 Stages of the urban water cycle.

(iv) Water extraction and drinking water treatment

Water can be extracted from surface water (rivers or lakes), ground water (aquifers) and seawater (desalination) and transported to the drinking water treatment plant. Different methods are applied to remove disease-causing agents such as coagulation and flocculation, sedimentation and filtration. After being treated, the water is disinfected, usually with chlorine, to avoid pathogens. Once the water is suitable for drinking, it enters the water transport and distribution network.

(v) Water transport and distribution network

After the treatment, the drinking water is pumped (or carried by gravity) to the primary water storage tanks. Then, it is sent through the water transport network until the secondary water storage tanks. The water is then delivered to the consumption points using the distribution network. There can be other intermediate water tanks before reaching the consumption point. More complex or simpler schemes can apply depending on the situation of the city and treatment plant and the orography, among other factors. Regarding the geometry of the network, there are three basic configurations: branched networks, looped networks or a combination of both.

(vi) Water use

Water is used at the consumption point and a part becomes wastewater that is discharged to the sewers. As will be explained below, there are alternative water sources such as harvested rainwater and greywater that can cover uses that do not require drinking water.

(vii) Sewer network

After using drinking water, the resulting wastewater is discharged into the sewer. Usually, the sewer collects not only wastewater but also the stormwater in the urban area, although they can have different networks. Wastewater is transported to the wastewater treatment plant, being pumped if necessary when gravity transport is not possible.

(viii) Wastewater treatment and discharge

In the wastewater treatment facility, the wastewater is treated to reach the necessary standards to be discharged back into the environment. Typically, the process includes a primary mechanical treatment to remove solids, a secondary biological treatment to remove dissolved organic matter and a tertiary treatment to remove further impurities. However, there is a great variability of possible schemes.

The environmental impacts derived from the construction and operation of the infrastructure described above were analysed in previous studies showing the contribution of each phase to the total environmental burdens of the UWC (Lundin and Morrison 2002; Venkatesh and Brattebø 2011a; Amores et al. 2013a). The expansion of cities and the creation of new urban areas as well as the substitution and refurbishment of old infrastructures will involve the urbanisation of new territory, which implies the installation of UWC infrastructures and possibly the extension of the existing ones. Thus, the appropriate initial design and optimisation of these infrastructures can prevent economic and environmental impacts both in the initial configuration and in future maintenance and extensions.

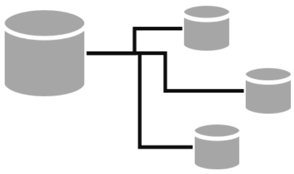
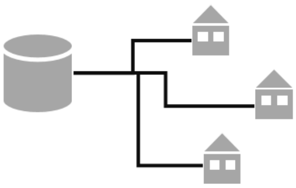
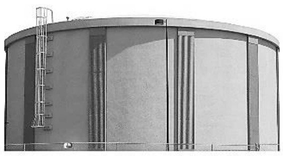
1.2.2 Water supply network

The drinking water transport system and distribution network or water supply network is the infrastructure required to transport water from the drinking water treatment plant to the consumption point. The core elements of the network are summarized in Table 1.1 and the necessary equipment in Table 1.2. As can be observed, this network involves the construction of necessary infrastructures whose characteristics will depend greatly on each specific case. Thus, the description of the elements below might not apply to certain networks but is adequate for providing common terminology to be used in this dissertation.

Elements of the network

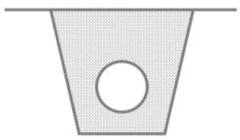
Drinking water in the network is always pressurised, and must have enough pressure to reach the consumption point. Although this pressure can be achieved by gravity if there is sufficient slope, pumping is usually needed. Indeed, the operation of water supply networks is characterised by the electricity consumption required for pumping (Venkatesh and Brattebø 2011a). Regarding maintenance, some operations such as an internal coating of the pipes, rehabilitation, replacement of smaller parts of a pipeline, repair and inspection are sometimes required (Venkatesh and Brattebø 2012a).

Table 1.1 Description of the main elements in the water supply network.

Element*	Description and Observations
Transport network 	The primary section of the supply network, usually from the first water tank after the treatment plant* until the secondary water tank before the distribution system. This section of the network has wider pipes and is typically made of strong materials such as reinforced concrete or ductile iron (depends on the conditions and customs of the region).
Distribution network 	Section of the supply network from the secondary water tank until the connection to households. This section is longer due to the capillarity of the network and the pipes hold smaller diameters. Pipes are usually made of polyethylene, PVC or steel.
Water supply tank 	The facility used to store drinking water. Municipal water tanks usually hold large volumes of water (hundreds of cubic meters) and are generally made of reinforced concrete or steel. Usually, there is another water tank before water reaches households in an urban area. There can be more tanks in the transport or the distribution network for flow regulation, pressure regulation and supply security

**Water extraction and treatment have not been excluded because they are before the water supply network, and thus out of the scope of the dissertation.*

Table 1.2 Description of the main equipment of the water supply network.

Element	Description and Observations
Pipe and appurtenances 	The basic infrastructure of the network made up of a tubular section for water conveyance. It can be made of different materials such as plastics (PVC, HDPE), iron or concrete. Pipes usually require certain appurtenances such as joints or additional pieces for proper functioning.
Trench or ditch section 	Section excavated in the ground for the installation of pipes. The ditch is backfilled with gravel, sand or other materials that protect the pipe.
Pumping station 	Facility for pumping water through the network. It includes pumps and the necessary equipment.
Valve 	Devices along the network that regulates the flow of water opening, closing or partially limiting the flow. There are different types depending on their function. For instance, valves can be used for pressure reduction or backflow prevention.
Hydrant 	Connections for the provision of water located along the distribution network.
Metering 	Flow meters are installed at key points of the network for the measurement of the water flow. At least, water is measured at the beginning of the first water tank and the entrance of households.

Operation of the network

The network normally has (particularly old networks) significant leakages because it is pressurised. It is well known in engineering that higher pressure in the network implies more likelihood of water leaks (Garcia and Thomas 2001). In Europe, estimates show that water loss through leakages can range between 5% and 50% (particularly in old networks) depending on the country (European Environmental Agency 2008). For this reason, this is a major concern in water management strategies, provided it increases the overall economic and environmental costs of water supply.

There is extensive scientific literature analysing different methods for the reduction of water loss due to leakages. Various methods are proposed such as effective detection of leakages using smart metering (Britton et al. 2013), predictive maintenance (Tsakiris et al. 2011), strategical pipe replacements (Creaco and Pezzinga 2015) or optimisation of valves control (Vairavamoorthy and Lumbers 1998). As a result of the increasing interest, the European Commission launched a reference document for good practices on leakage management on 2015 (European Comission 2015).

The administration of the water supply network is affected by the European Council Directive on the quality of water intended for human consumption (Council Directive 98/83/EC) (EC 1998) as well as by the Council Directive for a Community action in the field of water policy (Council Directive 2000/60/EC) (EC 2000). In Spain, these directives were transposed into the Royal Decree 140/2003 (Presidencia 2003) on sanitary criteria of water quality for human consumption and into the Royal Legislative Decree 1/2001 (MMA 2001) on water issues. In Catalonia, the water supply network is affected by the Legislative Decree on water issues 3/2003 (Departament de la Presidència 2003).

Environmental impacts of water supply

From an environmental perspective, the water transport and distribution network represents a significant contribution to the total environmental burdens of the urban water cycle. A study from Amores et al. (2013b) concluded that the water supply network accounted for between 20 and 40% in 7 out of 9 impact categories. The results from another study by Lemos et al. (2013a) showed that the supply network accounts for around 20% of the total UWC impacts, also in 7 out of 9 impact categories. One of the main contributions to these environmental impacts is the operating of the network, due to the energy consumption from pumping water. The electricity requirements can vary widely depending on the specific case, from low (250 kWh/MG) to high (1,200 kWh/MG) (Griffiths-Sattenspiel et al. 2009). The leakages of the network would increase these energy requirements (and hence the environmental impacts) because more pumping is required to maintain the adequate pressure.

In this context, the environmental assessment of water supply networks has the potential to reduce environmental impacts from the UWC. This assessment should reveal which factors of the materials, construction, use and maintenance of networks are crucial to improve the environmental performance.

1.3 Environmentally sound technologies in water-efficient buildings

Water reaches the consumption point at the end of the drinking water transport and distribution network. Water management is also key at this point because savings in consumption will avoid environmental and economic impacts throughout the whole UWC. Thus, the development of strategies for optimizing water consumption along with other measures such as reduction of leakages is of paramount importance, especially in areas suffering from water scarcity. In urban areas, significant advances were made using water-efficient devices in buildings. For instance, replacing hand washing by waterless alcohol hand rub (Widmer and Weinstein 2000) or the installation of waterless urinals, which in addition to saving water have a potential for nutrient recovery (Münch and Dahm 2009).

The use of alternative water sources is an option to reduce the pressure on water sources. One example is desalination, which has become a major alternative in countries with water scarcity issues. The use of desalination technologies has grown significantly in recent decades and an expansion is predicted in the following years (Bremere et al. 2001). However, this technology is very expensive and has negative environmental impacts due to its high energy demand (Tsiourtis 2001). In contrast, there are appealing alternatives such as rainwater harvesting or greywater re-use, which is made up of the utilization of wastewater from showers, washbasins, washing machines or dishwashers among others (distinct from blackwater, which includes wastewater from toilets) for further uses such as flushing toilets. These are local systems, usually applied on a small scale, that have relatively lower costs in comparison with the previously mentioned technologies (Yuan et al. 2003; Friedler and Hadari 2006; Ghisi and Ferreira 2007; Farreny et al. 2011a; Vargas-Parra et al. 2014). Many water uses can be covered with rainwater (Table 1.3), except some domestic demands that require drinking water such as water for cooking or personal hygiene (shower, washbasin at home).

As shown in Table 1.3, rainwater and greywater can be used in agriculture and industry, which represent 70 and 20% of water consumption worldwide (WBCSD 2005). In urban areas, there is a potential for both reducing freshwater consumption and wastewater treatment, which is especially significant in densely populated areas such as Barcelona. The optimization of these technologies implies the reallocation of water sources depending on the quality of the source and the quality standards required for the use. Other applications include environmental water enhancement, which is made up of increasing natural water schemes which are overexploited or not receiving enough water due to urbanisation. Similarly, groundwater recharge preserves groundwater for future use (UNEP 2004).

Table 1.3 Potential uses for rainwater harvesting and greywater reuse.

SERVICES AND INDUSTRY	**RESIDENTIAL** Toilet, cleaning, laundry, air conditioning **URBAN** Fire protection, construction **RECREATIONAL** Non-contact activities (fishing, boating, etc.) **INDUSTRIAL** Water for cooling systems, boiler feeds, air conditioning
IRRIGATION	**URBAN** Irrigation for gardening **FOOD CROPS (AGRICULTURE)** Irrigation of crops for human consumption **NON-FOOD CROPS (AGRICULTURE)** Irrigation of crops for fodder, fibre, flowers, etc.
ENVIRONMENT	**ENVIRONMENTAL ENHANCEMENT** Artificial wetlands, stream flows, etc. **GROUNDWATER RECHARGE** Potable water provision, control of subsidence or salt water infiltration, etc.

Source: Own elaboration with data from Asano and Levine (1996).

1.3.1 Rainwater harvesting systems

Rainwater harvesting systems were recently rediscovered in modern countries becoming an effective alternative to conventional water sources and providing water in case of scarcity. The mechanism is simple, normally made up of a surface with a certain area that collects rainwater and brings it to a tank by means of pipes for its storage (sometimes it includes a treatment) and later use (Figure 1.4). Rainwater harvesting has great potential as a sustainable source of water in urban areas. A previous case from previous literature showed that in a Mediterranean climate with low and variable precipitations it covered most of the needs for flushing toilets and 60% of the demand for landscape irrigation (Domènech and Saurí 2011). In Colombia, rainwater is a potential replacement for mains water in urban areas with high precipitations (higher than 1,550 $L/m^2/year$) (Morales-Pinzón et al. 2012b). Apart from residential uses, it is also used for agriculture, providing water in case of drought while reducing costs and soil erosion (FAO 2017a).

The main drawback for rainwater harvesting is the possible long payback period of the infrastructure and water treatment. However, rainwater harvesting can be economically advantageous if the correct strategy is undertaken for its implementation (Farreny et al. 2011b; Morales-Pinzón et al. 2012a). Moreover, research was conducted for the optimization of rainwater harvesting systems and the reduction of its environmental and economic costs, including scientific projects (Pluvisost 2011) and studies (Angrill et al. 2012; Vargas-Parra et al. 2013). In this sense, certain factors, mentioned in the following paragraphs, must be considered from an environmental perspective for the implementation of this technology.

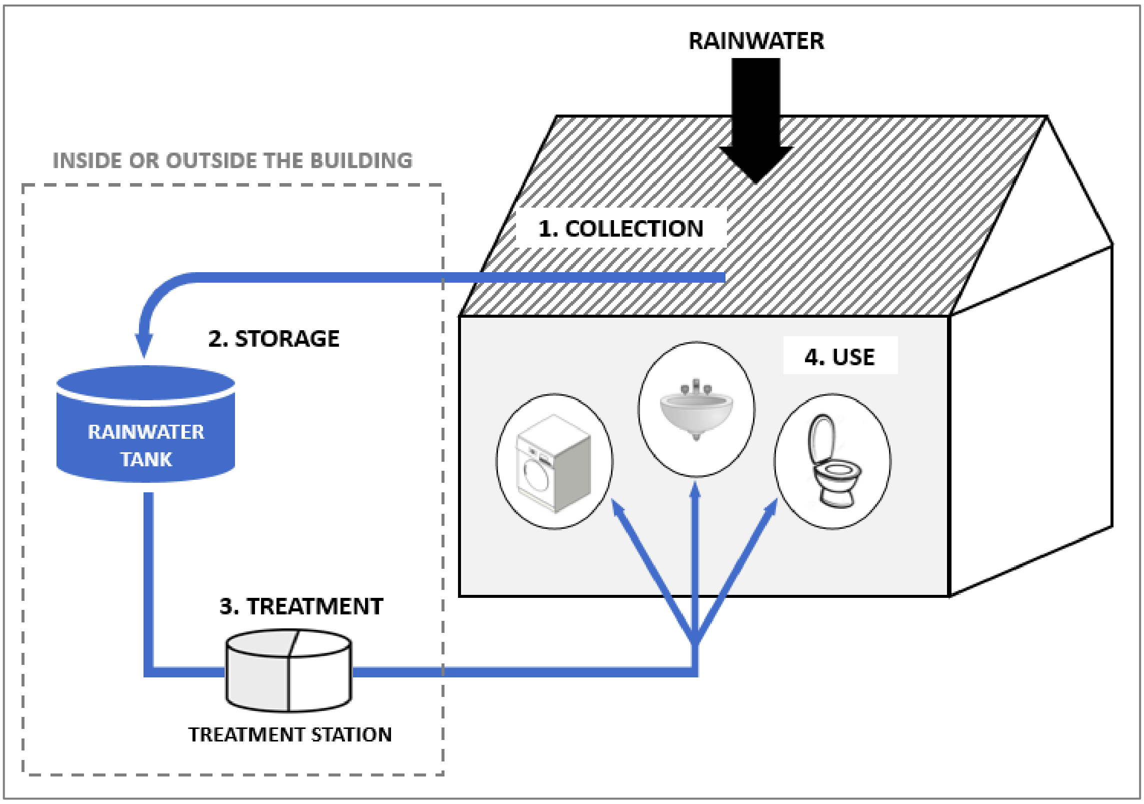


Figure 1.4 Example of a rainwater harvesting system on a building scale.

One of these factors is population density in urban areas, which has been shown to have a strong influence on the performance of rainwater harvesting systems (Angrill et al. 2012). More densely populated areas hold smaller catchment surfaces per inhabitant and thus a lower percentage of the demand is covered, but the utilization of the rainwater collected is greater (Herrmann and Schmida 2000; Nolde 2007). Furthermore, multi-family buildings hold advantages from cost-sharing arrangements and economies of scale, as shown in several previous studies (Villarreal and Dixon 2005; Ward et al. 2010). These systems can also be implemented at a neighbourhood scale, showing greater benefits from scale-economy and shorter payback periods (Farreny et al. 2011b).

The design of the system is also a significant factor. For instance, placing the rainwater storage tank on the roof instead of the ground allows the distribution of rainwater by gravity, avoiding environmental impacts (Vargas-Parra et al. 2014; Angrill et al. 2017b). Other basic parameters to consider for the design of rainwater harvesting systems are the building type, catchment area, precipitation, slope of the roof, roof material, occupancy, distribution of the demand in the household and percentage of non-potable water demand (Farreny et al. 2011c; Devkota et al. 2015; Angrill et al. 2017b).

Finally, one of the main concerns with the use of rainwater is the standards of quality. The quality of the rainwater collected is highly dependent on the type of material used for the collection and the specific location and characteristics of the system (Farreny et al. 2011c). For instance, asphalted urban spaces are prone to deposition and accumulation of particulate matter, whereas concrete slabs have a smoother surface in which particles are easily washed away, improving the quality of the runoff (Angrill et al. 2017a). However, the quality of the rainwater collected in these systems is usually outstanding, and some collection systems have reached standards similar to those of drinking water, as demonstrated in Zhu et al. (2004). Nevertheless, to avoid potential problems, most cases reported have used rainwater for activities requiring non-potable standards, avoiding the complications of further treatment and the consequent risks of its utilization.

1.3.2 Greywater reuse

Greywater reuse is made up of a) collecting water that has been used for some purpose (greywater) and b) use again untreated or with treatment to improve the quality (Figure 1.5). Experiences with different types of wastewater have been reported, but greywater is the most widely used due to the lower technological requirements and costs.

There are two main issues regarding the use of greywater: the quality of the reclaimed flow and the economic costs. In terms of quality, the potential risks for public health must be evaluated and minimized and adequate disinfection before being used is recommended to avoid the transmission of disease-causing microorganisms (Dixon et al. 1999; Winward et al. 2008). However, higher standards of reclaimed wastewater imply higher costs. Thus, appropriate technology must be selected according to the standards required to ensure economic feasibility (Li et al. 2009). For this reason, excluding the fraction from toilets is the most current practice in residential or service buildings. Another factor affecting the economic feasibility is the scale of application, larger installations being economically more advantageous (Friedler and Hadari 2006). For instance, installations in schools and small offices with simple physical and biological treatments have been shown to be more viable than single-house systems, with payback times between 5 and 10 years (Jefferson et al. 2000).

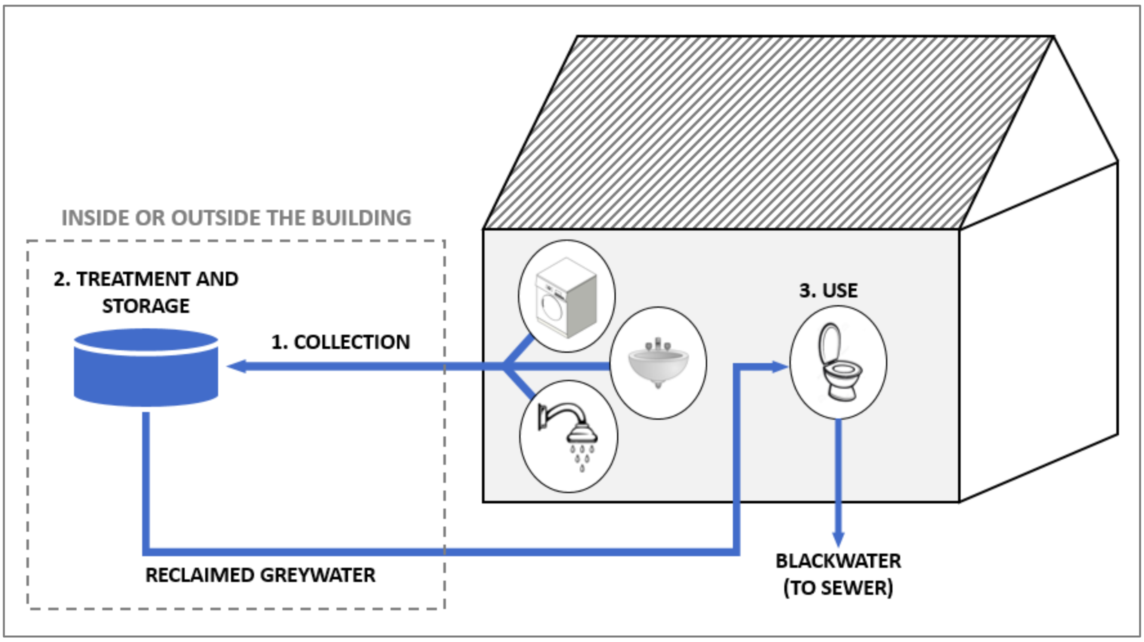


Figure 1.5 Example of a greywater reuse system on a building scale.

In urban areas, greywater stands for 60% of the households' outflow and contains few pathogens (90% less than blackwater), representing a great potential for ruse (Madungwe and Sakuringwa 2007). A successful experience was reported from Germany showing greywater reuse systems for toilet flushing in multi-storey buildings (Nolde 2000). Another experience was reported from Shinjuku (Japan), where a dual distribution system was adopted and sand-filtered water from the Ochiai Municipal Wastewater Treatment Plant was chlorinated and used for toilet-flushing.

Wastewater reclamation is a widely-used water source in agriculture, allowing the recovery of nutrients from wastewater. Indeed, 20% of the world population's food is grown with reclaimed wastewater (UNEP 2004). However, attention must be paid to the standard requirements because the uptake of microcontaminants has been reported in crops with reclaimed wastewater irrigation (Calderón-Preciado et al. 2013). The World Health Organisation elaborated an extensive guide for the use of wastewater in crops (WHO 2006).

1.4 The water-food-energy nexus

Water is inextricably linked to food and energy. Water is required to produce food and generate energy and energy is required to produce and transport food and water (Figure 1.6). In this context, the concept of water-food-energy nexus is defined by the FAO (2014) as follows:

> "A conceptual approach to better understand and systematically analyse the interactions between the natural environment and human activities, and to work towards a more coordinated management and use of natural resources across sectors and scales".

According to this concept, adopting a holistic approach to study the use of resources in urban areas is a key for success.

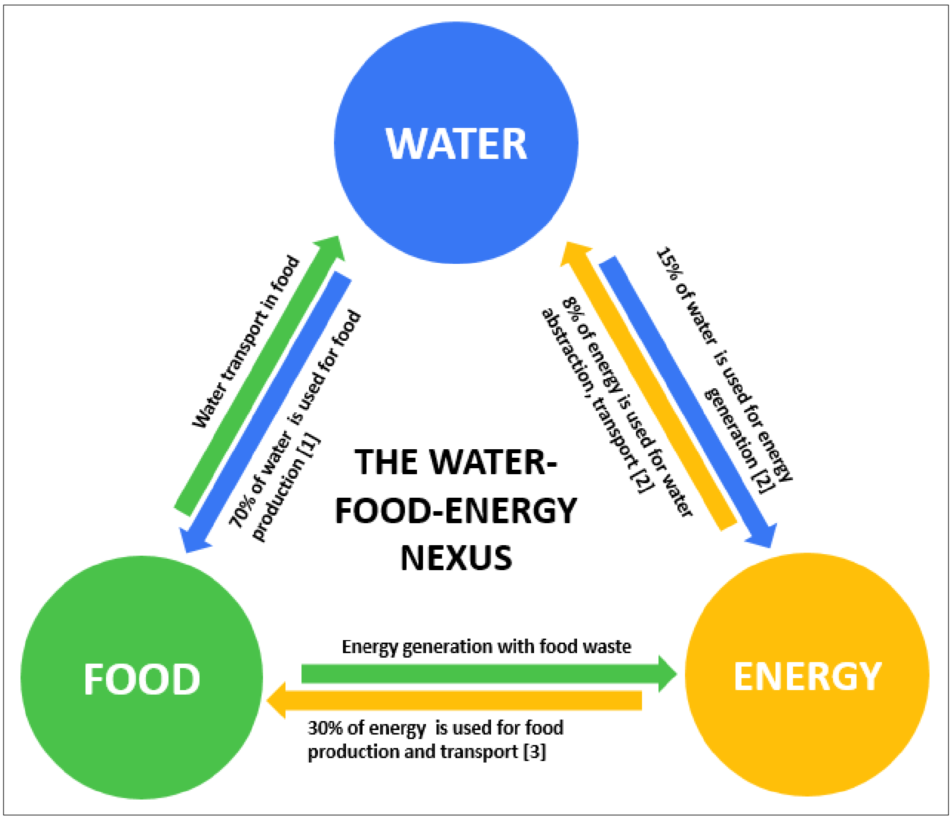


Figure 1.6 Diagram of the water-food-energy nexus. The percentages indicate the total resource used worldwide for this purpose.

Sources: [1] WBCSD (2005), [2] UNESCO (2014), [3] FAO (2014)

Adopting the perspective from the water-food-energy nexus, urban areas and buildings are not mere resource consumers. On the contrary, they can contribute to increase its self-sufficiency using environmentally sound technologies. As seen in previous sections, rainwater can be collected and used and greywater can be reclaimed for further uses. In terms of food, urban agriculture and vertical farming (section 1.4) can increase food production in cities increasing food security. Finally, energy can be produced (solar cells, geothermal energy, etc.) in urban areas and the application of innovative technologies such as passive ventilation can be key to self-sufficiency.

1.5 Food production in buildings. Exploring new uses for water and evaluating environmental impacts

The analysis of the environmental sustainability of food production is an issue of interest, and is linked to significant environmental problems related with the water management such as water scarcity or eutrophication. As discussed above, there is a substantial potential for the use of alternative water sources for food production in cities. This section introduces the concepts of urban agriculture and vertical farming, which are related to food production in urban areas.

1.5.1 Urban agriculture

Urban agriculture was defined by the FAO (2017b) as “the growing of plants and the rising of animals within and around cities”. It has been common practice throughout history, from floating gardens of Aztec Mexico to today’s Vertical Farming hydroponic systems (Lawson 2016). In recent years, urban agriculture has grown resulting in an increment in the areas designated to food production in cities. Nevertheless, it has gained recognition and importance in times of crises, increasing production and enhancing food security, understood as the access of all people to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life (FAO 2017c). For instance, during World War I and II urban gardens were largely implemented by civilians in the USA, promoted by the National War Garden Commission (Mok et al. 2014). Food production in cities was key in Cuba to stabilize the supply of fresh food after the collapse of the socialist bloc, including vegs, eggs and meat (Altieri et al. 1999).Although nowadays there are other motivations for its implementation, food security remains an important factor. For example, in the so called “food deserts” urban agriculture aims to cover the need for fresh food that cannot be supplied by conventional means (Guy et al. 2004). Some projects from the USA have attempted to alleviate this problem by means of urban food production (Block et al. 2011).

In terms of environmental impacts, urban agriculture has a great potential. Most of conventional production is normally intensive in the use of chemicals and pesticides and long distances of food transport. In contrast, urban agriculture tends to adopt environmentally friendly practices, being most production organic (Howe and Wheeler 1999). Also, being in a urban context reduces the need for transport and shortens the agri-food chain, making food traceability easier (Sanyé-Mengual et al. 2013).

The social benefits of urban agriculture have gained recognition recently. The promotion of health and dietary education is at the core of some experiences reported. Studies in the issue show that community gardening improves nutrition, access to food, increases physical activity and improves mental health (Kingsley et al. 2009; Kortright and Wakefield 2011). As an educational tool, it has shown promoting the intake of fruit and vegetables among the participants (Alaimo et al. 2008; D'Abundo and Carden 2008). In schools, urban agriculture can have a key role through the inclusion of garden activities, which have been shown to improve children's knowledge of nutrition and have enhances good dietary habits among children (Morris 2002).

1.5.2 Vertical farming: urban rooftop greenhouses

Vertical farming is a visionary type of urban agriculture based on growing food in and around buildings (Despommier 2010a). There are similar concepts linked to vertical farming that have been defined by different authors. Zero-Acerage (ZFarming) farming was stated by Specht et al. (2013) and emphasizes the non-occupation of land that implies farming inside buildings. Dickson Despommier defined the concept of Vertical Farm, describing skyscrapers used entirely for highly technological intensive farming in the inside (Despommier 2010a, 2011). But perhaps the definition that better fits the case study presented in this dissertation is the Building-Integrated Agriculture, an approach that includes the use of high-performance hydroponic farming systems in and on buildings and the use of local sources of energy and water, as well as the integration of flows between the building and the vertical farm (Caplow 2009).

Within vertical farming, there are different types of farms. As shown in Figure 1.7, the main aspects considered for classification are the placement, the growing medium, the exposure and the production purpose (Association for Vertical Farming 2016). The placement of the farm defines its position in relation to the building, which can be interior, exterior and even underground (requires artificial light). Regarding the growing medium there are three main categories, none of which uses soil. Aeroponics is the process of growing plants using mist, without soil or an aggregated medium. Hydroponic crops are irrigated with a nutrient solution (water plus fertilizers) and plants are directly placed in the water stream or in an inert substrate. Finally, aquaponics consists on the combination of hydroponic crops with aquaculture (farming fish). The exposure defines the degree of influence of outdoor conditions on the farm, which can be exposed (no barriers), enclosed (a barrier that isolates the farm but allows natural light in) or closed (complete isolation from exterior conditions). The last factor is the purpose of the vertical farm, which indicates its main aim. For instance, sharing would be the main purpose of community gardens.

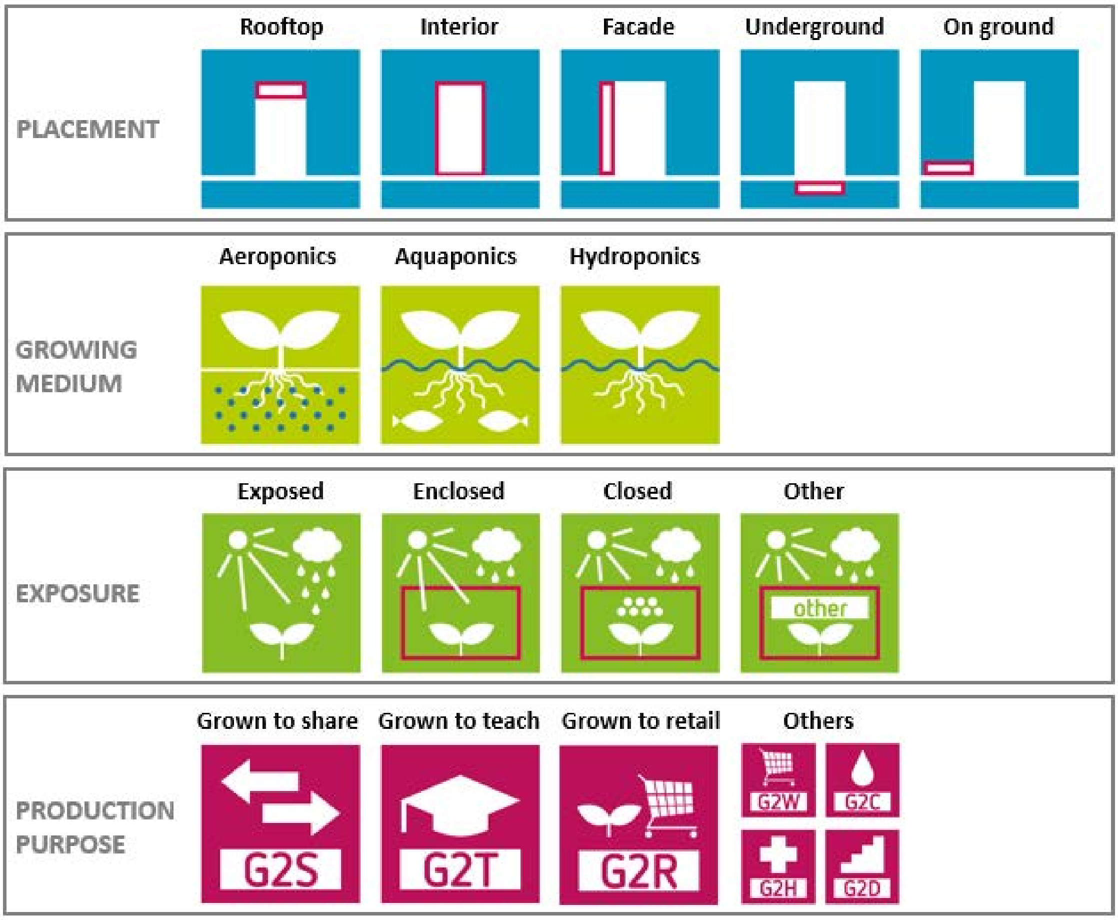


Figure 1.7 Main aspects for the definition of vertical farming typologies.

Source: Adapted from Association for Vertical Farming (2016)

Within vertical farming, rooftop farming is the production of food in the top of buildings. The occupation of rooftops have been shown to have a great potential to be implemented on a broad scale in urban areas (Rodriguez 2009; Astee and Kishnani 2010). For example, using the whole potential of the city of Bologna (Italy) for rooftop farming, 77% of the vegetable requirements of the city might be covered (assuming 15 kg/m^2) (Orsini et al. 2014).

Rooftop greenhouses (RTG), a specific type of rooftop farming, have the potential to reach higher productivities. Their implementation in available rooftops of a logistic park in Barcelona might produce annually 2,000 tons of tomato, which could cover the demand of 150,000 people (Sanyé-Mengual et al. 2015a). There are several experiences of RTGs reported around the world (Wilson 2002; Engelhard 2010). In North America, mature commercial rooftop farming and RTGs are more common. For instance, Brooklyn Grange1 produces vegetables, honey and sauces in New York (USA) in open rooftop farms, holding three farms with an extension of between 2,900 and 3,900 m^2. Lufa Farms 2, a similar project from Montreal (Canada), produces vegetables in a commercial RTG of between 2,900 and 3,900 m^2.

The case presented in this dissertation is an integrated rooftop greenhouse (i-RTG), which is connected to the building in terms of resources, and has the potential to

[1] http://www.brooklyngrangefarm.com/navyyard
[2] http://lufa.com/en/

increase both the productivity and the efficiency of crops because of these synergies. This is a pilot application of an innovative technology that has the potential to increase production while optimizing the use of resources, maximizing self-sufficiency (Caplow 2009; Cerón-Palma et al. 2012). The project Fertilecity aims at developing this first pilot i-RTG located in the ICTA-ICP building. Preliminary results have shown the potential for reducing the environmental impacts of food production (Sanyé-Mengual et al. 2015b) and for taking advantage of the residual flows of air in the building (Nadal et al. 2017).

1.6 Motivation

Water transportation and agriculture play a central role in the sustainability of urban areas. According to the current model, which is described in Figure 1.8, water supply provides water to cities and to agricultural activities, consuming the later ones more than 70% of the water worldwide (The World Bank 2017b). Indeed, food contains water that is transported from conventional food production systems to cities for its consumption. Thus, reducing the environmental impacts of the transportation of water is the unifying idea of the dissertation. On the one hand, the current system for the transportation of water must be analysed to improve the environmental performance along its life cycle. On the other hand, alternative food production systems in cities can reduce the transportation of food and reduce the water footprint of food production through the utilization of local resources available in buildings to increase self-sufficiency and to make food production in buildings sustainable.

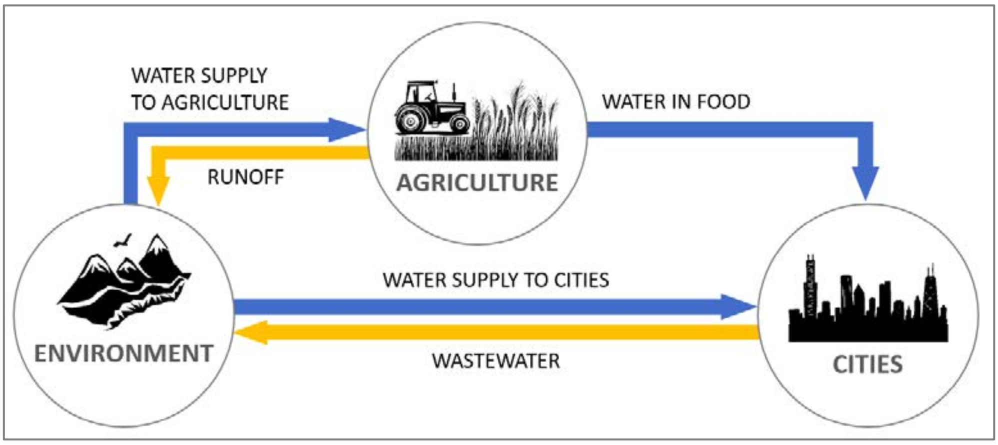


Figure 1.8 Diagram of water transportation in the current model of water supply and food production systems.

Drinking water supply networks must be assessed from a general perspective to obtain comprehensible information about the factors influencing their environmental impacts. Several studies have analysed water supply networks (Venkatesh and Brattebø 2011b, 2012b; Piratla et al. 2012b) or the whole urban water cycle (Lemos et al. 2013b; Amores et al. 2013b) focusing on specific networks or systems as individual case studies. However, the results from these studies show great differences due to the specificity of each case study and the influence of several factors on the characteristic of the network such as the location of the elements of the network in relation with the orography. For this reason, a comprehensive study is required to shed light on which are the key factors affecting their environmental impacts.

The life cycle phases of construction and operation of water supply networks must be analysed separately to cope with the diversity of variables influencing the impacts of one and another. For the construction of the network, the influence of factors such as the pipe material or the diameter should be assessed to determine its effect on the environmental performance and evaluating the less impacting options. Regarding the operation of the network, a top-down study is required to analyse statistically which are the variables that affect the environmental burdens of the network. This will allow understanding the variation in the results obtained in previous studies. Furthermore, the environmental analysis of municipal water storage tanks, which are a basic element of the water supply network, will provide new useful information regarding the environmental impacts of these constructions. Despite being a common element in the urban water cycle, no previous studies assessed water storage tanks from a life cycle perspective.

The consumption point is also a key element in the urban water cycle, and a proper management can generate water savings, avoiding costs and environmental impacts. The assessment of innovative water-saving technologies implemented in a building can provide useful information about these technologies, as well as recommendations to improve future projects. Although more case studies will be needed to consider the different scenarios and typologies, this case can represent a significant first step to evaluate the implementation of these technologies in cities.

Finally, cities hold a great potential for synergies between water, food and energy, which can lead to new systems integrating these flows. This dissertation will adopt this innovative approach and explore the potential uses of water for food production in a water-efficient building. As stated in previous literature from Vertical Farming, pilot projects are required applying rooftop farming in order to demonstrate its feasibility and to evaluate its performance (Specht et al. 2013; Sanyé-Mengual et al. 2016). A rooftop greenhouse integrated with the building in terms of water, air and energy will be analysed through experimental data. This data can provide reliable information about the metabolism of the system and prove the feasibility of integrated rooftop greenhouses. The environmental impacts of this type of food production system will be assessed, evaluating potential improvements and comparing its impacts with reference values.

1.7 Research questions and objectives

The main objective of this dissertation is **to assess the environmental performance of water supply networks and to evaluate a new model of building in cities with high water self-sufficiency and integrated food production**. With this purpose, the following research questions were formulated:

- **Research question 1**: What are the main factors affecting the environmental impacts of water supply networks in cities and which improvements should be implemented?
- **Research question 2**: How effective are water-saving technologies used at the building level in urban areas?
- **Research question 3**: Are integrated rooftop greenhouses an efficient and sustainable alternative for food production in cities?

With this purpose, the following specific objectives are stated:

Water supply networks

- **Objective I** – To assess the environmental impacts of drinking water supply networks comparing alternative constructive solutions. (Chapter 3)
- **Objective II** – To analyse the operation phase of water supply networks to identify the main factors affecting the environmental impacts. (Chapter 4)
- **Objective III** – To assess and optimize municipal water tanks from an environmental and a geometric perspective. (Chapter 5)

Water efficiency in buildings and vertical farming

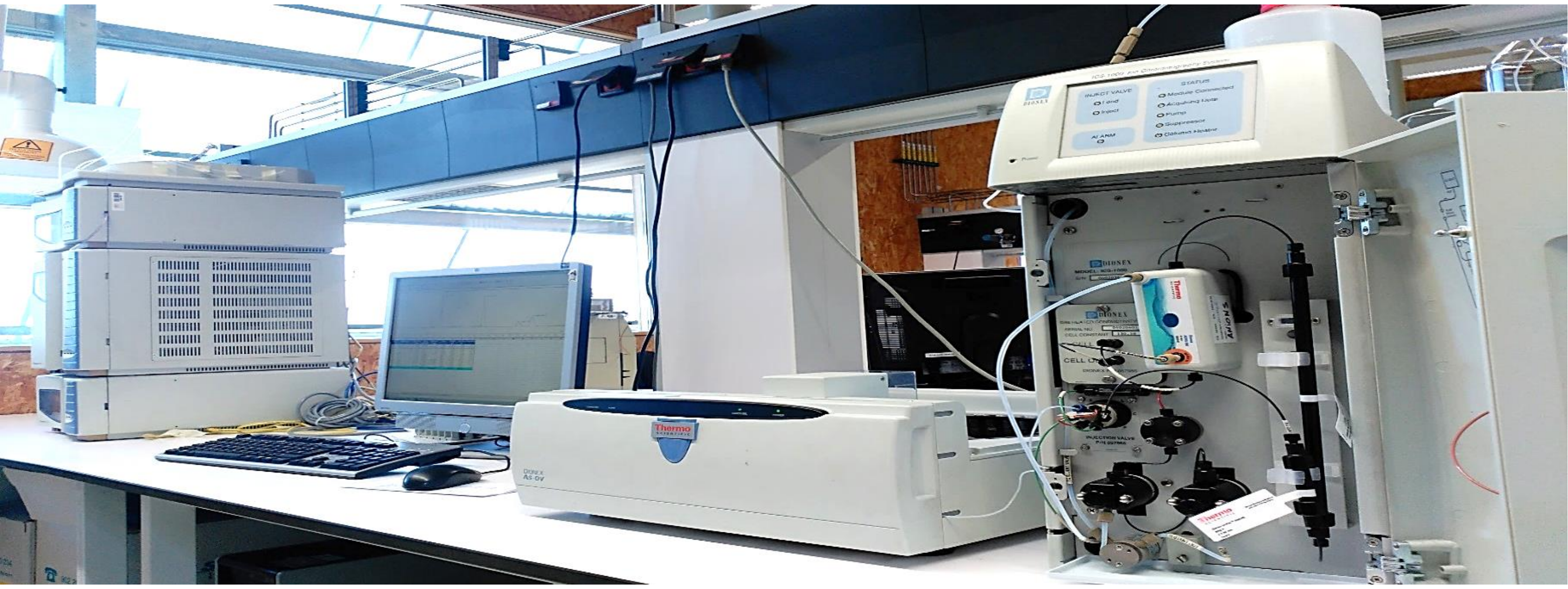
- **Objective IV** – To study the water flows of a building with innovative water-saving technologies to evaluate its water efficiency performance. (Chapter 6)
- **Objective V** – To analyse the nutrient flows in an integrated rooftop greenhouse with a hydroponic crop to define its metabolism. (Chapter 7)
- **Objective VI** – To evaluate the feasibility of integrated rooftop greenhouses and assess its environmental performance as food production systems. (Chapter 8)

Table 1.4 Classification of the objectives and chapters within the research questions of the dissertation.

	Objectives	Chapters
Research question 1: What are the main factors affecting the environmental impacts of water supply networks in cities and which improvements should be implemented?	**I** **II** **III**	3 4 5
Research question 2: How effective are water-saving technologies used at the building level in urban areas?	**IV**	6
Research question 3: Are integrated rooftop greenhouses an efficient and sustainable alternative for food production in cities?	**V** **VI**	7 8

Chapter 2

Methodological framework



Picture: Laboratory with the Ion Chromatography System

©David Sanjuan-Delmás

Chapter 2 Methodological framework

This chapter presents the methodology relevant for the dissertation. Since each study presented in the document includes the specific methodology implemented, this chapter will only describe the elements that have not been stated within each of the specific studies or that affect the whole dissertation and need further explanation.

2.1 Methodology overview

Different methods were used for the studies conducted in the dissertation, as shown in Table 2.1. The environmental life cycle assessment (LCA) methodology was used for the quantification of the environmental impacts of the system under study in chapters 3, 5 and 8. In the case of chapter 4, data regarding the management of water supply networks was statistically analysed. Finally, chapters 6 and 7 addressed the water balance in the ICTA-ICP building and the nutrient (and water) balance in the i-RTG, respectively, describing the water and nutrient dynamics of these systems.

Table 1 Methodology applied in each of the chapters and study system.

	Environmental LCA	Statistics	Nutrient/water balance	Study system
Chapter 3	•			Cities - Water supply network
Chapter 4		•		
Chapter 5	•			
Chapter 6			•	Building - ICTA-ICP
Chapter 7			•	Vertical farming - i-RTG
Chapter 8	•			

The water supply network, which was described in section 1.2.2, has been analysed in Part II (Chapters 3 to 5) following the methodology stated in Table 2.1. In terms of infrastructure, two different systems were assessed: the network (pipes, trench and appurtenances) and municipal water tanks, which are an element of the network required for its functioning. As commented above, the LCA methodology, which is described in section 2.2, was used for the assessment of these infrastructures. In the case of water tanks, the assessment of the tanks also included a structural analysis to estimate the quantity of steel and concrete required for its construction. This structural analysis was developed by the Universitat Politècnica de Catalunya (UPC), in the framework of a collaboration, but it is included in the dissertation due to its relevance within the assessment of water tanks.

The results of the environmental assessment of the water supply network infrastructure were applied to real case studies. For the infrastructure of the network, the water supply network of Betanzos (Spain) was considered. For the water storage tanks, tanks from the water supply network of Calafell (Spain) were considered. More details regarding these case studies can be found in section 2.4 of the methodology.

The use phase of the network (including network and tanks) was excluded from the assessment due to the variability of the impacts depending on the case study. These variations are due to variables such as the distribution of the elements of the network in relation with the orography or the distance between the drinking water treatment plant and the consumption point. As shown in Table 2.2, a statistical analysis was conducted considering a sample of networks from Spanish municipalities. Additionally, the carbon footprint was included in the study in order to provide some basic information about the environmental impacts of this life cycle phase.

Table 2.1 Methodology for each life cycle stage assessed in the water supply network.

Life cycle stage	System of study	Methodology	Chapter
Extraction of materials	Network and water tanks	LCA + structural analysis*	3&5
Production			
Transport and distribution			
Installation			
Use		Statistical analysis + carbon footprint	4
End of life		LCA + structural analysis*	3&5

**Used for the assessment of water tanks, conducted by the Universitat Politècnica de Catalunya.*

Part III of the dissertation focuses on water consumption and vertical farming systems in buildings, analysing a specific case study, the ICTA-ICP building, which includes research-oriented facilities and is in the campus of the Universitat Autònoma de Barcelona. This building was designed aiming at being efficient in the use of water, energy and materials, including systems for the harvest and use of rainwater, the reclamation of greywater, the utilization of geothermal energy as well as passive climate control to reduce energy consumption. The building holds an integrated rooftop greenhouse (i-RTG) on the top.

The general features of the building and all the information regarding the water flows are presented in Chapter 6, which focuses on the analysis of water flows at a building level. The i-RTG is connected to the building in terms of water, energy, carbon dioxide and food, generating synergies that allow improving the efficiency of both the greenhouse and the building. The details of the i-RTG are described in Chapter 7 and 8, which assess the operation of the system conducting tomato crops. Chapter 7 implements a nutrient balance to quantify the flows of nutrients and water in the crop, whereas Chapter 8 calculates the environmental impacts of tomato production in the i-RTG following the LCA methodology.

During the tomato crops conducted in the framework of Chapters 7 and 8, the concentration of nutrients in the different flows of the crops were measured, as detailed in the respective chapters. Regarding the nutrient solution and the leachates, these concentrations were analysed along the crop using ion chromatography. Ion chromatography was a new method that had not been previously used in the research group, and the student had to develop the procedures for its use, as detailed in section 2.3 of the methodology.

Finally, the ICTA-ICP building and the i-RTG are described in Part III, but section 2.4 of the methodology includes complementary information about the energy flows in the ICTA-ICP building and the start-up and operation of the i-RTG.

2.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is an analytical tool to quantify the environmental impacts of a product, system or activity. The main characteristic of a typical LCA is that the whole life cycle of the product is assessed, including raw materials acquisition, production, use, end-of-life treatment, recycling and final disposal, considering all the significant inputs and outputs affecting the environment in each phase.

During the last decades, the LCA methodology has gained recognition and now it is an extended method for the environmental analysis of products and systems. In 1997, the International Organization for Standardization (ISO) published the first version of the ISO 14040 standard for Life cycle assessment – Principles and framework (ISO 2006a), a document that normalizes the application of LCA. The document defines four main stages for the application of LCA that have been represented in Figure 2.1 and are described below. However, LCA is an iterative process and these stages might need to be redefined along the development of the study.

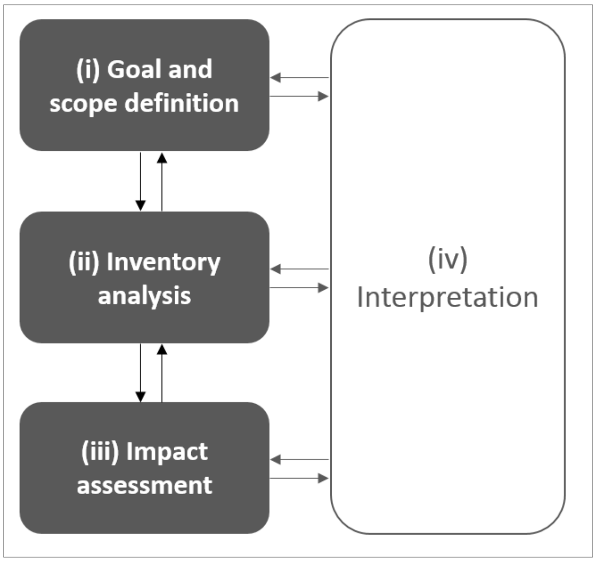


Figure 2.1 Main stages of the life cycle assessment methodology.
Source: ISO (2006)

(i) Goal and scope definition

The first phase of the LCA is the definition of the goal and scope of the study. The goal of the study must be stated along with the reasons for carrying the study, the intended audience and the applications. The scope of the study includes all the relevant information regarding the assessment of the product system. The most relevant elements of the scope are the definition of the functional unit, which is the reference to which all inputs and outputs are normalized and the system boundaries, which states which unit processes must be included within the LCA. The ISO recommends including a flow diagram with the unit processes and its inter-relationships to clarify the elements included in the study.

(ii) Inventory analysis

The inventory analysis or life cycle inventory analysis (LCI) is made up of the collection of all the qualitative and quantitative data from the unit processes of the system. The inventory usually includes the quantity of raw materials and energy used, the waste generated, the treatments conducted and the emissions to the air, water and soil. These inputs and outputs must be provided for each unit process, and data can be measured, calculated or estimated. Obviously, the reliability of the information and results is highly dependent on how this stage is conducted.

(iii) Impact assessment

In the impact assessment or life cycle impact assessment (LCIA) the environmental impacts of the functional unit are calculated from the results of the inventory. Firstly, the impact categories for the assessment must be selected and each of the emissions derived from the LCI are classified into the impact categories in which they have an impact (one emission can affect several categories). Then, for each impact category all emissions are multiplied by a characterisation factor, converting these emissions into a single indicator that quantifies the impact of this category in a comprehensive manner. After characterisation, there are three optional steps: normalisation, grouping and weighting, which were not considered in this dissertation. These steps are scientifically less accepted because they entail a greater uncertainty and subjectivity, and thus were not implemented for the dissertation. All the information for the calculation in the LCIA is included in the calculation method. The resulting indicators from characterisation can be at midpoint or at endpoint level. Midpoint indicators are problem-oriented, and show the total emissions for an impact category (e.g. kg of CO_2 eq for global warming). Endpoint indicators are damage-oriented, and represent the final impact of the emissions in three areas of protection: human health, natural environment and natural resources (e.g. disability adjusted life years for the effects of toxicity) (EC-JRC 2010).

In order to conduct the LCIA in the dissertation, the newest version available of the Software Simapro and the database ecoinvent were used. Thus, different versions were used in Part II and III because a new version of the software and the database was launched during the development of the dissertation. Similarly, different methods were used in Part II and III because there was a significant update. In Chapters 3 and 5, Simapro 7 (PRé Consultants 2010a), and ecoinvent 2 (ecoinvent 2009) were used, along with the calculation method CML Baseline 2001. In Chapter 8, Simapro 8 and ecoinvent 3 (Swiss centre for life cycle inventories 2013) were used with the calculation ReCiPe Midpoint with hierarchical perspective. Table 2.3 shows the impact categories selected in each part of the dissertation, as well as the methods used for the calculation.

(iv) Interpretation

Finally, the interpretation of the LCA includes the identification of the significant issues based on the results of the LCI and LCIA, the evaluation of completeness, sensitivity and consistency and the conclusions, limitations and recommendation of the study. Provided the iterative nature of LCA, the interpretation of results may involve a revision of any of the stages.

Table 2.2 Impact categories considered in each of the chapters of the dissertation and methods used for the calculation.

Acronym	Name	Unit	Definition
Method: CML 2001			**Chapters 3 & 5**
Acronym	**Name**	**Unit**	**Definition**
ADP	Abiotic depletion potential	kg Sb eq	Reducing the stock of natural resources regarded as non-living, such as iron ore or crude oil.
AP	Acidification potential	kg SO_2 eq	Some pollutants have the effect of acidifying soil, water, organisms, ecosystems or materials (buildings). It can lead to problems such as fish mortality in acidified lakes.
EP	Eutrophication potential	kg PO_4^{3-} eq	The impact of high concentrations of macronutrients (especially nitrogen and phosphorus) in aquatic and terrestrial ecosystems, which can lead to depressed oxygen levels in water.
GWP	Global warming potential	kg CO_2 eq	The impact of certain anthropogenic emissions to the atmosphere enhance radiative forcing, increasing earth's surface temperature.
OLDP	Ozone layer depletion potential	kg CFC-11 eq	Some anthropogenic emissions reduce the thickness of the stratospheric ozone layer, which increases the fraction of solar UV-B radiation reaching the earth's surface, with potential harm on human and animal health and ecosystems.
PCOP	Photochemical oxidation potential	kg C_2H_4 eq	Solar radiation affects some primary air pollutants forming reactive chemical compounds such as ozone that can damage human health, ecosystems and crops.
Method: Cumulative energy demand			**Chapters 3 & 5**
CED	Cumulative energy demand	kg 1.4 DB eq	Direct and indirect energy used throughout the life cycle of the product.
Method: ReCiPe Midpoint (H)			**Chapter 8**
CC	Climate change	kg CO_2 eq	Described above.
ET	Terrestrial ecotoxicity	kg 1,4-DB eq	Ecotoxicity refers to the impact of chemicals affecting ecosystems, and is calculated considering the persistence of these chemicals and its toxicity (effect). Terrestrial ecotoxicity refers to the effect on industrial soil.
	Freshwater ecotoxicity	kg 1,4-DB eq	Ecotoxicity affecting freshwater.
	Marine ecotoxicity	kg 1,4-DB eq	Ecotoxicity affecting seawater.
TA	Terrestrial acidification	kg SO_2 eq	Deposition of inorganic acidifying inorganic substances such as sulphates, nitrates and phosphates that can deviate pH from the optimum or acceptable.
FE	Freshwater eutrophication	kg P eq	Eutrophication (described above) caused by phosphorus enrichment of freshwater.
ME	Marine eutrophication	kg N eq	Eutrophication (described above) caused by nitrogen enrichment of seawater.
FD	Fossil fuel depletion	kg oil eq	The reduction in the availability of fossil fuels as a consequence of its use, which leads to an increment on the costs of extracting these fuels.

Source: Guinée et al. (2001); Hischier et al. (2010); Goedkoop et al. (2013)

2.3 Ion chromatography

During the crops conducted in the i-RTG, samples of the nutrient solution and the leachates were collected and analysed using ion chromatography. The main goal of these analyses was to measure the quantity of nutrients supplied and leached and to adapt the nutrient solution to the needs of the plants. The results were used to adjust the nutrient supply during the crops and to study the nutrient balance in i-RTG crops.

The ion chromatography methodology had not been used in the Sostenipra research group previously. The equipment used was twelve years old and had been unused for a long period, for this reason it had to be prepared. The equipment was a Dionex™ ICS-1000 Ion Chromatography System (ICS-1000), which had been unused for years. A tune-up was done by Vertex Technics S.L., an external enterprise, checking all the elements and making the necessary repairs.

The main elements of the ion chromatography system (ICS) are described in Figure 2.2 and Table 2.4. In the operation of the system, a mobile phase or eluent is constantly pumped along the circuit while the system is running. The sample that must be measured is injected into the stream of eluent and goes through the ion separation columns, where the different ions of the solution are separated (each has a different speed while going through the resin of the column). The ions arrive at the conductivity cell one after the next, which enables identifying and quantifying its concentration in the sample according to the chromatogram (Figure 2.3).

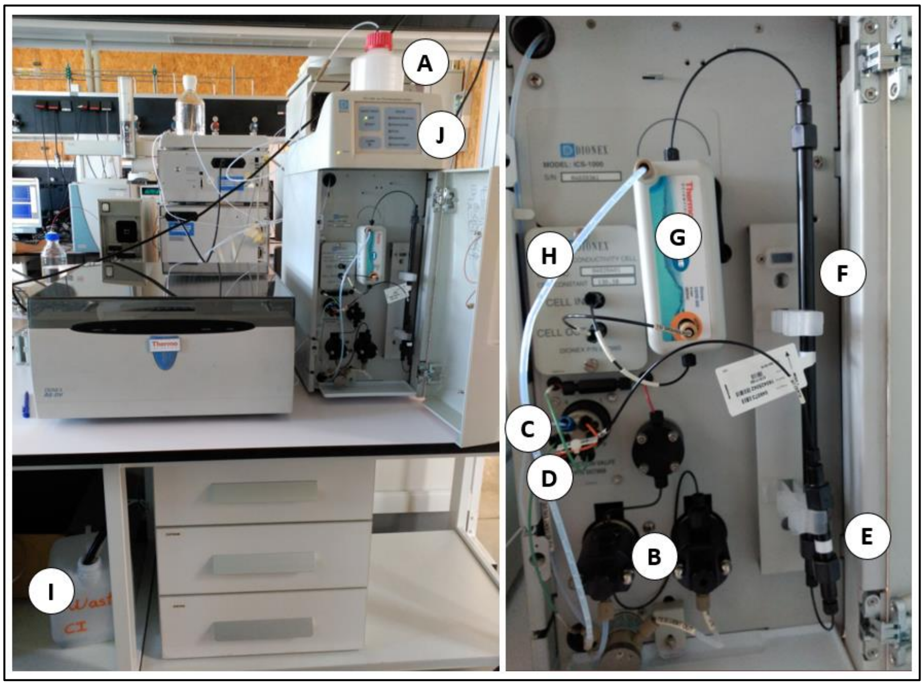


Figure 2.2 Picture of the interior of the ion chromatography system, with each of the elements marked (names in Table 2.4).

Table 2.3 Description of the elements of the ion chromatography system (picture in Figure 2.2).

Code	Element	Description
A	Eluent bottle	Recipient that holds the eluent or mobile phase to feed the circuit of the ion chromatography system.
B	Pump	Device for pumping the mobile phase.
C	Injection valve	This valve connects the following tubes: eluent entrance (from the eluent bottle), sample (autosampler), waste (to waste container) and columns (to guard column). It has two positions: charge and inject. Charge: Eluent entrance and columns are directly connected, and the sample is connected to waste through the loop. If a sample is injected, it fills the loop. Injection: Eluent entrance and columns are connected through the loop, sweeping the sample within it.
D	Loop	A section of tube in the injection valve that stores the sample when it is injected until it is swept by the eluent into the mobile phase.
E	Guard column	A tubular component similar to the separation column but shorter that has the function of protecting the separation column.
F	Column	Tubular component that separates the ions in the problem sample, which enables its identification and quantification.
G	Suppressor	A component with prismatic shape that reduces the background noise of the conductivity detection and improves the signal of the ions being measured.
H	Conductivity cell	A device that makes continuous measuring of the conductivity of the eluent and sample. The data generated allow defining the chromatograms.
I	Waste container	Recipient that collects the waste liquid.
J	Control panel	Panel that shows the state of the different components of the ion chromatography system (green LED on=running).

To obtain the concentration of each element in the sample from this chromatogram, a calibration must be done defining a quantification method. The quantification method is made up of one calibration curve for each of the elements analysed, which shows the relation between the concentration of the element and the value of conductivity measured in the cell. This method is obtained sampling standard solutions with known concentrations for each of the different ions (Figure 2.3). Although when new columns are used each ion has a characteristic speed, this speed through the columns is reduced over time and thus the quantification method must be updated (calibrated) periodically sampling new standards. In order to detect when a new calibration was needed, a standard was measured once per week to check the accuracy of the system and a new calibration was done if the error was higher than 10%. However, for the measurement of the samples carried out during the dissertation a calibration was done at least once per month even if the errors of the standards were lower than 10%.

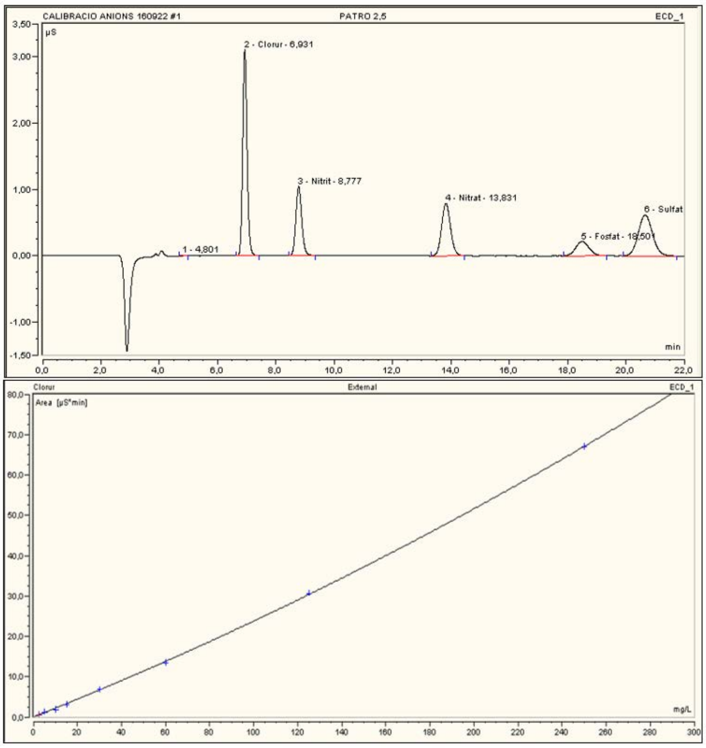


Figure 2.3 Chromatogram with anion measurement (top) and calibration curve with eight standards (bottom).

The equipment (defined in Figure 2.2 and Table 2.4) has two sets of columns and suppressor for the measurement of anions and cations. Regarding the anions, a Dionex™ IonPac™ AS9-HC column was used for the ion separation and a Dionex™ IonPac™ AG9-HC as guard column. The suppressor used was a Dionex™ Anion Self-Regenerating Suppressor ASRS® 300 (4-mm). For the cations, a Dionex™ IonPac™ CS16 column, a Dionex™ IonPac™ CG16 guard column and a suppressor Dionex™ Cation Electrolytically Regenerated Suppressor CERS 500 (4 mm) were used. After the second crop, the separation columns for anions and cations reached its end of life and were replaced (columns are consumable equipment). A more appropriate model for the conditions of the system was selected for the column of cations, improving the resolution and reducing the time required per sample. The new columns were a Dionex™ IonPac™ CS12A column and a Dionex™ IonPac™ CG12A guard column. Regarding the rest of the components, a Dionex™ injection valve (P/N 057968) with a 25 µL loop was used, along with a Dionex™ DS6 Heated Conductivity Cell (P/N 057985). A 2 L bottle was used to contain the eluent and a container to store the waste from the eluent circulation and the samples.

Apart from the ICS, a Thermo Scientific™ Dionex™ AS-DV Autosampler was used to run the samples and both the ICS and the autosampler were operated using the software Dionex™ Chromeleon™ 6.8. Figure 2.4 shows these three main elements of ion chromatography ion chromatography (ICS, autosampler, software).

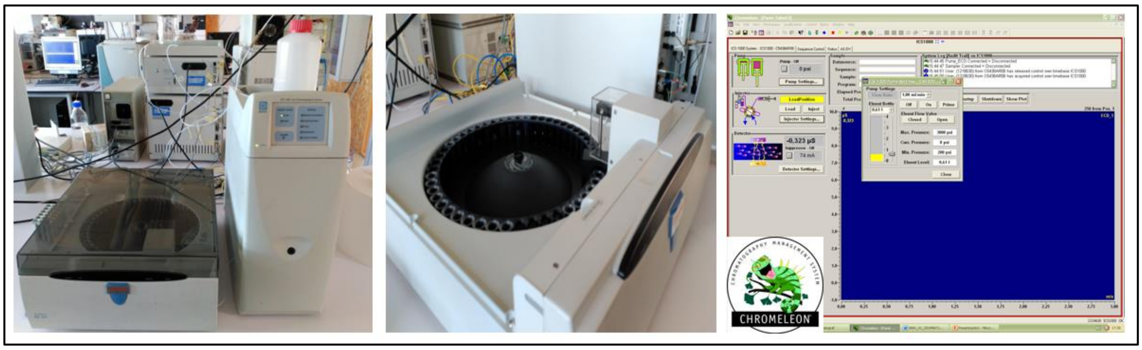


Figure 2.4 Autosampler and Ion chromatography system (left), interior of the autosampler (centre), screenshot of the software Chromeleon (right).

During the operation of the system, only anions (Cl^-, NO^{2-} , NO^{3-}, SO^{4-}, PO^{4-}) or cations (Ca^+, K^+, Mg^+) can be measured at a time because only one set of columns and suppressor can be installed in the equipment. Changing from one to the other involved uninstalling one set and installing the other one. A different eluent is used for anions and cations, it is important to use the adequate eluent and not to mix them because it would spoil the resin of the column, with a risk of breakage. When a set of columns and suppressor (for anions or cations) is installed, eluent must be circulated at least once per week, even if the equipment is not used, to avoid breakage (the column can dry). The procedure to change from one set to another includes the cleaning of the tubes that connect the different elements and the cell circulating deionized water to avoid mixing eluents and the hydration of the suppressors (the one being removed to store it and the one being installed to activate it). The cleaning of the tubes and the cell must also be done when the equipment is uninstalled and will not be used for more than a week.

To start using the equipment, a purge must be done first to remove any bubble of air in the tubes of the circuit. A basic purge is required when the eluent bottle has been changed and air has entered the tube (purging the tube from the bottle to the pump) and a complete purge when the set of columns and suppressor has been installed (purging each section of tube between the elements installed). Then, eluent must be circulated until stabilization, reached when the second decimal place of the value measured in the conductivity cell (in µS) do not vary for 1minute (when the baseline of the chromatogram is completely flat). Table 2.5 shows the values that the system should hold when it is stable.

Table 2.4 Values of the parameters in the ion chromatography system when it is stabilized.

CATIONS	ANIONS
Temperature of the conductivity cell: **40°C**	Temperature of the conductivity cell: **35°C**
Suppressor current: **88 mA**	Suppressor current: **45 mA**
Conductivity stabilized*: **0.6-1.2 µS**	Conductivity stabilized*: **20-30 µS**
Pressure stabilized*: **1,150 psi**	Pressure stabilized*: **2,070 psi**

**These values can vary depending on the components and the age of the equipment.*

The eluent used for cations was methanesulfonic acid with a concentration of 20 mM, which is a slightly lower concentration than indicated by the manufacturer to compensate the lack of heating recommended for that column model to improve resolution (this adaptation is common practice and the results obtained were acceptable). However, it was changed to 25 mM methanesulfonic acid after the second crop, according to the specification for the new model of separation column. For anions, the eluent used was sodium carbonate (Na_2CO3) with a concentration of 9 mM. To ease the preparation of the eluent, a stock solution of Na_2CO_3 with a concentration of 900 mM was done.

The standard solutions used for the calibration of the ion chromatography system included all the ions measured. Various standard solutions were prepared for each calibration, holding each a different concentration of the ions contained. A stock solution was prepared to ease its preparation, with a concentration of 500 ppm for all the elements included. The following solid reagents were used for anions: NaCl, $NaNO_2$, $NaNO_3$, Na_2SO_4, KH_2PO_4; and the following ones for cations: $CaCl_2 \cdot 2\,H_2O$, $MgCl_2 \cdot 6\,H_2O$, KCl. Between six and eight standard solutions were measured to obtain the curves of the quantification method, each with a different concentration.

The samples measured were diluted 1:5 to improve the accuracy of the measurements because usually samples held high concentrations of nitrogen, which were close to the upper measurement limit of the ion chromatography system.

All the water used for the preparation of eluent, standard solutions and samples must be deionized and the eluent must be degasified before being used to avoid air in the circuit of the ICS. For the measurement conducted in this dissertation, all the water used was deionized with a Milli-Q® Integral Water Purification System and the final eluent was degassed using an ultrasonic degassing equipment. Moreover, the samples analysed and the stock solutions were filtered using disposable nylon filters of 0.2 µm for syringe.

In order to transmit the know-how to future users of the ICS in the group, a guide was written in the framework of the dissertation including all the procedures and frequently asked questions affecting the equipment. This guide can be found in the Appendix I.II of the chapter.

2.4 Water supply network: case studies

The results of the LCA of water supply networks and water tanks were applied to specific case studies from medium-sized towns. For the assessment of the network, the municipal water supply network of Betanzos (Spain) was assessed considering all the elements of the network: pipes with ditch and appurtenances, hydrants, valves and pumps. For the water tanks, three case studies from Calafell (Spain) were considered, using the dimensions of the tanks to quantify its environmental impacts. The main characteristics of these municipalities and data regarding the water supply network can be observed in Figure 2.5. Additional information regarding the water extraction, treatment and supply in Betanzos is shown in Figure 2.6.

General characteristics

	Betanzos	Calafell
Population	13,540	24,980
Area (km²)	24.2	20.2
Population density (inhab./km²)	560	1,240
Climate	Oceanic	Mediterranean
Precipitation (mm/year)	1,010	505
Seasonality	Low	High
Gross income per capita (€/capita)	14,400	17,000

Water supply network

	Betanzos	Calafell
Transport network (km)	4.6	14.3
Distribution network (km)	119	148
Water supply (m³/year)	848,000	2,250,000
Water demand per capita (m³/inhabitant·year)	53.8	84.9
Electricity consumption (kWh/m³·year)	0.033	0.051

Figure 2.5 General data regarding the municipalities of Betanzos and Calafell and its water supply networks.

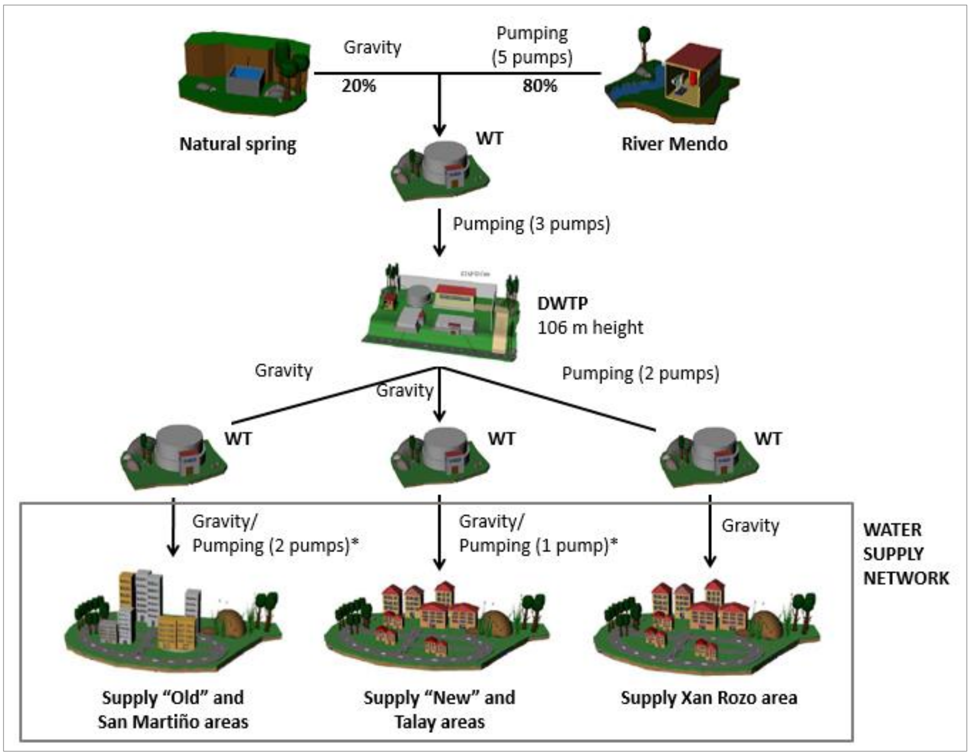


Figure 2.6 Diagram of the Betanzos water supply system, including extraction, treatment and distribution.

**Water is transported by gravity or pumping depending on the sector, DWTP=drinking water treatment plant, WT=water tank*

2.5 ICTA-ICP building and integrated rooftop greenhouse (i-RTG)

The main characteristics regarding the ICTA-ICP building and the water flows at regional scale are shown in Figure 2.7. The building uses two different sources of water: drinking water from the water supply network and rainwater collected in the roof. Regarding the outflows of the building, it can be observed that a part of the wastewater goes to the sewer network and a part goes directly to the environment after a natural treatment outside the building (biofiltration). The water flows within the building are described in detail and analysed in Chapter 6.

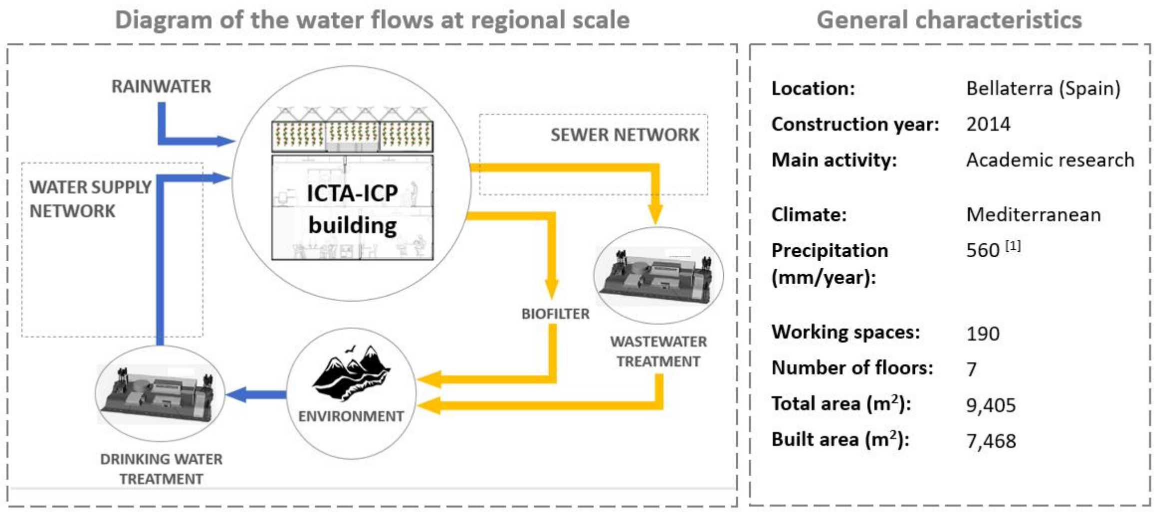


Figure 2.7 Conceptual diagram of the water flows related with the ICTA-ICP building at regional scale.

The building holds an integration with the i-RTG in terms of energy, carbon dioxide, water and food, as shown in Figure 2.8. The i-RTG uses rainwater collected in the roof for the irrigation of crops. Moreover, the waste air from temperature-controlled areas in the building is injected to the i-RTG, improving the temperature of the greenhouse and providing an extra CO_2 concentration for plants. Although this air connection is unidirectional, it contributes to improve the temperature of both the building and the greenhouse. The bidirectionality of this flow will be implemented in future studies.

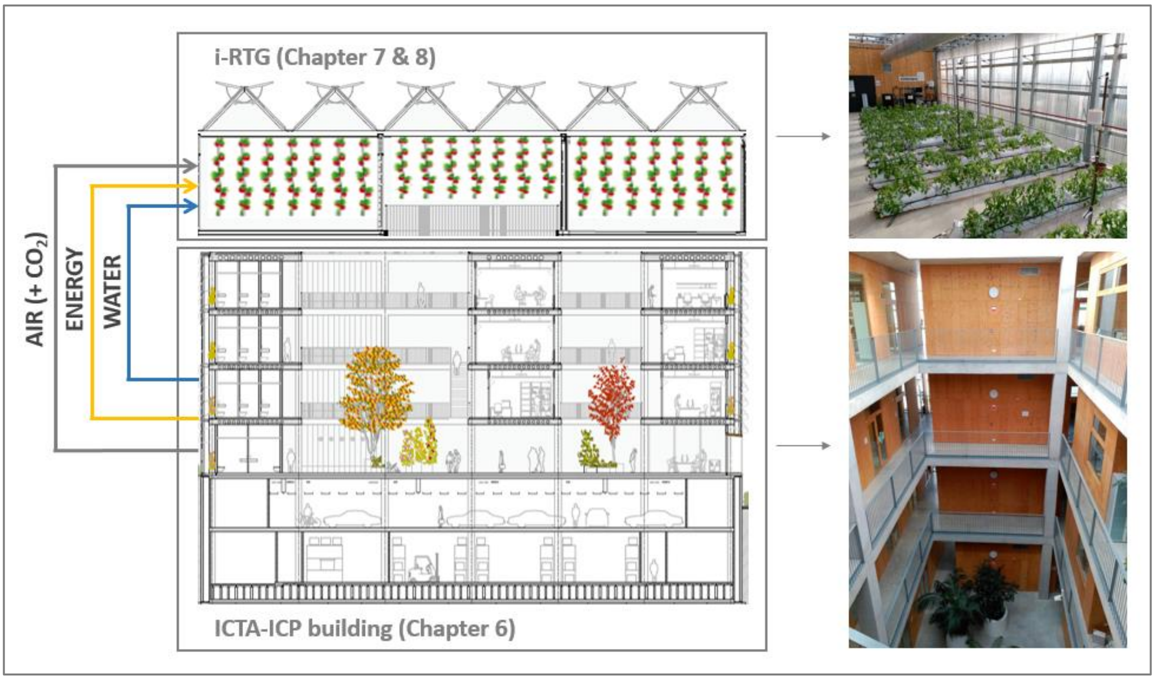


Figure 2.8 Conceptual diagram of the connection between the i-RTG and the ICTA-ICP building.

In terms of energy, the building was conceived aiming at reducing the energy consumption while maximizing comfort. The whole building holds a "double skin" made up of a structure with a steel framework and polycarbonate sheets that open and close automatically for ventilation (Figure 2.9). Temperature in semi-open spaces such as corridors and atriums is only controlled by this double skin by means of the opening and closing of the sheets. Offices and other areas such as the dining room or conference rooms have crossed ventilation, which are windows placed in opposite walls that generate a draught when opened (Figure 2.9), and a climate control system based on the use of geothermal energy. This system is made up of a circuit of pipes that transport water underground to capture geothermal energy and pump it through a circuit integrated in the floor and the ceiling of conditioned spaces. Finally, laboratories have air-conditioning (active climate-control) because they must ensure constant temperature along the year. All these climate-control systems are regulated by hardware and software specifically designed for the building that works in accordance with a set of sensors measuring temperature, humidity and CO_2.

Figure 2.9 Corridors opened to the atrium with no climate control (left), window for cross-ventilation system in an office (centre) and polycarbonate sheets of the building structure opening (right).

The 4th floor of the building is the rooftop, a space covered by the double skin of polycarbonate and steel of the building. This floor holds several rooms for machinery and accesses to the emergency stairs of the building. Although the whole floor could potentially be considered a greenhouse, only the spaces in the corners can be connected to the building to become i-RTGs. As shown in Figure 2.10, these spaces have part of the walls and the roof covered with the double skin of the building and another part are wooden walls belonging to the rooms. Moreover, each of these spaces is open to one of the four atriums in the building, but the i-RTG has a plastic canvas that allows being isolated from the atrium if necessary.

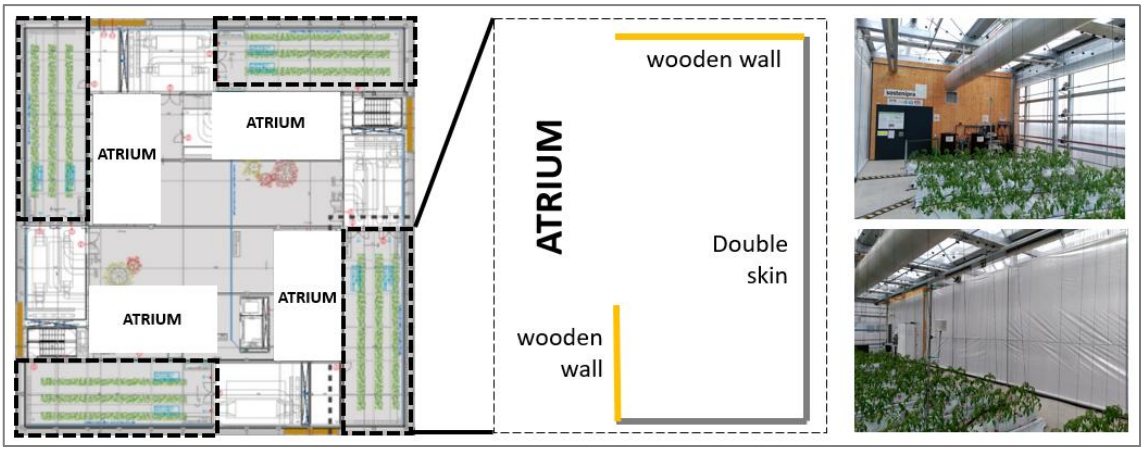


Figure 2.10 Blueprint of the 4th floor of the building and the i-RTG (left) and images of the i-RTG (right).

2.5.1 Start-up of the i-RTG

The i-RTG was initially empty, with only the connections to the drinking water network and the rainwater harvesting system of the building. Firstly, the hydroponic irrigation system was installed connected to the drinking water network, in collaboration with the Agrifood Research and Technology Institute (IRTA). This system was made up of an irrigation head supplying the water with the necessary nutrients to the circuit that distributes this solution in the crop. A network of pipes distributes the nutrient solution from the irrigation head to the plants, delivering the solution through drippers (one per plants). Figure 2.11 shows the diagram of the initial system with its main elements.

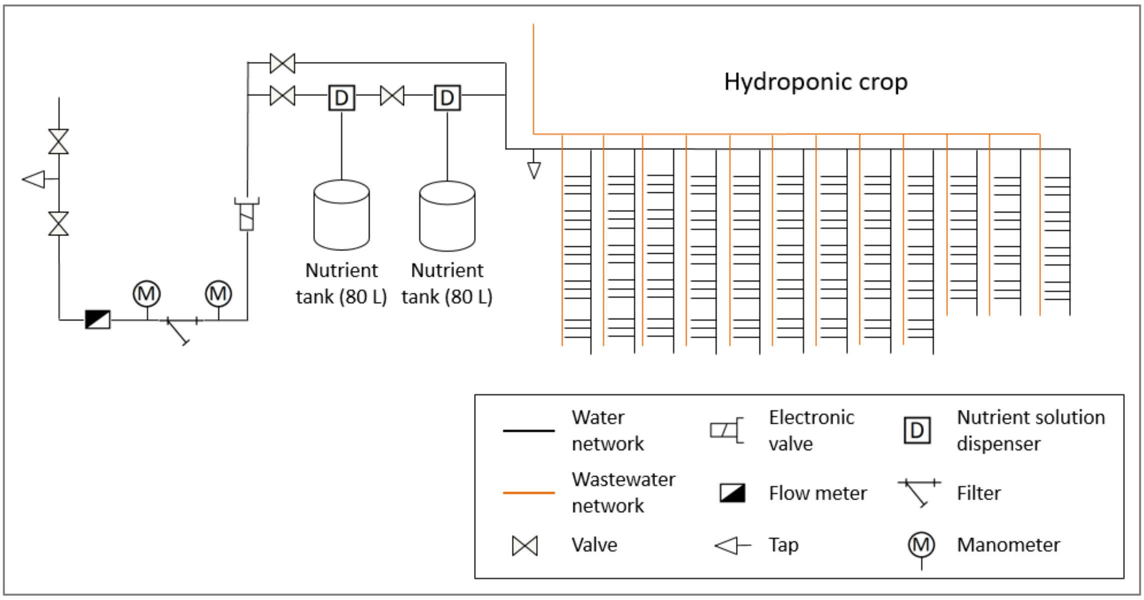


Figure 2.11 Schema of the irrigation system of the crop.

At the beginning of the circuit, the incoming water goes through a flow meter to account the volume and a water strainer with a 50-mesh filter (wires per square inch) to retain any particles. Two manometers were included, before and after the filter, to check that there was enough pressure for an adequate irrigation and to quantify the loss of pressure in the filter to detect possible clogging (if the second manometer had unusual lower pressure than the first one). The system included an irrigation timer Hunter® X-CORE with a solenoid valve Rain Pro 8410B, which controlled the timing for irrigation. Two black polyethylene tanks with 80 L in volume contained concentrated nutrient solutions that were separately injected to the water stream by means of two injectors to obtain a nutrient solution with the adequate concentration of nutrients. Each of the injectors supplied different mineral nutrients; Nutrient Tank 1 contained K_2SO_4, KPO_4H_2 and KNO_3, whereas Nutrient Tank 2 contained $CaCl_2{\cdot}2H_2O$, $Mg(NO_3)_2$, $Ca(NO_3)_2$, Tradecorp® AZ and Sequestrene® 138Fe (the later ones are compounds with micronutrients such as iron or manganese). The circuit included a bypass to deliver water without nutrient solution in case of breakdown. After the irrigation head, a primary pipe transported the nutrient solution to each of the rows, and a secondary pipe in each row delivered the water to the drippers, which were placed in the substrate.

The substrate bags were placed in rows of 5 (15 plants per row), except for two of the rows, which only included 4 bags to respect the security distance to an emergency exit. The bags were placed on expanded polystyrene (EPS) leachate collection trays, which lead the excess of irrigation from the bags to a drain located in one side of the i-RTG, as shown in Figure 2.12. Two individual iron trays were placed under two of the substrate bags to store its leachates. The volume stored in these two trays was used to estimate the total volume of leachates generated in the crop. According to the expertise of the agronomic experts in the Fertilecity project, this water irrigated in excess must be between 30 and 40% of the incoming nutrient solution, and the irrigation timing must be adapted daily to maintain this value within the range.

Figure 2.12 Pictures of the perlite bags on the leachate collection trays.

Regarding temperature control, the opening and closing of the building “double skin” was controlled by a software. In collaboration with SIEMENS (the designers of the software of the building), the part of the double skin affecting the i-RTG was partially separated in terms of management from the rest of the building to be able to define different ranges of temperatures and humidity. Thus, the polycarbonate sheets in this part of the rooftop open and close in accordance with the needs of temperature and humidity of the i-RTG. Moreover, the software was also modified to collect specific data from some elements in the building affecting the management of the greenhouse, such as the level of the rainwater tank or the consumption of rainwater and drinking water. Additionally, sensors were installed in the i-RTG and in the atrium of the building to measure temperatures and humidity and ease the management.

To check the system, two pilot crops of lettuce were conducted (not included in the studies of the dissertation) with the goal of detecting problems and limitations. The system showed being sufficient to grow food, but a series of problems were detected and afterwards solved as shown in Table 2.6. Grup Sabater S.A., an external enterprise specialised in agriculture, modified the irrigation system to include two water tanks of 300 L each, a water pump and a set of pipes and valves that allowed switching from drinking water to rainwater and vice versa when necessary. Figure 2.13 and 2.14 show the diagram and the picture of the resulting irrigation system in the i-RTG. The modifications implemented were effective, and the problems stated in Table 2.6 were solved in the following crops.

Table 2.5 Problems detected during the lettuce pilot crops and solutions implemented.

Problem detected	Solution implemented
Low water pressure from the water supply network, which leads to precipitation of calcium and clogging in the drippers.	A pump was installed to provide adequate pressure independently from the pressure of the supply network.
Risk of water shortage if the provision from the building was stopped (due to breakdown or maintenance).	Two water tanks of 300 L each were installed within the i-RTG to feed the pump. These tanks were constantly replenished with water from the network, and its water level was controlled with a mechanism made up of a buoy and a solenoid valve (Figure 2.13).
Not possible to switch from rainwater to drinking water when necessary.	Installing a set of pipes with valves connected to both the conventional water supply network and the rainwater harvesting system that allowed selecting the type of water (drinking water or rainwater) used to replenish each of the water tanks and switch easily when necessary.
Excess of algae in the channels of the trays collecting the leachates.	Installing EPS lids on the channels of the leachate collection trays to stop solar radiation from reaching the channel.

EPS= expanded polystyrene

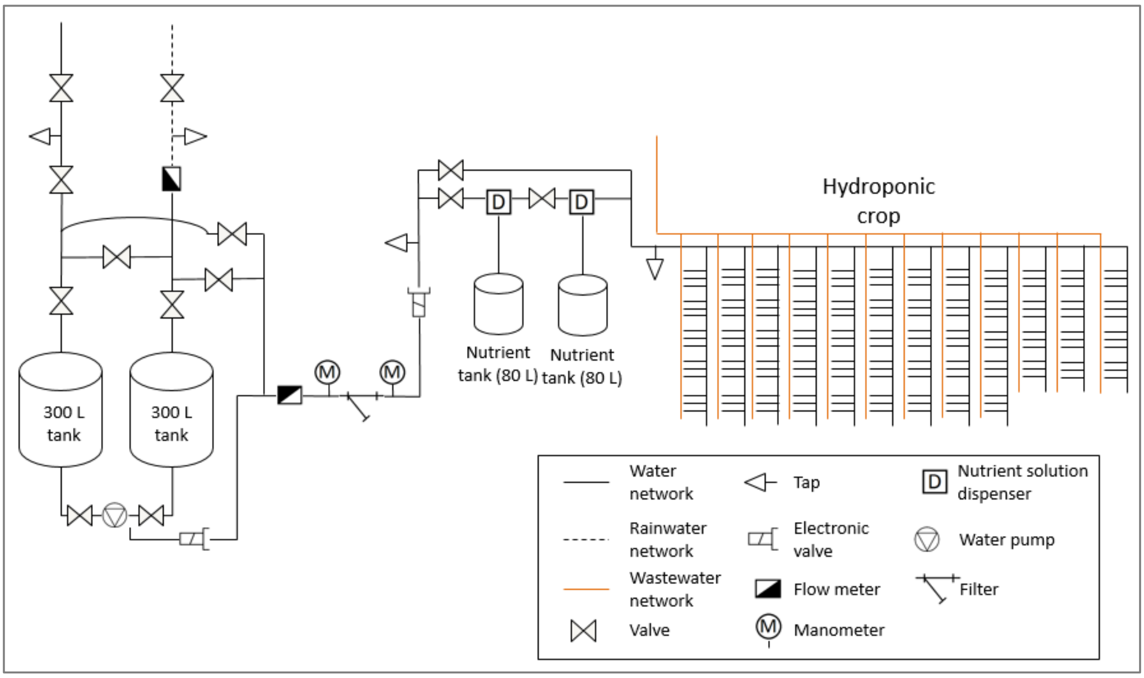


Figure 2.13 Schema of the irrigation system of the crop after implementing the improvements.

Figure 2.14 Final irrigation system of the i-RTG (top), water pump of the greenhouse (bottom left) and interior of a water tank with a buoy mechanism (bottom right).

2.5.2 Operation of the i-RTG

As for the installation of the crop infrastructure, the procedure for the operation of the i-RTG had to be defined from zero. An initial procedure was developed during the two pilot lettuce crops with the help of agronomic experts from the Institute of Agrifood Research and Technology Institute (IRTA). After these pilot crops, three tomato crops were conducted from February 2015 to July 2016 in the framework of this dissertation for the analysis of the i-RTG operation phase. Beef tomato was selected for the crops because it has an added value in comparison with other types of tomato. Table 2.7 shows the basic information of the crops. The management of the i-RTG kept improving along this period, adopting new methods to become more efficient.

Table 2.6 Characteristics and periods of the tomato cultivation.

Cultivation	Season	Starts	Finishes	Days (n)	Variety
S1	Spring-summer	10/02/2015	23/07/2015	164	Arawak
W	Fall-winter	15/09/2015	04/03/2016	169	Tomawak
S2	Spring-summer	08/03/2016	20/07/2016	133	Arawak

S=spring crop, W=winter crop

During the cropping periods, there was constant access to agronomic experts from IRTA, who also visited the i-RTG periodically to check the progress (between once per month and once per week, depending on the period). These experts oversaw issues related to the irrigation, the composition of the nutrient solution, breakdowns in the system and the regulation of temperature and humidity by means of software for the control of temperature and humidity. Additionally, an external expert in plagues inspected the crop every two weeks and provided support along the cropping period. This expert oversaw the application of phytosanitary treatments when necessary and the evolution of plagues and insects in the crop, being the powdery mildew and plant lice the most common affectations.

In order to facilitate the implementation of the procedures and techniques initiated in the framework of this dissertation, all the necessary information for the operation of the i-RTG was written in standard work procedures (Appendix I). Similarly, a guide was elaborated with all the procedures and supporting information required to use the ion chromatography system (Appendix I.II).

During the crops, a daily routine was implemented to detect possible problems. This routine was made up of the following actions:

- To review the equipment in the i-RTG to detect anomalies or breakdowns:
  - The manometers before and after the filter for the incoming water in the irrigation system must indicate similar values.
  - The level of the concentrated nutrient solution in the 80 L polyethylene tanks must be similar in one and another tank and must be sufficient in both tanks.
  - The 300 L water tanks must be full or almost full.
  - The drippers must deliver the nutrient solution to plants with a normal flow.
  - The irrigation timer must work properly.
  - The climate control software must work properly.
- To review the plants to detect any possible anomaly e.g. plagues, death plants, insects.
- To take the reading of the flowmeter that measures the incoming water used for irrigation.
- To measure the volume of leachates collected in the iron trays and to estimate the total leachates from the crop.
- To collect the necessary samples of nutrient solution and leachates (Table 2.8).
- To analyse the pH and the electric conductivity (EC) in the nutrient solution and the leachates to have a quick estimation of the nutrient concentration.
- To adapt the timing for irrigation in accordance with the drainage (% of leachates over the total water supplied).

In addition to the daily checking of the crop, managing tomato crops requires some additional actions that vary depending on the stage of the crop:

- To stake tomato plants as they grow to maintain them straight.
- To prune tomato plants, including the lateral stems and dead leaves and stems in the inferior parts of plants.

- To harvest and weight tomatoes that are ready to be eaten, taking note of the number of tomatoes and the total weight. The production from each row must be accounted separately as well as production from perimeter plants.

In order to analyse the composition of water and nutrient flows in the i-RTG, a procedure was implemented to collect and analyse samples of nutrient solution, leachates, fruits (tomatoes), leaves, stems and substrate (perlite) from each of the crops in accordance with the expertise of the agronomic experts of the Fertilecity project. The details of these procedures are described in Chapter 7. Table 2.8 shows the periodicity of the samples collected and the nutrients analysed in each of the samples, as well as the method used for the analysis.

More details about the i-RTG and the materials and methods used in the crops can be found in chapters 7 and 8, where the studies about the crops are presented.

Table 2.7 Elements analysed in the water and nutrient flows of the i-RTG, methods for the analysis and regularity of the sample collection in each crop.

		Regularity	Ion chromatography								External analysis											
			Cl^-	NO_2^-	NO_3^-	SO_4^-	PO_4^-	Ca^+	K^+	Mg^+	N	P	K	Ca	Mg	Na	S	Fe	Zn	Mn	Cu	B
S1	Nutrient solution	1/week	•	•	•	•	•	•	•	•												
	Leachates	3/week	•	•	•	•	•	•	•	•												
	Leaves	4/crop									•	•	•	•	•	•	•	•	•	•	•	•
	Stem	4/crop									•	•	•	•	•	•	•	•	•	•	•	•
	Tomatoes	2/crop									•	•	•	•	•	•	•	•	•	•	•	•
	Perlite	1/crop									•											
W	Nutrient solution	1/week	•	•	•	•	•	•	•	•												
	Leachates	3/week	•	•	•	•	•	•	•	•												
	Leaves	4/crop									•	•	•	•	•	•	•	•	•	•	•	•
	Stem	4/crop									•	•	•	•	•	•	•	•	•	•	•	•
	Tomatoes	2/crop									•	•	•	•	•	•	•	•	•	•	•	•
	Perlite	1/crop									•	•	•	•	•	•	•	•	•	•	•	•
S2	Nutrient solution	Daily		•	•							•	•	•	•	•	•	•	•	•	•	•
	Leachates	Daily		•	•							•	•	•	•	•	•	•	•	•	•	•
	Leaves	3/crop									•	•	•	•	•	•	•	•	•	•	•	•
	Stem	3/crop									•	•	•	•	•	•	•	•	•	•	•	•
	Tomatoes	2/crop									•	•	•	•	•	•	•	•	•	•	•	•
	Perlite	1/crop									•	•	•	•	•	•	•	•	•	•	•	•

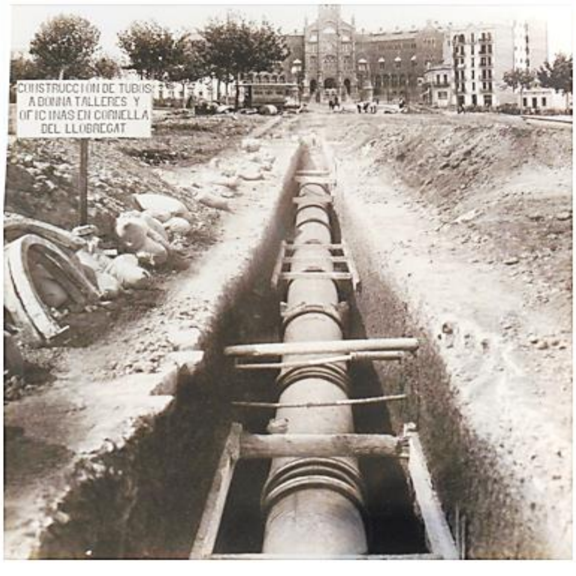
S1=summer crop 1, S2=summer crop 2, W=winter crop

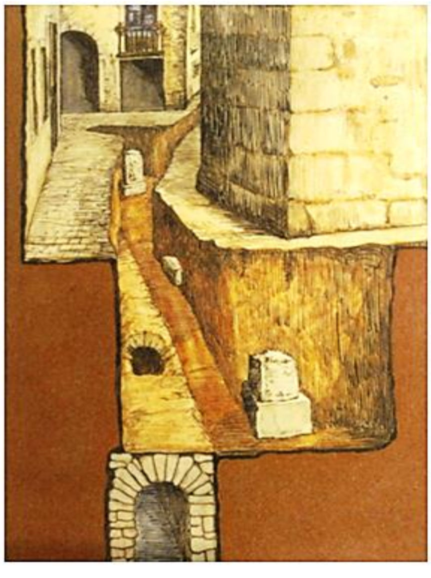
Environmental assessment of urban water supply networks

Part II

Chapter 3

Environmental assessment of different pipelines for drinking water transport and distribution network in small to medium cities: a case from Betanzos, Spain



Pictures:
(left) Open trench for the installation of the water supply network at Las Ramblas in Barcelona (Primo de Rivera Avenue) - summer 1927.
(centre) Open trench for the installation of the water supply network at Catalonia's square – summer 1927.
(right) Romanic non-pressurized canalisation documented in Palma de Sant Just for the supply of thermal water.

Pictures from the exhibition *Barcelona. L'aigua, xarxes I arquitectura. Aigües de Barcelona*
organised by Col·legi d'Arquitectes de Catalunya

Chapter 3 Environmental assessment of different pipelines for drinking water transport and distribution network in small to medium cities: a case from Betanzos, Spain

This chapter is based on the following journal paper:

Sanjuan-Delmás, D., Petit-Boix, A., Gasol, C., Villalba, G., Suárez-Ojeda, M., Gabarrell, X., Josa, A., Rieradevall, J. (2014). Environmental assessment of different pipelines for drinking water transport and distribution network in small to medium cities: a case from Betanzos, Spain. Journal of Cleaner Production, 66, 588–598. https://doi.org/10.1016/j.jclepro.2013.10.055

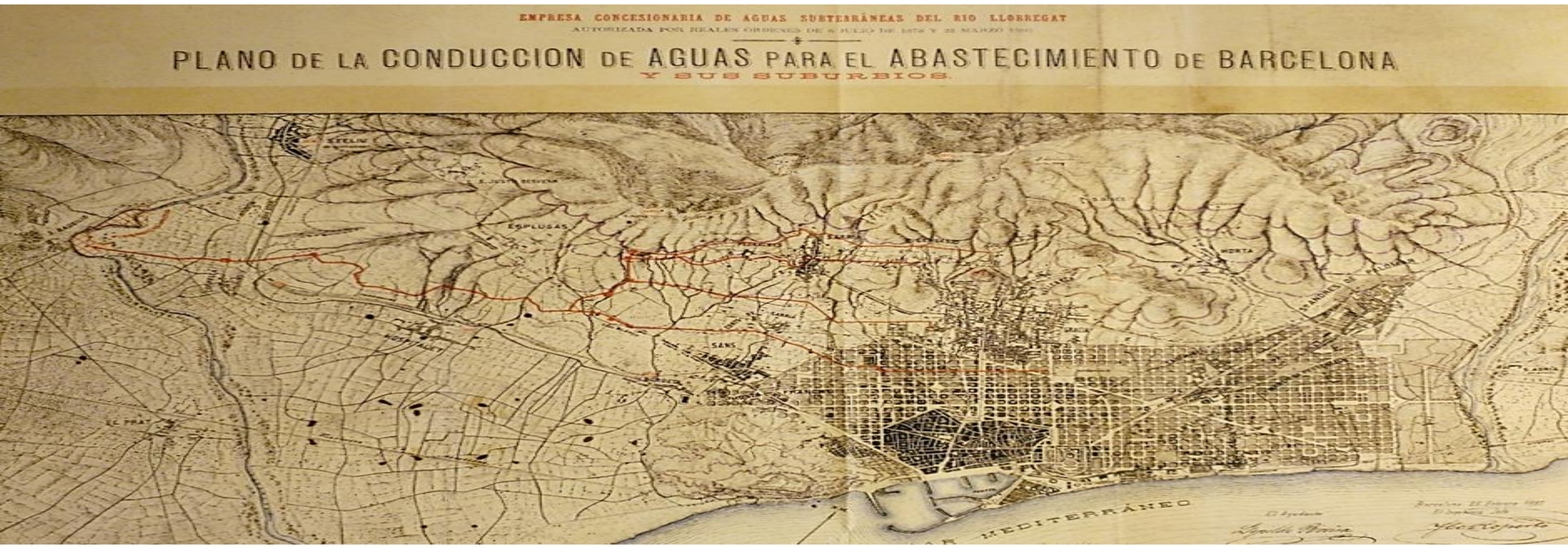
Abstract

Until now, few studies had focused on the environmental impact of the construction phase of a drinking water transport and distribution network (DWTDN). Using the life cycle assessment (LCA) methodology, this article compares the environmental impact of pipes made of different materials as constructive solutions for the DWTDN. Two pipe diameters (90 and 200 mm) commonly used in small to medium-sized cities are analysed. The results show that polyvinyl chloride (PVC), high density polyethylene (HDPE) and low density PE have similar environmental impacts in the case of 90 mm pipe diameter. In the case of 200 mm pipe diameter, ductile iron (DI) and glass fibre reinforced polyester show higher environmental impacts than HDPE and PVC, which in the case of DI are between 3 and 11 times higher than those of HDPE for all the midpoint impact categories. Regarding the different construction phases, installation has a higher percentage of environmental impact for 90 mm pipe diameter (40 to 68% for HDPE in all the impact categories) than for 200 mm pipe diameter (24 to 57% for an HDPE) due to the difference in the amount of material required for the manufacture of the pipe. The assessment methodology was applied to calculate the environmental burdens derived from a case study. The impact of the different elements of the case study network has been added to obtain the global impact. The potential reduction of the environmental impacts of the case study has been calculated substituting the whole actual network by less impacting constructive solutions. A potential reduction of between 6 and 16% of the impact has been found for the case study, although the savings might be greater in networks with greater abundance of more impacting pipe materials such as DI. This methodology allows the improvement of the network and the design of more eco-efficient DWTDN.

Keywords: network; pipe material; LCA; urban infrastructure; eco-efficiency; construction

Chapter 4

Environmental assessment of drinking water transport and distribution network use phase for small to medium-sized municipalities in Spain



Picture from the exhibition *Barcelona. L'aigua, xarxes I arquitectura. Aigües de Barcelona* organised by Col·legi d'Arquitectes de Catalunya

Picture: Blueprint of the water supply network of Barcelona - 1881

Chapter 4 Environmental assessment of drinking water transport and distribution network use phase for small to medium-sized municipalities in Spain

This chapter is based on the following journal paper:

Sanjuan-Delmás, D., Petit-Boix, A., Gasol, C. M., Farreny, R., Villalba, G., Suarez-Ojeda, M. E., Gabarrell, X., Josa, A., Rieradevall, J. (2015). Environmental assessment of drinking water transport and distribution network use phase for small to medium-sized municipalities in Spain. Journal of Cleaner Production, 87(1), 573–582. https://doi.org/10.1016/j.jclepro.2014.09.042Abstract

Previous studies assessing the environmental impacts of drinking water supply networks have considered a bottom-up approach, analysing single case studies. This paper presents a top-down approach for the assessment of the operational phase of a water supply network. A representative sample of 50 cities was statistically analysed to find relations between different variables regarding electricity and water consumption linked with the environmental impacts of the network. The results show that some of the variables are clearly related to the relative energy consumption of the network. Such is the case for population size, where small municipalities have up to 14 times higher relative electricity consumption compared with medium-sized municipalities (1.15E-2 as opposed to 8.3E-4 kWh/m^3 registered water·km of network) due to case-specific factors such as a strong gradient between a water tank and the consumption point. Similarly, the cases showing low population density exhibit 7 times higher relative electricity consumption because of the longer distances that must be covered and the correlation between population density and size. The values found for greenhouse gas (GHG) emissions derived from the energy consumption are consistent with results from previous studies: on average, 5.53 kg of CO_2 eq emissions/inhabitant·year are released, but the variability is very high, ranging from 0.005 to 67.8 kg of CO_2 eq emissions/inhabitant·year. No clearly significant correlations were found between the relative water demand and variables such as seasonality or income per capita, which might indicate that water consumption depends on individual decisions of the population rather than on the variables assessed. Models for the estimation of water demand, length of network and electricity consumption were defined. However, the modelling of electricity consumption presented more difficulties because of its high variability. A protocol for data collection should be defined and implemented in the future to enable the analysis of more high quality case studies and for the definition of more accurate and reliable models.

Keywords: urban water cycle, energy, water supply, water pipeline, sustainability, CO_2 emissions

Chapter 5

Environmental and geometric optimisation of cylindrical drinking water storage tanks

Picture: Historical centre of Calafell

Retrieved from: Ajuntament de Calafell (http://calafell.cat/municipi/patrimoni)

Chapter 5 Environmental and geometric optimisation of cylindrical drinking water storage tanks

This chapter is based on the following journal paper:

Sanjuan-Delmás, D., Hernando-Canovas, E., Pujadas, P., de la Fuente, A., Gabarrell, X., Rieradevall, J., & Josa, A. (2015). Environmental and geometric optimisation of cylindrical drinking water storage tanks. The International Journal of Life Cycle Assessment, 20(12), 1612–1624. https://doi.org/10.1007/s11367-015-0963-y

Abstract

Purpose: Urban water cycle construction processes are an important element to consider when assessing the sustainability of urban areas. The present study focuses on a structural and environmental analysis of cylindrical water tanks. The goal is to optimise cylindrical water tanks from both an environmental (environmental impacts due of life cycle assessment (LCA)) and a geometric perspective (building material quantities for construction purposes depending on the tank characteristics).

Methods: A sample of 147 cases was defined based on different positions (buried, superficial and partially buried), dimensions (combinations of heights and radii) and storage capacities (between 100 and 10,000 m^3). A structural analysis was conducted for a defined set of cases to determine the quantities of steel and concrete required for its construction. The environmental impacts of the entire life cycle were assessed through a life cycle assessment (LCA). Additionally, environmental standards (the less impactful option for each dimension assessed: geometry, storage capacity and position) defined in the study were applied to realistic cases to evaluate potential environmental savings.

Results and discussion: The LCA shows that materials are the main contributor to environmental impacts (more than transport, installation and end of life life cycle stages). For this reason, the results of the structural and environmental assessments coincide. Taller water tanks have shown to be less impactful (60 to 70% less impact for a 10.000 m^3 tank). Regarding the position, superficial water tanks have shown to have between 15 and 35% less impact than buried ones. The environmentally preferred water storage capacity is between 1,000 and 2,500 m^3, being between 20 and 40% less impact. For instance, an 8,000 m^3 tank would emit 1,040 t of CO_2 eq. Applying the environmental standards 170.5 t of CO_2 eq could be saved (16% of the total amount).

Conclusions: The results of this study show that among the cases analysed, superficially positioned cylindrical water tanks of 8.5 m in height and of between 1,000 and 2,500 m^3 in storage capacity present fewer impacts. The use of these standards in municipal water tanks construction projects may significantly reduce environmental impacts (10 to 40%) in all impact categories.

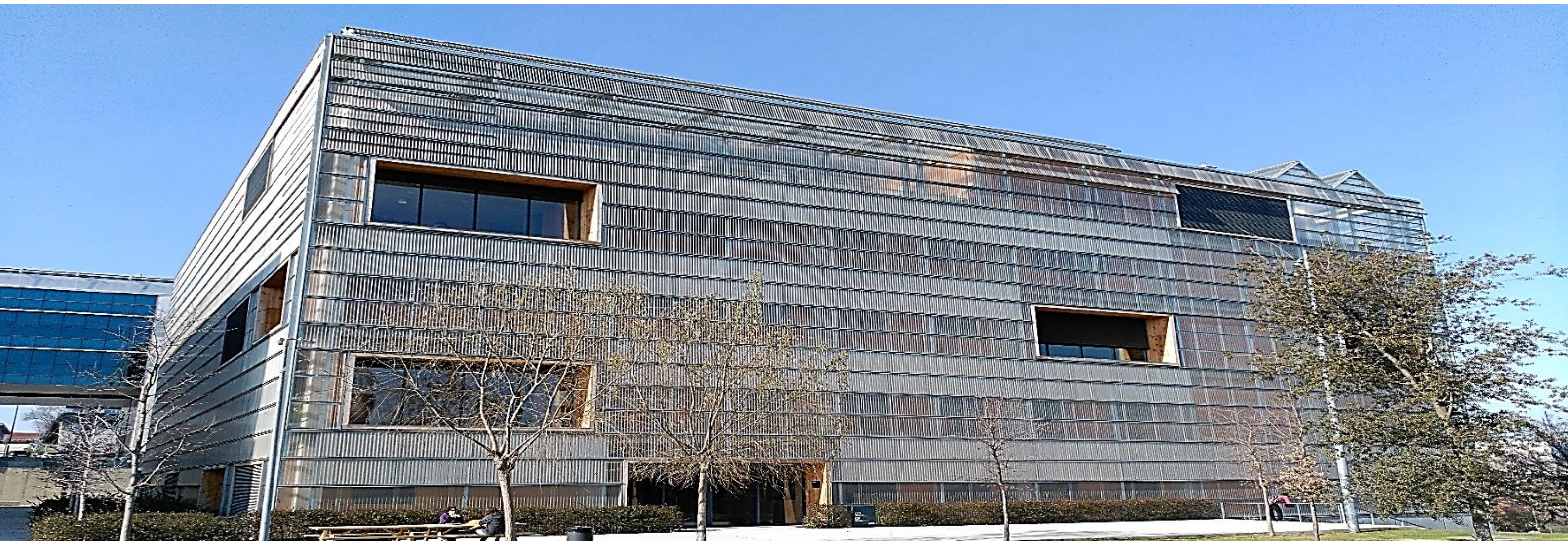
Keywords: urban water cycle, energy, water supply, water pipeline, sustainability, CO_2 emissions

Water flows and vertical farming in buildings

Part III

Chapter 6

Analysis of the water flows in a building with vertical farming from a sustainable perspective



Picture: ICTA-ICP building

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Chapter 6 Analysing water use efficiency in a building with rainwater harvesting and greywater reclamation in a Mediterranean climate

This chapter had the following collaborators:

David Sanjuan-Delmás, Pere Llorach-Massana, Ana Nadal, Mireia Ercilla-Montserrat, Pere Muñoz, Juan Ignacio Montero, Alejandro Josa, Xavier Gabarrell, Joan Rieradevall

Abstract

Previous studies assessing the environmental impacts of drinking water supply networks have considered a bottom-up approach, analysing single case studies. This paper presents a top-down approach for the assessment of the operational phase of a water supply network. A representative sample of 50 cities was statistically analysed to find relations between different variables regarding electricity and water consumption linked with the environmental impacts of the network. The results show that some of the variables are clearly related to the relative energy consumption of the network. Such is the case for population size, where small municipalities have up to 14 times higher relative electricity consumption compared with medium-sized municipalities (1.15E-2 as opposed to 8.3E-4 kWh/m^3 registered water·km of network) due to case-specific factors such as a strong gradient between a water tank and the consumption point. Similarly, the cases showing low population density exhibit 7 times higher relative electricity consumption because of the longer distances that must be covered and the correlation between population density and size. The values found for greenhouse gas (GHG) emissions derived from the energy consumption are consistent with results from previous studies: on average, 5.53 kg of CO_2 eq emissions/inhabitant·year are released, but the variability is very high, ranging from 0.005 to 67.8 kg of CO_2 eq emissions/inhabitant·year. No clearly significant correlations were found between the relative water demand and variables such as seasonality or income per capita, which might indicate that water consumption depends on individual decisions of the population rather than on the variables assessed. Models for the estimation of water demand, length of network and electricity consumption were defined. However, the modelling of electricity consumption presented more difficulties because of its high variability. A protocol for data collection should be defined and implemented in the future to enable the analysis of more high quality case studies and for the definition of more accurate and reliable models.

Keywords: urban water cycle, energy, water supply, water pipeline, sustainability, CO_2 emissions

6.1 Introduction

Chapters 3, 4 and 5 of this dissertation focused on the transport of drinking water, assessing the construction and operation of the water supply network and municipal water storage tanks. From a general perspective, the next step in the urban water cycle is the consumption point, which has been addressed in chapters 6, 7 and 8, as shown in Figure 6.1. It was not possible to analyse together the supply network and the water use at the consumption point due to the complexity and variability of these systems, which depend on very different parameters such as the need for pumping or the consumption habits. For this reason, they were evaluated separately in two distinct parts of the dissertation.

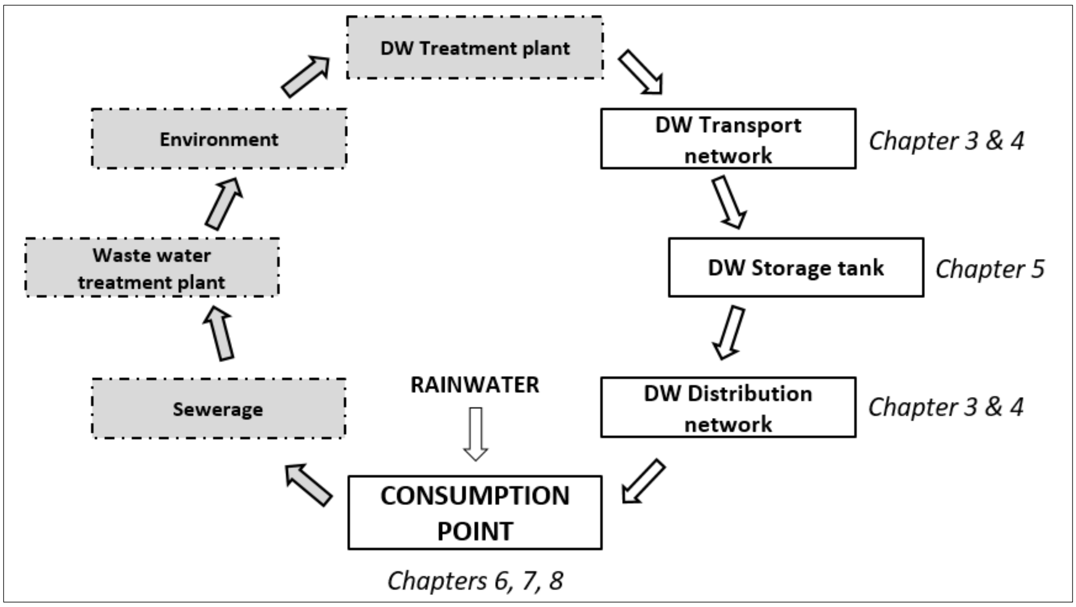

Figure 6.1 Diagram of the urban water cycle and phases analysed in the different chapters.

Grey boxes are not included in the dissertation. DW=drinking water

The management of the consumption of water is a key issue in the urban water cycle to prevent environmental impacts and to save water. As observed in Chapter 5, water use habits are one of the main factors affecting the environmental burdens of the operation of water supply networks. Moreover, water stress in some areas like the Mediterranean can result in severe scarcity during dry seasons. This phenomenon is likely to get worse as a consequence of global warming, which will increase temperature and reduce precipitation in Mediterranean areas (UNESCO 2016). Although the most important water-demanding sectors in Europe are agriculture and industry (80% of the water demand) (European Environmental Agency 2008), the main destination for direct water flows in densely populated areas is domestic uses. Indeed, in cities like Barcelona (considering the metropolitan area) around 70% of water consumption is used for such purposes (IDESCAT 2014). In this context, optimising the water consumption in buildings can be decisive to improve the overall environmental performance of the urban water cycle, saving water and preventing environmental impacts.

Furthermore, there is a substantial potential for synergies of resources in urban areas. The water-food-energy nexus approach highlights the inextricable link between such three aspects for a better understanding of the interactions between human activities and the environment. According to with this new paradigm, urban areas are not mere consumers of water but have an important role producing resources and generating synergies in the use of water, energy and food. This dissertation aims to adopt this approach for the environmental assessment of innovative systems to enhance water use efficiency and to integrate food production into buildings.

The evaluation of the abovementioned issues was done using a specific case study: the ICTA-ICP building. This building is located in the Mediterranean area of Barcelona and has ultimate technology for the utilisation of local water resources, aiming at achieving hydric self-sufficiency. Moreover, in the framework of Vertical Farming, a new concept that consists of growing food in and around buildings, it holds a rooftop greenhouse for research and demonstration purposes. This rooftop greenhouse affects the water flows of the building due to the water consumption of crops and the leachates generated. Furthermore, it has a significant innovation; it is integrated with the building in terms of water, air, energy and food; exchanging flows and increasing the efficiency of both the building and the greenhouse. This new system was named integrated rooftop greenhouse (i-RTG). Chapters 7 and 8 focus on the production of food in the i-RTG. Chapter 7 analyses the balance of nutrients whereas Chapter 8 quantifies the environmental burdens from its food production.

This chapter (6) will assess the water flows in the ICTA-ICP building, discussing drawbacks and possible future improvements. The goal of this study is to describe and analyse the efficiency of water-saving technologies in the ICTA-ICP building, as well as to propose measures for the improvement of the system.

6.2 Methodology

6.2.1 Presentation of the study system

The system under study is the ICTA-ICP building, which includes research-oriented facilities and is located on the campus of the Universitat Autònoma de Barcelona. The building has six floors, four of them (ground floor to the third one) dedicated to offices and labs and two underground floors (-1, -2) to storehouse, labs and parking. Its design was intended to have high standards of sustainability, maximising resource efficiency and comfort. As a result, it was awarded several distinctions such as the *LEED GOLD* certificate for energy efficient buildings (U.S. Green Building Council 2017), the Catalonia Construction Award in 2015 (CAATEEB 2017) and the Catalan ecolabel *Distintiu de Garantia de Qualitat Ambiental* (Catalan Government 2017) for the category of office buildings. These awards recognised the efforts undertaken in the design of the building to integrate water-saving technologies.

The building is a cubic construction characterised by a “double skin” made of polycarbonate that surrounds the main structure (Figure 6.2). On the inside, it holds wide open spaces with lots of natural light and community areas for comfort. It also has several conveniences such as a community full-equipped kitchen and dining room; a changing room with showers; and conference rooms. For aesthetic and comfort reasons, there are ornamental plants within the building, in the space between the walls of the building and the polycarbonate skin and the surroundings outside the building.

Figure 6.2 ICTA-ICP building from the outside (left), one of the four atriums in the building (centre) and a community area for comfort (right).

6.2.2 Description of the water flows

Water is on of the core issues considered in the environmental conception of the building, for this reason, specific devices and technologies were implemented to maximise the efficiency of its use. In general terms, three main strategies have been adopted with this purpose: minimisation of the water demand, use of rainwater harvested and reuse of greywater. Figure 6.3 shows a schematic diagram of the main water flows in the ICTA-ICP building.

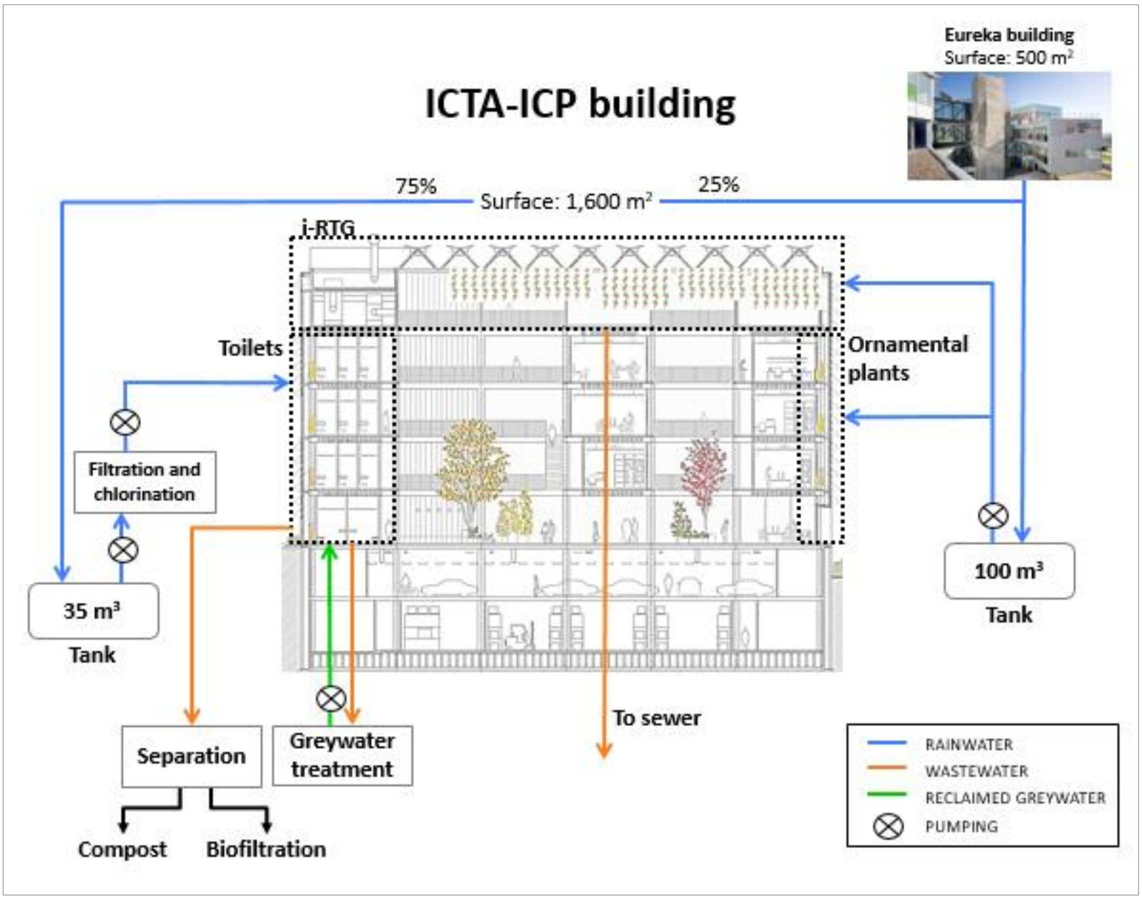

Figure 6.3 Qualitative diagram of water flows in the ICTA-ICP building.

i-RTG=integrated rooftop greenhouse.

Minimisation of the water demand

The aim of this strategy is to reduce as much as possible the demand for water. Firstly, there are several water-efficient devices in the building, such as bathrooms with automatic taps that supply water only when hands are in the washbowl and have a reduced flow of 5.5 L/min. Man's bathrooms hold waterless urinals that only have an anti-odour system (Figure 6.4). However, this is not the case for toilets, which have a discharge volume of 7 L/discharge and 9 L/discharge in bathrooms adapted for disabled people. Each plant from the ground level to the third floor has six bathrooms, forming groups of three (man, women and adapted) in opposite corners. Finally, the ornamental plants are watered using drip irrigation, which delivers 30 mL/min and minimises water losses in comparison with other watering systems.

Figure 6.4 Automatic tap and waterless urinal in the bathroom (left), chlorination system (centre) and secondary tank with chlorination system (right).

Rainwater harvesting

The building holds a rainwater harvesting system that collects and stores rainwater from the roof for its later use. This system is divided into two subsystems: one provides chlorinated rainwater for washbasins in the bathrooms, and the other one provides untreated rainwater for the irrigation of crops and ornamental plants. All the water consumption points in the building are connected to the conventional water supply network, including those that supply rainwater (to maintain the supply in case rainwater is over). Figure 6.5 shows a diagram with the water flows in the building.

Rainwater falling on 1,200 m^2 of the ICTA-ICP roof (75% of the total surface of the roof) is collected and stored in a 35 m^3 water storage tank located underground (buried with an opening to the surface) outside the building (in front of it). This rainwater is stored and pumped to the -1 floor of the building, where it is treated and chlorinated to remove any impurity and contaminant. Treatment consists of a filtration process with a 30-micron filter made of anthracite in a silica cylinder and a disinfection process with chlorination (Figure 6.5). The quality of this resulting water is similar to that of drinking water from the tap, although it is not considered suitable for drinking to avoid any possible risk. After the treatment, chlorinated water is stored in a secondary tank with 3 m^3 of capacity located in the same room that holds the water treatment system. From this auxiliary tank water is pumped to be used in the washbasins of the building.

A separate subsystem collects rainwater from 400 m^2 of the ICTA-ICP roof (the remaining 25% of the surface) and 500 m^2 of the Eureka roof (50% of the total surface of the Eureka building), which is the closest building to the ICTA-ICP. This water is stored in a 100 m^3 water storage tank located next to the 35 m^3 tank mentioned above, also buried in front of the building with an opening to the surface. This water is only filtered for gross solids before being stored in the tank and is later pumped from the storage tank to the building, where it is used for irrigation.

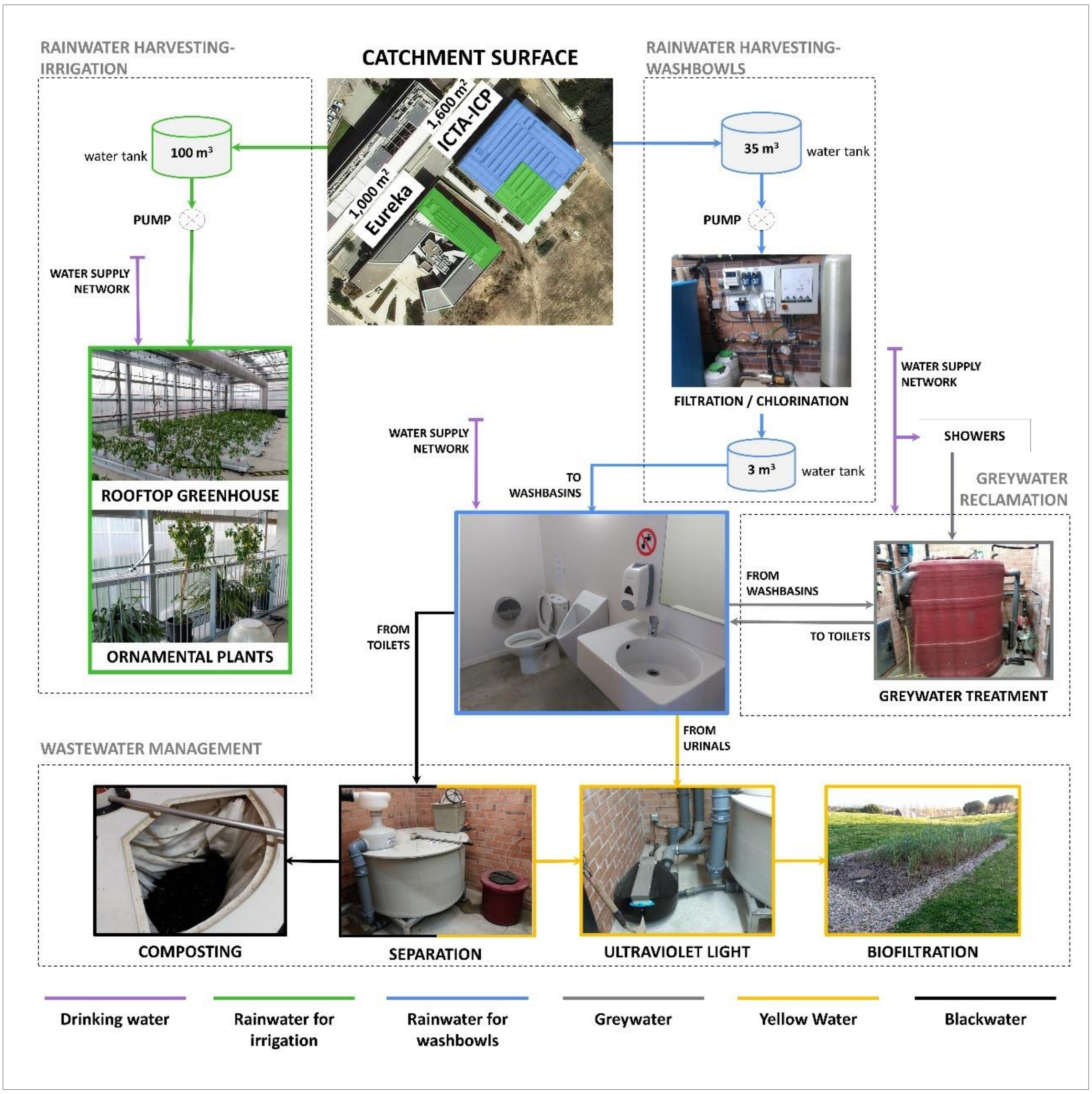

Figure 6.5 Diagram of the water flows in the ICTA-ICP building, including rainwater harvesting, greywater reclamation and wastewater management (separating greywater, yellow water and blackwater).

Greywater, yellow water and blackwater

The third strategy for water efficiency in the building includes the reclamation of greywater for its use in toilets and the management of wastewater to reduce its environmental burdens, as can be observed in Figure 6.5.

Greywater from washbasins (mostly from washing hands) and showers is collected and treated to be used again. There are two greywater treatment stations with similar installations and functioning, made up of a cylindric structure with 1.6 m in diameter and 1.8 m in height that includes an accumulation tank, a filter and a chlorination system. One of the stations reclaims greywater in the northwestern part of the building and the other one in the southeastern part. When there is not enough greywater to cover the demand of toilets, the accumulation tank is automatically filled with drinking water from the water supply network.

Blackwater (wastewater from toilets) in the building goes to two separation stations, which are physically placed in the same room as the greywater treatment stations. As for the later ones, there is one separation station in the northwestern half of the building and another one in the southeastern half, collecting blackwater from toilets in each part. Within the stations, the organic matter in the water is retained and remains there for composting in four compartments that rotate every three months, being filled only one at a time. When the compartment has made a whole round after one year, it is considered that the organic matter is completely composted and can be removed. The wastewater from the separation stations (mostly urine without organic matter) is mixed with urine from waterless urinals in toilets (yellow water), and the resulting flow is treated with ultraviolet light for disinfection. After that, yellow water is stored in a 2 m^3 tank and discharged into a biofilter. The biofilter consists of a plot with soil and plants with high nutrient retention rates located in front of the building.

Drinking water and wastewater flows to the sewers

As stated above, all the water supply points in the building have a connection to the water supply network to provide drinking water if necessary. Furthermore, the wastewater outflows that are not generated in toilets or showers, such as chemical wastewater from labs, the kitchen or the leachates from the vertical farm are discharged into the sewers. In the case of labs, wastewater must be discharged to the sewers to avoid risks derived from possible contaminants being recirculated in toilets or directly released into nature. In the kitchen, the flow cannot be filtered in the greywater treatment station due to the large quantities of soap and organic matter. Finally, the leachates of the vertical farm are currently discharged to the sewers, although other treatments or uses for this flow will be considered in the future.

6.2.3 Quantification of the water flows

A period of 331 days (11 months) was considered for the analysis, from 21/05/2015 to 15/04/2016. Although the data collected could not reach a whole year due to time restrictions of the project, it provides enough data to study the functioning of the building.

Data was collected from flow meters installed in the study system using software specifically designed by SIEMENS for the monitoring and control of the building. The flow meters used were part of the installations of the building, and no additional devices have been installed for the study. Unmeasured flows have been estimated to balance calculations, as explained in the following paragraphs and in Appendix V. Figure 6.6 shows a diagram representing the flows that were measured and those that were estimated.

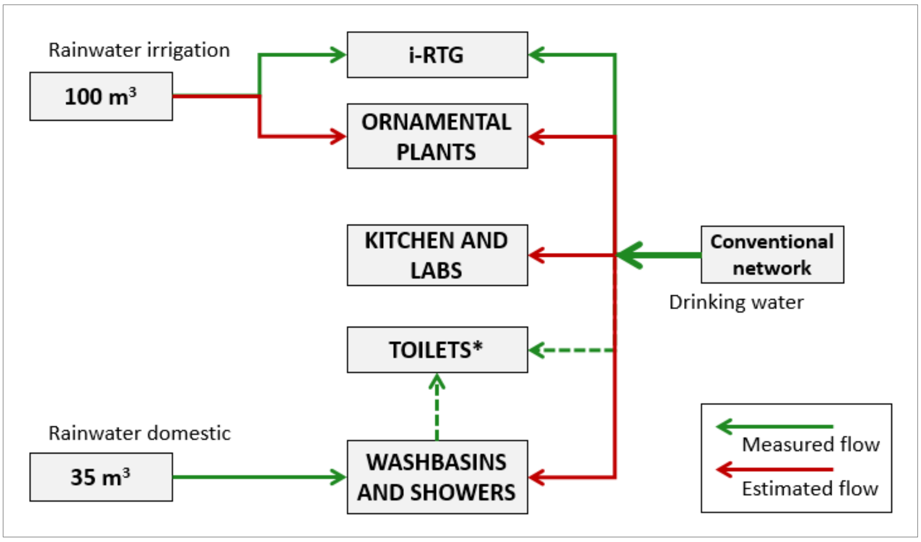

Figure 6.6 Diagram of the water flows measured and estimated in the ICTA-ICP building. Discontinuous lines mean that the flow has only been measured for one of the two greywater reclamation stations in the building.

As seen, the following flows in the building were measured experimentally:

- Total drinking water demand (from conventional supply network)
- Rainwater used in washbasins
- Drinking water and rainwater used for irrigation in the i-RTG

Water used for flushing toilets from the north-western treatment station, including reclaimed greywater and water from the conventional supply network.

The flows that have been estimated (Figure 6.6) have a lower reliability than the measured ones. The specific methodology employed for the estimations is detailed in the following paragraphs. Despite the uncertainty of these flows, the total amount of water from the water supply network used was measured. Thus, the overall efficiency of the building is reliable, although the distribution of this total amount between the different flows has a substantial uncertainty. Moreover, a reliable estimation was done for the largest water flow of the building (flushing toilets), which consisted of measuring the water consumed in one of the two halves of the building and estimating the water in the other half based on the number of working places, as explained hereunder.

Reclaimed greywater

As mentioned in section 2.1.1., there are two greywater treatment stations in the building. There was only one flowmeter measuring the outflow of the south-eastern station (reclaimed greywater plus additional drinking water required), but the north-western station had no flowmeter. The outflow of the south-eastern station was estimated from the number of people working in each half of the building. The number of working places in each half was counted, showing that the south-eastern half held nearly 60% more people than the north-western one. Thus, the demand for flushing toilets in the south-eastern sector was assumed to be 60% higher than in the measured one.

Ornamental plants

The staff in charge of watering was interviewed to estimate the water used for the irrigation of ornamental plants in the building. They provided data including the watering patterns, the number of drippers supplying water and its flow.

6.2.4 Application of the Plugrisost software

The software Plugrisost® (Morales-Pinzón et al. 2012c, 2015), which is used for modelling water harvesting systems, was applied for the evaluation of the 35 m^3 rainwater storage tank. The goal was to obtain the percentage of the water demand for flushing toilets that could be covered with this harvesting system and the optimal size that the tank should have. For the calculations, data for seven years of precipitations in the area (from 2009 to 2015) was used (retrieved from RuralCat (2016)), obtaining results for each of the years. The average value for the seven years was used for the interpretation of the results, defining the optimal storage capacity of the tank with a precision of 1 m^3.

6.3 Results and discussion

6.3.1 Water use efficiency at ICTA-ICP

The results of the water demand quantification in the study system are compared in Table 6.1 with a reference value from an office building at the same university campus and for the same period. The building holds the chancellor's office and the central offices of the University. This building has similar characteristics to ICTA-ICP and, in both cases, the water consumption includes the irrigation of a certain area of ornamental gardens. In the case of ICTA-ICP, only the consumption and the building surface related to offices is considered, excluding the water and surface used for crops and labs.

The results show that the total water demand per person is around 10% lower in the ICTA-ICP building, which proves it is more efficient in the use of water. Moreover, if the use of rainwater is excluded and only the external water demand of the building is considered, the consumption per person is 18% lower than the reference value. The lower consumption per square meter is due to the large collective spaces in the building, but the demand per user is a more appropriate indicator because it holds a clearer connection to the function of an office building, which is providing working spaces.

Table 6.1 Comparison between water consumption in the ICTA-ICP and a reference building of the same campus during 11 months.

		Rainwater	Drinking water	Total water
ICTA-ICP office flows[1]	L/ user·day	2.23	23.41	25.64
	L/ m^2·day	0.05	0.56	0.61
Reference value[2]	L/ user·day	-	-	28.40
	L/ m^2·day	-	-	1.12

[1]*Considering 230 working days from May 2015 to April 2016 and excluding the water demand and area from labs and crops.*
[2]*Data from an office building from the same university campus, considering 230 working days from May 2015 to April 2016.*

Although a lower water demand per user was observed, this difference is limited (10 and 18% depending on the approach) considering the measures undertaken to enhance water use efficiency in the building. Previous studies assessing the application of rainwater harvesting systems in Mediterranean climate show that they can provide rainwater to cover most of the needs for flushing toilets in households and 60% of the demand for the irrigation of urban landscape (Domènech and Saurí 2011). In comparison with these figures, the savings in the case study are relatively low. The quantification of the water flows in the building is presented in the following sections, analysing the effectiveness of the water-saving technologies implemented.

6.3.2 Water flows in the building

Water flows in the building were represented in a Sankey diagram (Figure 6.7), and a detailed breakdown of the demand is shown in Table 6.2 (for more details on the calculations see Appendix V). Regarding the reliability of the data, it can be observed that 38% of the water used was measured, and another 53% is based on reliable estimations. The remaining 9% consists of minor flows that were adjusted to approach the total 1,054 m^3 of drinking water measured. For this reason, the total amount of drinking water estimated and measured are similar.

The results show that the water used for flushing toilets is the most significant demand, accounting for 90% of the total. Previous studies analysing water consumption patterns in office buildings show a similar trend, with more than 60% of the water dedicated to flushing toilets, being also faucets (26%) and urinals (5%) significant contributors (USAID 2011). These two uses (faucets and urinals) are not present in the ICTA-ICP building because faucets are fed by rainwater and urinals do not use water, as explained in section 2. Moreover, toilets hold a normal mechanism with single discharge and normal-sized tanks (of 7 and 9 L/discharge), in contrast with the ultimate technology for the rest of the water-consuming elements, such as the automatic faucets.

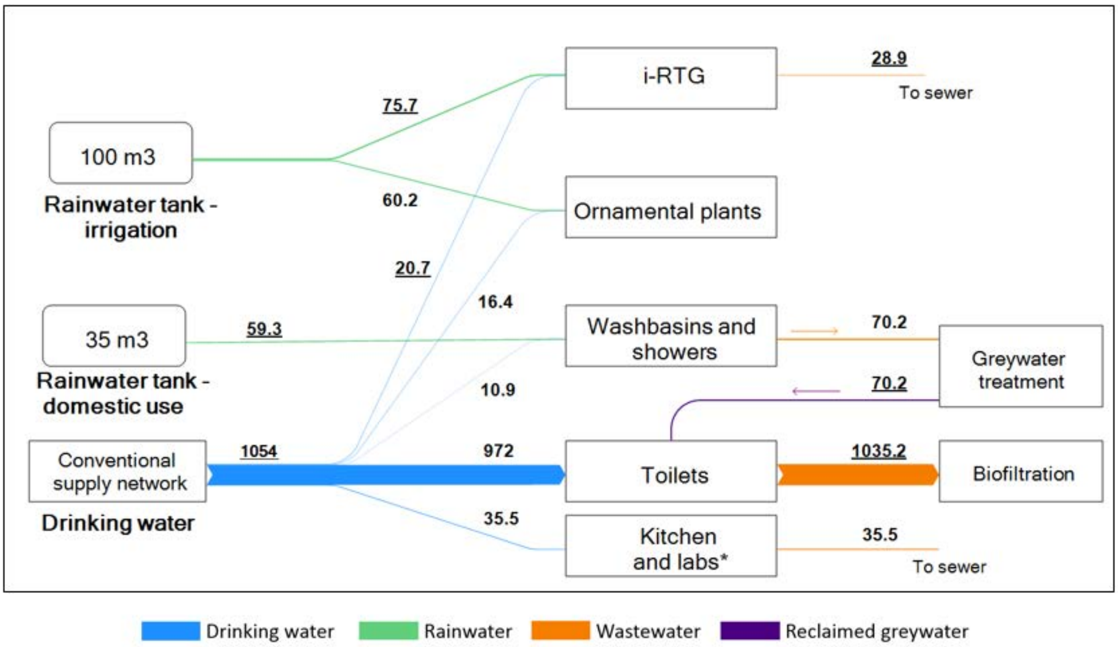

Figure 6.7 Diagram of the water flows in the ICTA-ICP building during the period 21/05/2015-15/04/2016. Experimentally measured flows are underlined.

**This box includes other minor uses such as drinking fountains or the coffee machine.*

The main measure implemented in the building to alleviate the demand for flushing toilets, which is the most significant contributor to the total demand, is to reclaim the greywater from washing hands and showers. However, this contribution only recycles 70 m^3 of water, which represents 6% of the final demand for flushing toilets. For this reason, most of the water used in toilets is drinking water from the water supply network, although the building holds a rainwater harvesting system that might provide rainwater for such purposes.

The rainwater collected in the 35 m^3 storage tank is filtered and chlorinated and used in the washbowls of the bathrooms, mainly for washing hands. The main problem of this system is that the demand for washing hands is relatively low (70 m^3), and a significant part of the rainwater harvested remains unused in the water tank. Thus, the rainwater harvesting system is underused despite the considerable demand of toilets, which must be covered with drinking water from the supply network (970 m^3). The result is that rainwater is treated using energy and reagents whereas drinking water, which could be used for washing hands with no additional treatment, is used for flushing toilets, which in turn could use rainwater without treatment.

Table 6.2 Breakdown of the ICTA-ICP building water demand (shaded cells indicate estimated flow).

	Drinking water (m³)	Reclaimed greywater (m³)	Rainwater (m³)	Total water demand (m³)
Toilet flushing - NW[1]	600.0	36.2	-	636.2
Toilet flushing - SE	372.0	34.0	-	406.0
Irrigation crops	20.7	-	75.7	96.4
Irrigation ornamental plants[1]	16.4	-	60.2	76.6
Labs[2]	9.8	-	-	9.8
Washbasins – NW[2]	-	-	36.2	36.2
Washbasins – SE[2]	-	-	23.1	23.1
Kitchen[2]	9.8	-	-	9.8
Showers[2]	10.9	-	-	10.9
Drinking fountains[2]	2.0	-	-	2.0
Cleaning separation station[2]	6.0	-	-	6.0
Cleaning yellow water tank[2]	4.0	-	-	4.0
Inefficiency decalcifier[3]	2.3	-	-	2.3
Coffee machine[2]	1.8	-	-	1.8
Total estimated	1,055	78	203	1,336
Total measured	1,054	-	-	-

[1]*Reliable estimation (methodology in section 2.2).*
[2]*Estimation with low reliability: observation, interviews to the staff and surveys to users. These flows were adjusted to approach the total 1,054 m³ of water measured.*
[3]*Estimated from data provided by the manufacturer: 0.023 L for each cycle of decalcification (10.4 L)*

These results show that the system has been badly designed regarding the utilisation of water. Consequently, the consumption of drinking water is relatively high (compared to the expectations) and the self-sufficiency of the system is low, using mainly drinking water from the water supply network. The authors believe that future projects including these water-saving technologies in buildings should be optimised at the design phase estimating the water flows in the building and adapting the technologies applied in such a way that its efficiency is maximised. The following section (3.3) presents a proposal for the efficient redesign of the water system of the case study.

Regarding the wastewater, 1,170 m³ of wastewater were generated during the period, of which only 5% was discharged into the sewer network. Greywater from washbasins and showers is treated and reclaimed, and blackwater from toilets is separated into manure and yellow water, being the later one disinfected and discharged into a natural biofilter and released to the environment. All this avoided wastewater (which is not discharged to the sewers) saves environmental impacts, both for the transport along the sewer network and for its treatment in a municipal wastewater plant.

6.3.3 Proposal for an efficient design of office buildings with water-saving technologies

This section presents a low-cost redesign of the network that might be key to improve the overall efficiency of the building, saving significant economic costs and preventing environmental impacts (avoiding additional treatment of water).

The redesigned system should use the rainwater collected directly to flush toilets, improving the utilisation of the rainwater harvesting system and avoiding filtration and chlorination. The demand of the washbowls could be fulfilled with drinking water from the network, which does not require further treatment. In this way, both rainwater harvesting and greywater reclamation would contribute to cover the demand of toilets, reducing the consumption of drinking water.

For doing so, the only change that should be implemented in the network is the connection of the 35 m^3 water tank to the greywater treatment stations, which supply the toilets. This modification would only imply connecting the pipe that leaves the rainwater tank with each of the pipes going to the greywater treatment stations. These connections should be made at the point where these pipes are the closest in the building so that only the installation of two short sections of pipe would be required. All the appliances for the treatment of rainwater would remain unused, saving reagents and energy.

The evaluation of the water tank with the software Plugrisost® shows that the optimal size of the tank with the conditions of the building (considering a catchment area of 1,200 m^2) would be 31 m^3 of capacity. Thus, the size of the current water tank (35 m^3) is adequate, approaching the optimal volume. According to the modelling from the software, the system would be able to fulfil 45% of the current demand for flushing toilets, increasing the building's self-sufficiency significantly.

Reducing the discharge volume of the toilette cisterns in the building would be another effective measure to reduce the drinking water demand from toilets. A device for the regulation of the discharge volume and with a double-discharge option would be effective and could lessen the discharge to 3 and 6 L. Another option would be to introduce a two-litre bottle or just a ceramic, concrete or stone block with a similar volume, which could reduce the discharge by 30% for 7 L cisterns and by 20% for 9 L ones. The cost of this measure would be nearly zero, and its effect on the reduction of the water demand would be immediate.

Figure 6.8 shows a diagram representing the changes that would be implemented with the redesign of the network. The redesign of the system might reduce by 30% the water demand for flushing toilets, and the rainwater harvesting system could provide 65% of the remaining demand with rainwater. The combination of these measures could reduce by 75% the consumption of drinking water for flushing toilets.

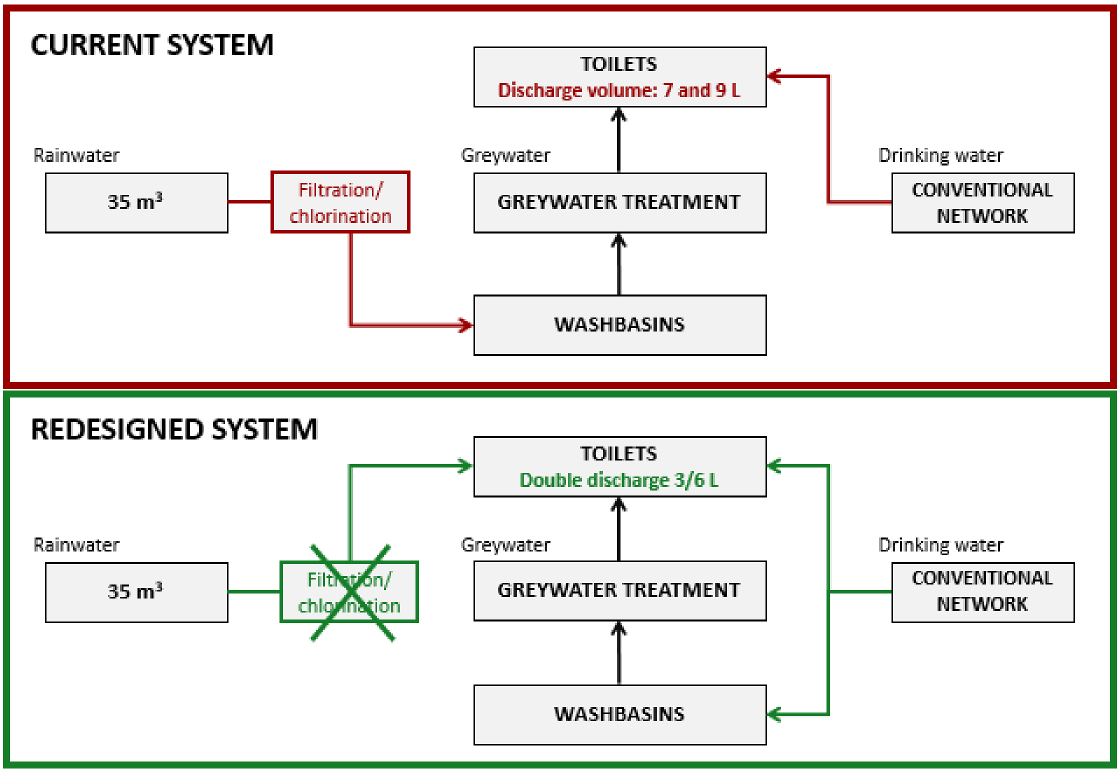

Figure 6.8 Current water network system in the ICTA-ICP building and proposal for its redesign.

Future projects including water-saving technologies should estimate the water flows of the system during the design phase. This estimation will allow optimising the system to maximise the water use efficiency. In the case of rainwater harvesting, the size of the water storage tank should be optimised to prevent environmental impacts in the manufacture of the tank (specially to reduce the amount of material required) while maximising rainwater utilisation. With this optimisation in the design phase, a similar efficiency to that of the redesigned system can be achieved.

6.4 Conclusions

The ICTA-ICP building on the campus of the Universitat Autonòma de Barcelona holds ultimate water-saving technologies, including rainwater harvesting and greywater reclamation. This system represents an opportunity to assess new forms of water management at the consumption point and to obtain information about the effectiveness of these technologies.

The results show that the water use efficiency in the building is limited, due to a bad design affecting the overall utilisation of water. Over the period assessed, the building had a total water demand of 23 L/user, which is 18% lower than the reference value considered. These savings are low compared with the values reported in previous literature, and might not justify the environmental and economic costs of implementing rainwater harvesting and greywater reclamation. The technologies applied in the building to enhance water self-sufficiency might have been effective for households, where a significantly higher percentage of the water is used in the shower and washbowls, generating more greywater that can potentially be reclaimed for flushing toilets. However, the generation of greywater in an office building is much lower because the water used in showers is not significant. The design of the building's water networks should have estimated the magnitude of the different water flows to make a proper planning applying the most appropriate technology to reduce the demand for drinking water.

The study presents a proposal for a low-cost redesign of the system, which consists of reducing the discharge volume of toilets and using the rainwater collected for flushing toilets. These measures may help to reduce by 75% the external demand for water of the current system and would avoid the treatment of rainwater, saving energy and reagents. The water flows in other buildings with similar water-saving technologies should be assessed, since a redesign may imply little effort and a small economic investment but improve the efficiency of the system substantially. Furthermore, future projects for the implementation of rainwater harvesting and greywater reclamation systems should estimate the water flows in the building during the design phase to ensure its optimisation.

Some of the flows quantified in the study rely on estimations due to the lack of flow meters in key sections of the water networks in the building. In particular, the installation of a flow meter at the outflow of the southeastern greywater treatment station would allow measuring the water demand for flushing toilets in the southeastern half of the building. Although the results of the study were coherent, the installation of these devices would be of interest to evaluate the accuracy of the results in this study. Further research is also needed to address other case studies with similar technology and to implement these water-saving systems to other types of buildings.

Chapter 7

Balancing nutrient flows in an integrated rooftop greenhouse (i-RTG) with open hydroponic tomato crops

Picture: Tomato plants in perlite bags
©David Sanjuan-Delmás

Chapter 7 Applying the nutrient dynamics methodology to close the nutrient and water balance in hydroponic crops

This chapter had the following collaborators:

David Sanjuan-Delmás, Alejandro Josa, Pere Muñoz, Xavier Gabarrell, Joan Rieradevall

Abstract

Global food production systems generate significant environmental impacts, such as eutrophication caused by nutrients runoff from agriculture or climate change. In this context, this study aims to assess the nutrient flows in hydroponic crops, which are a common cultivation method in Mediterranean areas, to close a gap in previous literature. With this purpose, among others, three tomato crops were conducted in an 84 m^2 greenhouse in Barcelona from February 2015 to July 2016. The flows of macronutrients (nitrogen, phosphorus, potassium, sulfur, magnesium and calcium), macronutrients (sodium, iron, zinc and manganese), carbon and water in the greenhouse were defined and experimentally quantified along the crops. The results show that most of the nutrients are drained with the leachates (51% in average), which might be reduced adjusting the nutrients supplied to the needs of the plants or implementing recirculation of nutrients (closed hydroponic) provided that the plant requirements are not compromised. The second largest flow of nutrients is the plant uptake, which accounts 37% of the incoming nutrients in average. Moreover, the study reveals that a significant amount of nutrients are retained in the substrate (perlite) during the crop, reaching in average 5% of the incoming calcium, 6% of the nitrogen and 7% of the phosphorus. In the case of phosphorus and calcium, a regression model is presented for the estimation of its retention in hydroponic crops. The analysis of micronutrients was not conclusive due to their small concentration in the flows, that could be influenced by external contamination making difficult to close the balance. The carbon balance in the crop showed that between 42 and 58% of the biogenic carbon fixed in the biomass would be retained in the material if it was used as a byproduct, contributing to climate change mitigation. Although further studies should confirm the trends observed, the article makes a significant contribution to understand the metabolism of nutrients in hydroponic crops and to close the nutrient balance.

Keywords: fertigation, phosphorus, nutrient budget, element balance, substance flow analysis, vertical farming

7.1 Introduction

7.1.1 Nutrient and water dynamics in hydroponic crops

The current global food production system generates significant negative impacts on the environment and consumes vast amounts of resources. On the one hand, agriculture accumulates 70% of the total water demand on Earth (FAO 2011). On the other hand, pesticides and nutrients from agriculture runoff are a major source of pollution, representing a threat to the environment (Andersen 2006). These impacts are often caused by leaky irrigation systems that have excessive water demand and wasteful field application methods (WWF 2017). In this context, improving the efficiency of agricultural systems is of paramount importance to reduce its environmental impacts.

Within agriculture, hydroponic crops are a common cultivation method used in greenhouses, which consists of growing plants in an inert substrate (such as perlite or rock wool) irrigating the crops with a nutrient solution that provides water plus nutrients (also called fertigation). Previous studies show that the use of fertilisers in these crops is the largest contributor to the environmental impacts of the system (Muñoz et al. 2005), and thus its assessment is of interest to improve the environmental performance.

Previous literature has analysed the sustainable management of fertilisers from a nutrient efficiency perspective. Current practice in greenhouses with hydroponic crops surpasses the recommended amount of nutrients significantly (Thompson et al. 2007). The nutrients consumed and leached can be reduced maintaining or even increasing the yield of the crop only adjusting the nutrients provided to the needs of the plant (Savvas and Gizas 2002; Muñoz et al. 2008a; Şirin 2011). In fact, previous studies show that an excess of salinity (electric conductivity) in the nutrient solution for the irrigation of crops can reduce the crop yield (Adams 2015). A similar practice from cultures recycling the leachates consists of the elimination of the input of nutrients some days before the end of the crop (only recirculating the remaining nutrients) (Le Bot et al. 2001; Siddiqi et al. 2008).

This study focuses on the assessment of water and nutrient flows in hydroponic crops without recirculation of water and nutrients, which are the most commonly used system in Mediterranean greenhouses (Muñoz et al. 2010d). Water and nutrients are intrinsically linked in these systems because modifying the fertigation affects both at the same time. Furthermore, these flows are linked with eutrophication and water scarcity, which are e most significant environmental issues concerning greenhouses and agriculture in general (Andersen 2006; Iglesias et al. 2006).

The nutrient dynamics or nutrient budget methodology (also known as nutrient accounting, element balance or nutrient flows) consists of balancing all the nutrient inputs and outputs of the farming system to analyse the nutrient flows in the crops (Öborn et al. 2003). This methodology has been widely applied in soil-based agriculture, where implementing the nutrient budget methodology involves several estimations due to the complexity of the system (Khai et al. 2007; Oelofse et al. 2010). However, to the best of our knowledge, this methodology has never been implemented in hydroponic systems.

Closing this research gap is of interest to obtain useful information that can help to understand the functioning of hydroponic crops and manage fertigation efficiently. Previous studies on the issue have only considered the nutrient solution, the leachates and the plant uptake, calculating the nutrient and water balance from these flows (Goins et al. 2004; Grewal et al. 2011). As Bugbee (2004) noticed, the assumption that these three flows (nutrient solution, leachates and uptake) include all the inputs and outputs of the system has not been checked implementing a detailed mass balance. Bugbee (2004) showed the low recovery of some nutrients in recirculating crops; for instance, 70% of the nitrogen and 50% of the calcium was not recovered. A comprehensive assessment must be implemented to address this problem contemplating all the paths that nutrients can follow.

There is a particular research gap regarding the amount of nutrient retained in the inert substrate used in hydroponic crops. Perlite, which is a material commonly used for this purpose, could retain significant amounts of nutrients due to its porosity. Moreover, recent studies proved that the volatilization of nutrients might be a major source of nutrient loss in hydroponic crops (Hashida et al. 2013; Yoshihara et al. 2016). For nitrogen, the volatilization in the form of N_2O can reach 16% of the total nitrogen supplied (Hashida et al. 2013; Yoshihara et al. 2016). Although this specific flow is out of the scope of this study due to the methodological complexity of its assessment, there is undergoing research on the field.

7.1.2 Analysing crops from an industrial ecology perspective: the integrated rooftop greenhouse (i-RTG)

The research conducted in this study was developed in an innovative food production system called integrated rooftop greenhouse (i-RTG), located in the research-oriented building ICTA-ICP, on the campus of the Universitat Autònoma de Barcelona (Spain). This system is a vertical farm, a type of agriculture that consists of growing crops in buildings. The main innovation of this greenhouse is its symbiosis with the building, based on its connection with the building regarding water, energy and CO_2, which allows saving resources and environmental and economic impacts (Fertilecity 2016).

This study system is being assessed from an industrial ecology perspective, evaluating its potential to boost food production in cities and to prevent environmental impacts (Sanyé-Mengual et al. 2012; Cerón-Palma et al. 2012; Pons et al. 2015). In this context, the analysis of different flows in the system provides useful insights on the utilisation of resources for agriculture.

The main goal of this article is to analyse the nutrient and water flows in hydroponic crops, implementing the nutrient dynamics methodology to greenhouse crops in a Mediterranean climate. The specific objectives are:

- To define all the flows and stocks of water and nutrients in an open hydroponic system.
- To measure the nutrient flows for experimental tomato crops considering three cultivating periods (15.5 months in total) and using the nutrient dynamics methodology.
- To make a balance of water and carbon in the crops.
- To provide recommendations to improve nutrient efficiency in open hydroponic crops.

7.2 Materials and methods

7.2.1 Description of the integrated rooftop greenhouse (i-RTG)

The i-RTG is located in the south-eastern corner of the rooftop of the ICTA-ICP building (Figure 7.1). Regarding the symbiosis with the building, there is a rainwater harvesting system that provides water for the irrigation of crops and ornamental plants. Moreover, an automatic system injects air from temperature-controlled labs (always at 22ºC) to the i-RTG, to take advantage of the temperature and the CO_2 in the waste air.

The building has an external "double skin" that surrounds the rooftop (including the i-RTG), as shown in Figure 7.2. This structure is made up of a metal frame with corrugated polycarbonate sheets that open and close depending on internal and external temperatures, allowing passive acclimatisation and ventilation in the building and the greenhouse.

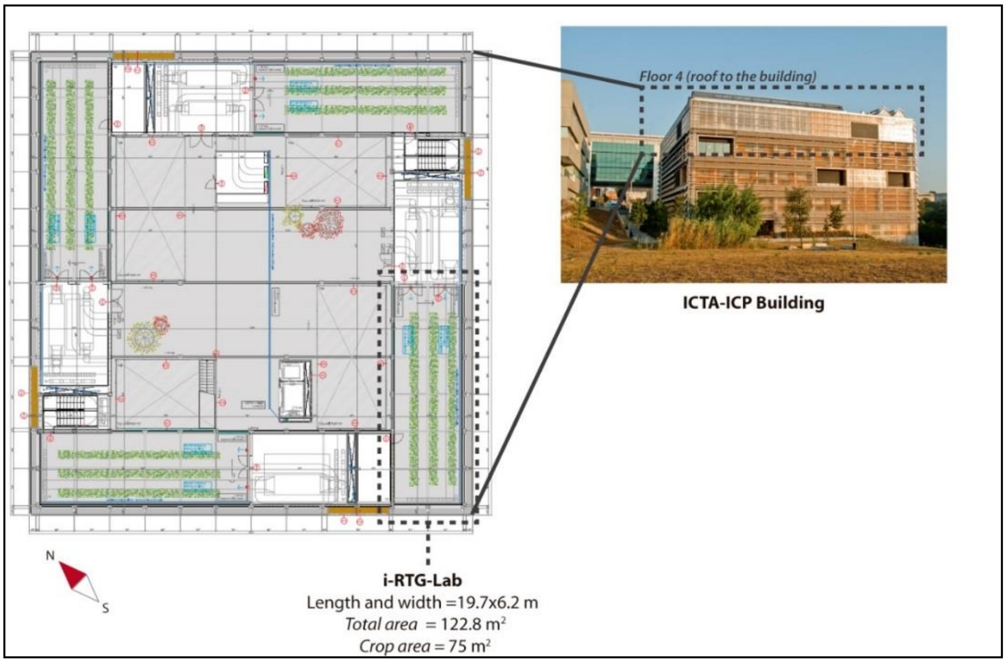

Figure 7.1 Layout of the rooftop of the ICTA-ICP building and the i-RTG.

Figure 7.2 ICTA-ICP building in the UAB Campus (left), walls of the greenhouse (centre), roof of the greenhouse (right).

7.2.2 Plant materials and growth conditions

The laboratory has an area of 122.8 m^2 (Figure 7.1), and the crop area is 84,34 m^2. The crop included 171 tomato plants, 47 of which were on the perimeter and 124 were non-perimeter plants.

The cultivation was made with beefsteak tomato (*Lycopersiconesculentum* var. *Arawak*). Seedlings grown in peat for 4 to 6 weeks (in a local garden centre) were transplanted into perlite bags in the greenhouse. Perlite was used as a substrate in bags with 40 L of volume and 1 m of length; these bags were placed in lines, each providing substrate for three plants. New bags were placed at the beginning of the first crop and maintained until the end of the third one. An open hydroponic system was used for irrigation, providing the nutrient solution to plants using drippers with 2 L/h of flow.

The cultivation started in February 2015 and ended in July 2016, excluding August 2015 because there is no activity in the building during this month and high temperatures made cultivation difficult. Three cultivation periods were made, but the third crop was interrupted due to its critical condition (affected by various plagues).

Regarding the nutrient solution, Table 7.1 shows the concentration of nutrients provided to the crop for the three cultivation periods, which were defined in accordance with the agronomic expertise of the authors. The irrigation was constantly readapted to keep the drainage between 30 and 40%. The electric conductivity (CE) and the pH of the nutrient solution and the leachates was measured daily to detect any alteration in the nutrient content of each flow. The nutrient solution was adjusted when necessary according to the quantity of nutrients in the leachates.

Table 7.1 Concentration of nutrients in the nutrient solution supplied between 10/02/2015 and 20/07/2016.

	Days (n)	Nutrient concentrations (mM)						
		NO_3^-	$H_2PO_4^-$	SO_4^{2-}	Cl^-	K^+	Ca^{2+}	Mg^{2+}
S1	77	10	1	1.5	2	7	3	1.5
	87	11.5	1	2	2.5	7	4	2
W	111	7	1	1.5	3	5	3	1.5
	21	7.5	1	1	3	5	3	1.25
	37	7.5	1	1	3	5	3	1.25
S2	24	8.5	1	2	2	6	3.75	1
	122	9	1	1.5	2	6	3.5	1

S=summer crop, W=winter crop

7.2.3 Quantification of the nutrient flows

For the evaluation of the system, the following flows were considered:

- Nutrient solution: Incoming solution for irrigation.
- Leachates: Outgoing solution, excess of water drained from the substrate.
- Fruits: Production of the culture (tomatoes).
- Biomass: Leaves and stem of tomato plants.
- Perlite: Substrate of the crop.

For each flow considered in the assessment, two different parameters were measured experimentally. On the one hand, the total amount of the flow, such as the volume of nutrient solution or the kg of produce. On the other hand, the concentration of the nutrients in the flow, for instance, the ppms of N in the nutrient solution or the g of N per kg of produce. The product of these two parameters provided the quantity of the flow, for example, the total g of N in the nutrient solution supplied along the crop or contained in the produce collected.

The study of the consecutive crops has been an iterative process. Although the measurement of the flows was similar for the three crops, the procedures and techniques for the analysis of the concentration of nutrients were modified in the second and third crops according to the experience of the previous ones. Table 7.2 shows the analytical techniques employed to analyse the concentration of nutrients in each of the crops.

Table 7.2 Measurement techniques used to analyse the concentration of nutrients in the different flows considered.

	S1/W/S2							S2			
	N	**P**	**K**	**S**	**Mg**	**Ca**	**Carbon**	**Na**	**Fe**	**Zn**	**Mn**
Nutrient solution	IC						-	ICP-OES			
Leachates	IC						-	ICP-OES			
Biomass	ICP-OES						EA	ICP-OES			
Production	ICP-OES						EA	ICP-OES			
Perlite	EA*	ICP-OES					EA	ICP-OES			

*S1=Summer crop 1, W=winter crop, S2=Summer crop 2, IC=Ion chromatography, ICP-OES=Inductively Coupled Plasma Optical Emission Spectroscopy, EA=elemental analysis, *spectrophotometry was used for S1*

The following sections explain in detail the methodology implemented for each flow and each crop.

7.2.3.1. Nutrient solution and leachates

The volume of nutrient solution used in each crop was measured with a conventional flow meter at the entrance of the irrigation head circuit. For the leachates, two water collection trays (three for crop S2) were placed under substrate bags in different parts of the crop to collect the leachates and to measure their volume. This value was used to estimate the total volume of leachates leaving the system.

Regarding the concentration of nutrients in these flows, samples of the nutrient solution were analysed once per week whereas the leachates were analysed three times per week during crops S1 and W. For the third crop (S2), a more accurate procedure was used to increase the reliability of the quantification. A sample was collected daily for each of the flows, and a representative sample for each week was prepared taking the proportional volume of the daily samples according to the water used for irrigation and the leachates generated.

As shown in Table 7.2, the analysis of the samples was made using ion chromatography to obtain the concentrations of nitrite, nitrate, phosphate, potassium, sulfur, magnesium and calcium for the three crops. In crop S2, additional micronutrients were measured: sodium, iron, zinc and manganese. These micronutrients were measured using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES).

The product of the volume and the concentration of nutrients in the flow provided the total flow of nutrients supplied and leached.

7.2.3.2. Fruits, biomass and perlite

Regarding the fruits (tomatoes), all the production from the three crops was weighed to obtain the total amount of produce. Two samples of tomatoes were collected for crop S1 and six for W and S2 to assess the concentration of nutrients in the produce. Each sample was prepared collecting six representative tomatoes (average sized, normal shaped and non-perimeter) from one line of plants, which were dried at 343 K and mixed. The resulting sample was analysed for nitrogen, phosphorus, potassium, sulfur, magnesium, calcium, sodium, iron, zinc and manganese using ICP-OES (Table 7.2). For each crop, average nutrient concentrations from the samples analysed were considered. The product of these average concentrations and the total produce of the crop provided the total nutrient flows.

A similar methodology was implemented for biomass. During the crops, all the biomass from pruning was weighed, as well as the remaining biomass from the plants at the end of the crop. Regarding the concentration of nutrients in the biomass, four representative plants (three for S2) were cut from different lines at the final stage of the crop (to minimise the influence on production). For each plant, leaves, stems and the remaining fruits were separated, and the leaves and steams were analysed following the same process and techniques used for tomatoes (for the same nutrients). As for tomatoes, the average concentration of the nutrients in the samples analysed was considered for each crop and the product of this value and the total biomass from each crop provided the nutrient flow.

For the retention of nutrients in perlite, the total amount of perlite was measured weighing a dry bag (unused), multiplying its weight by 57 (bags in the crop) to obtain the perlite in the crop. The concentration of the nutrients was measured at different points during the three crops conducted to obtain the accumulation of nutrients in this perlite.

Firstly, a preliminary assessment was performed for nitrogen analysing a sample of perlite after S1 and a blank (unused perlite) using an autospectrophotometer (Bran+Luebbe AutoAnalyser3). After this previous assessment, samples of perlite that had been used for different periods of time were analysed. At the end of the second crop (W), two perlite bags were replaced by new ones and kept. Therefore, at the end of the experiment the bags removed had only been used for the first and second crops (S1, W), the replaced bags only for the last crop (S2) and the rest of the bags for the three crops (S1, W, S2). A sample was taken from each bag plus one blank, but some of the results obtained were not conclusive and a second batch of samples was collected to observe the variability among the bags. In this second batch, two samples were taken from two perlite bags used in S1 and W (four samples in total), three samples were taken from two perlite bags used for crop S2 (six in total) and 12 samples of the blank were taken from six unused perlite bags. The concentrations of nutrients found in these analyses can be found in Appendix VI.

The process for the collection of samples and the analysis of perlite is illustrated in Figure 7.3 Each bag (number 1 in Figure 7.3) was opened (number 2) and spread on the floor, mixing well the perlite with the hands and making a layer of perlite with uniform thickness. To take a representative sample, this layer of perlite was divided into 20 sections (number 3), and approximately the same amount was taken with a spoon from each section. The sample was then carried to the lab in a plastic jar (number 4), and a similar process was conducted using a plastic tray to obtain a smaller sample for its analysis (number 5). For each sample (except the blank) the roots of the plant were carefully removed to measure only the nutrients retained in perlite, not the organic matter (number 6). The sample was then dried at 383 K and ground using an analytical mill (number 7).

Figure 7.3 Pictures of the methodology for the collection of samples from perlite bags and their preparation.

The samples of perlite were digested in duplicate with concentrated HNO_3 in a microwave oven together with digestion blanks. Then, they were lixiviated, and the solids were removed, remaining the liquid solution with the extracted nutrients from perlite, which were analysed using ICP-OES for nitrogen, phosphorus, potassium, sulfur, magnesium, calcium, sodium, iron, zinc and manganese.

The results from this assessment provided the variation of the nutrient concentration (mg of nutrient per g of perlite) in the perlite along the crops. The correlation between these values and certain key variables of the crops was assessed to look for patterns in the accumulation of nutrients. The variables considered were: concentration of the nutrient in the nutrient solution and the leachates at the end of the crop, nutrient load of the nutrient solution and the leachates (quantity of nutrient supplied and leached) and duration of the crop (number of days that perlite was used).

The accumulation of nutrient in perlite was obtained from the difference between the concentrations measured and the total amount of perlite in the crop. For the nutrients that presented a clear pattern of accumulation, the quantity of nutrient accumulated in each crop was estimated.

Finally, an elementary analysis was done for all the solid samples discussed (fruits, biomass, perlite) to get the content of carbon, hydrogen and nitrogen in the sample. The results from these analyses were used similarly as the concentrations of the nutrients in the samples.

7.3 Results

7.3.1 Characterisation of water and nutrient flows

All the water and nutrient flows in the crop that are potentially significant were identified and represented in Figure 7.4.

The paths followed by water and nutrients are similar because nutrients are provided to plants dissolved in the water (fertigation solution). The major flows of water and nutrients are the nutrient solution supplied to the crop, the leachates (excess of water, that must be between 30 and 40% of the income) and the evapotranspirated water (plant uptake released to the atmosphere). A part of the water and the nutrients remains in plants in the form of biomass (plants) and fruits (tomatoes). However, there is no evapotranspiration of nutrients like for water, they are incorporated into the biomass, drained and a certain percentage is volatilized, as recently demonstrated (Hashida et al. 2013; Yoshihara et al. 2016). Nutrients can also be sorbed by perlite or precipitated in substrate bags.

Regarding the minor flows, a small quantity of the water supplied is lost through occasional leaks, and it is mostly evaporated or drained. Finally, a relatively small amount of water is retained in the substrate (perlite) at the end of the crop, which will eventually evaporate or will be kept in the bag for the following crop.

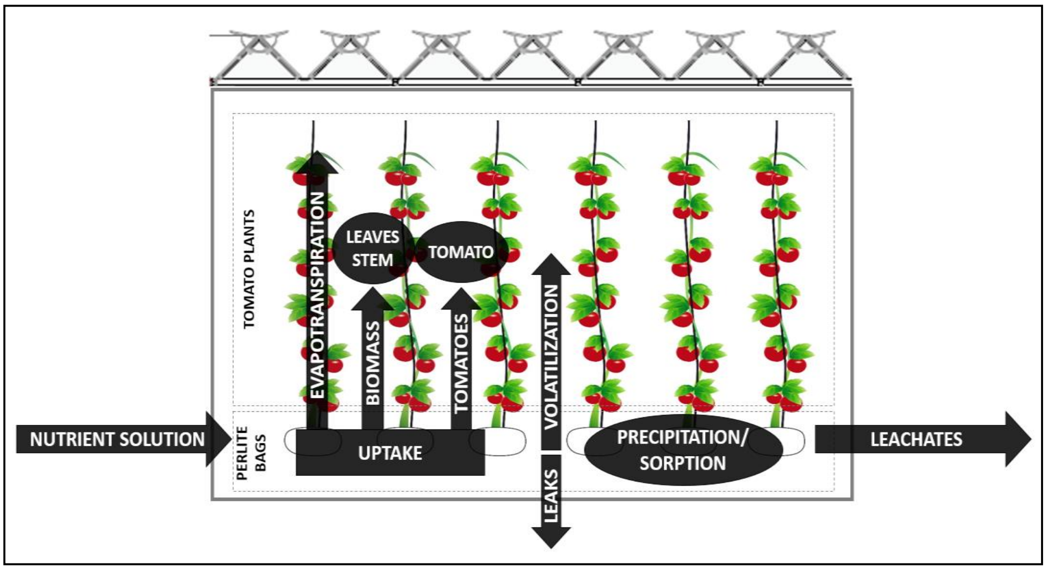

Figure 7.4 Schema of the nutrient and water flows in the crop.

7.3.2 Nutrient dynamics for macronutrients

The quantification of the macronutrient flows (N, P, K, S, Mg and Ca) is shown in Figure 7.5, considering the addition of the three crops (S1, W and S2). The results of the analysis of the nutrient solution and leachate samples from crop S2 are shown in Appendix VI to provide some direct data from the measurements conducted. As can be observed, most of the nutrients are leached, representing 51% of the incoming nutrients. The second largest flow is the plant uptake for biomass and fruit production, which accounts for 37% of the nutrients supplied, of which 26% go to biomass, and 11% go to production. The rest of the flows represent relatively minor percentages, but perlite absorbs 3% of the incoming nutrients, which can reach significant amounts for some specific nutrients. The global nutrient balance aggregating the three crops is 94%, ranging between 85 and 111%. This balance should not surpass the 100%, but due to possible errors derived from some estimations, these higher values were obtained for some nutrients.

As stated in section 1, the nutrient dynamics methodology had not been implemented in open hydroponic crops before, and thus comparing these results with reference figures is complicated. However, the nutrient use efficiency of these crops is similar to that from previous analyses regarding the nutrient uptake of hydroponic crops (Kläring 2001). These results show for the first time a quantification of the main paths followed by nutrients and provide a first approach to these trends that will be further analysed in future research. For instance, a relatively small but significant quantity of nutrient is retained in the substrate (perlite), which will be further discussed below.

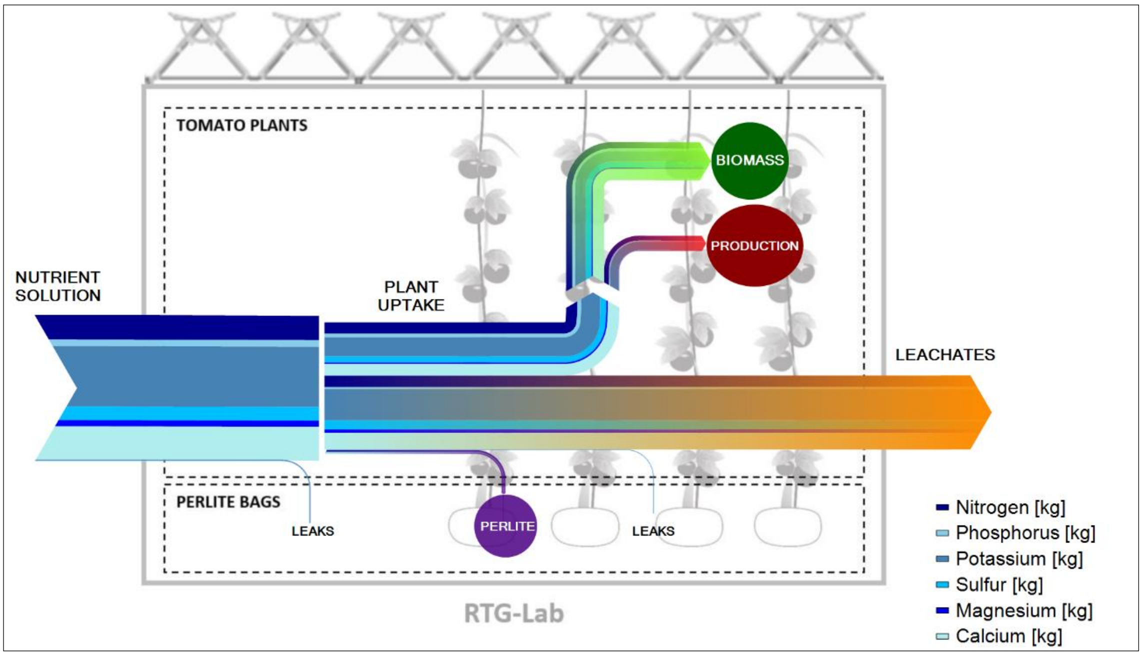

Figure 7.5 Global flows of nutrients for the open hydroponic tomato crops with perlite substrate between February 2015 and July 2016 (addition of the three crops).

Regarding the balance for each of the macronutrients analysed, individual diagrams are shown in Figure 7.6 aggregating the results for the three crops, and the detailed results for each of the crops are shown in Table 7.3.

Summer crops show larger amounts of nutrients supplied and leached due to the greater need for irrigation derived of the higher temperatures and radiation during this season. However, the efficiency in the nutrient use is lower in winter if the produce from the crop is considered, because winter crops are much less productive. For instance, S1 and S2 crops use 1.75 and 1.16 g of phosphorus per kg of tomato produced, whereas W crop uses 3.54 g per kg of tomato.

The optimisation of the nutrients supplied would reduce the emissions to nature and prevent environmental impacts, since the use of fertilisers was identified as the main environmental hotspot of greenhouses (Montero et al. 2011a). Indeed, the runoff of nitrogen and phosphorus from agriculture leachates is one of the main concerns worldwide (Andersen 2006). However, adjusting too much the nutrient solution would increase the risk of nutritional deficiencies and generate agricultural problems. Moreover, the nutrient solution is the result of a combination of the different nutrients that must keep certain proportions and are usually added in the form of salts providing not only one specific nutrient but various. Thus, it is difficult to adjust the exact quantity of nutrient required. Despite these limitations, periodic measurements should be conducted during hydroponic crops to optimise the nutrient solution and reduce the nutrients leached.

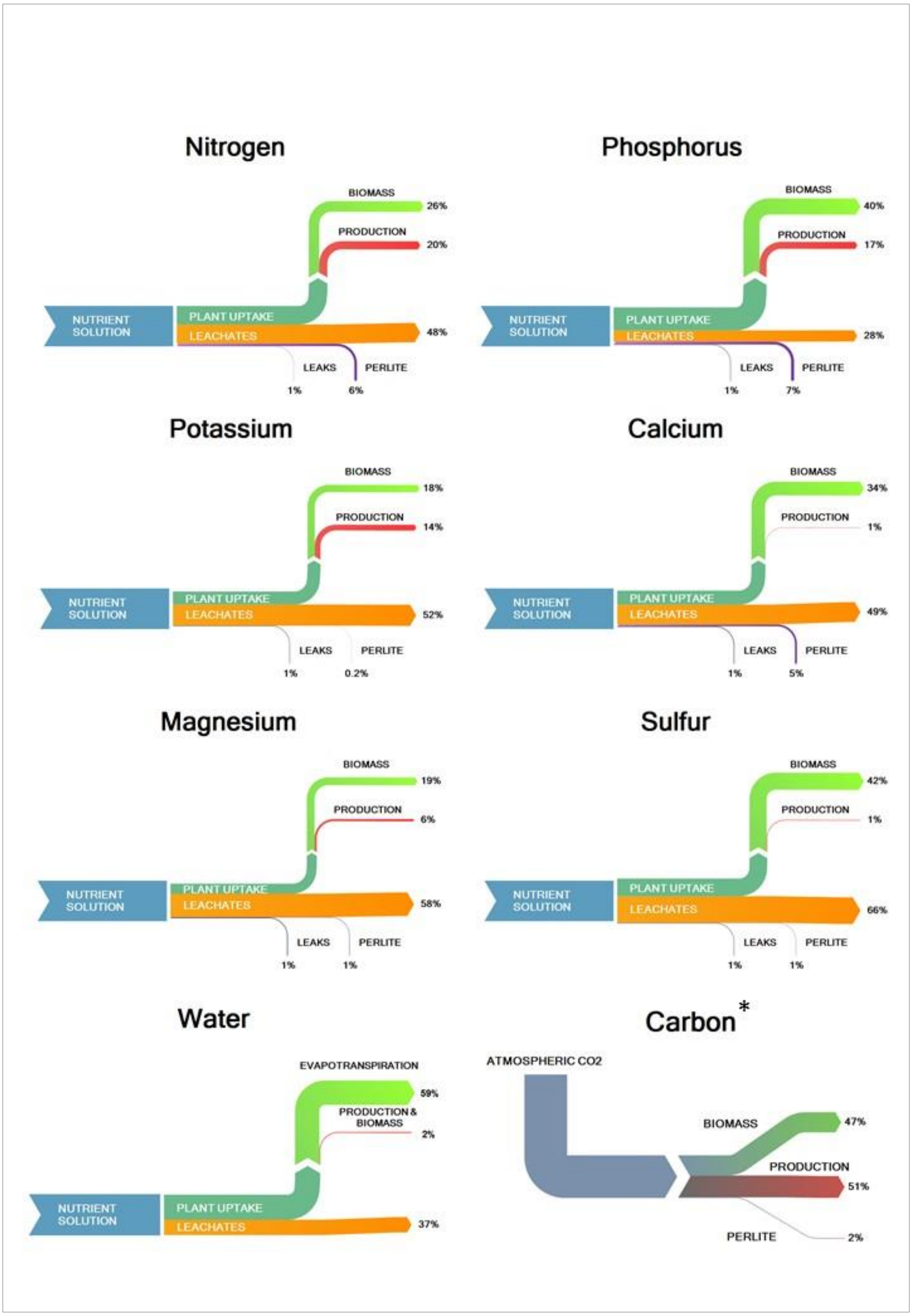

Figure 7.6 Diagram of the flows of macronutrients aggregating the three crops conducted between February 2015 and July 2016.

**The atmospheric carbon fixed was calculated by the addition of carbon fixed in the biomass, the produce and the perlite.*

Table 7.3 Results of the quantification of the nutrient flows for the three crops conducted between February 2015 and July 2016.

		Nutrient solution	Leachates		Production			Biomass			Perlite		Evapotranspiration		Balance
		g	g	%[1]	g	%[1]	mg/100 g d.s	g	%[1]	mg/100 g d.s[2]	g	%[1]	L	%[1]	%[3]
N	**S1**	10,549	5,366	51%	1,738	16%	2,260	1,571	15%	2,674	646	6%	-	-	90%
	W	2,825	1,097	39%	514	18%	2,393	1,335	47%	3,919	184	7%	-	-	112%
	S2	3,698	1,659	45%	1,147	31%	2,036	1,504	41%	3,213	204	6%	-	-	124%
P	**S1**	2,264	712	31%	425	19%	553	711	31%	1,189	139	6%	-	-	89%
	W	1,027	249	24%	131	13%	612	625	61%	1,831	63	6%	-	-	105%
	S2	1,303	323	25%	230	18%	408	494	38%	1,108	122	9%	-	-	91%
K	**S1**	24,276	13,084	54%	3,091	13%	4,019	2,833	12%	5,419	0	0%	-	-	80%
	W	8,910	4,063	46%	1,012	11%	4,711	2,351	26%	6,933	0	0%	-	-	85%
	S2	9,099	4,859	53%	1,853	20%	3,289	2,382	26%	5,935	105	1%	-	-	103%
S	**S1**	5,403	3,678	68%	1	0%	210	2,198	41%	3,086	0	0%	-	-	110%
	W	1,901	1,134	60%	54	3%	280	611	32%	1,775	0	0%	-	-	96%
	S2	2,171	1,408	65%	86	4%	197	1,176	54%	2,087	53	2%	-	-	127%
Mg	**S1**	2,364	1,366	58%	128	5%	166	260	11%	415	0	0%	-	-	76%
	W	1,135	613	54%	38	3%	179	299	26%	879	0	0%	-	-	85%
	S2	872	566	65%	75	9%	133	264	30%	542	44	5%	-	-	111%
Ca	**S1**	13,640	6,957	51%	90	1%	117	3,499	26%	5,093	472	3%	-	-	82%
	W	5,024	2,097	42%	47	1%	217	1,811	36%	5,285	296	6%	-	-	86%
	S2	4,890	2,477	51%	52	1%	93	2,588	53%	4,652	322	7%	-	-	113%
Water[4] (L)	**S1**	82,142	28,102	34%	1,250	2%	-	318	0%	-	417	1%	50,952	62%	-
	W	38,539	13,707	36%	350	1%	-	309	1%	-	417	1%	23,340	61%	-
	S2	41,796	18,479	44%	848	2%	-	253	1%	-	417	1%	21,195	51%	-
Carbon[5]	**S1**	-	-	-	24,909	57%	-	18,267	42%	-	364	1%	-	-	-
	W	-	-	-	7,348	39%	-	10,820	58%	-	511	3%	-	-	-
	S2	-	-	-	16,067	50%	-	15,176	48%	-	608	2%	-	-	-

[1]Percentage in relation to the incoming nutrients in the nutrient solution, [2]Average from steam and leaves, [3]Total balance (addition of all the flows in relation with the incoming nutrients), [4]The evapotranspiration was calculated substracting to the irrigation (nutrient solution) the rest of the flows. [5] The percentage refer to the total carbon fixed (addition of the biomass, produce and perlite). S1=Summer crop 1, S2=Summer crop 2, W=Winter crop, d.s.=dry sample

The nutrients contained in the biomass and the fruits varies depending on the nutrient and the crop. A significant part of the nitrogen, phosphorus and potassium (between 14 and 20%) ends up in the fruits (produce). In absolute terms, these quantities depend on the amount of production of the crop, being higher for summer crops (especially for S1) than for winter ones. In contrast, the amount of nutrients in the biomass (leaves and stem of the plant) is similar for the three crops, but it represents a smaller percentage of the nutrients supplied in S1 because of the high irrigation required in this crop. The nutrients in the biomass of the crop are higher than in the fruits (production), and represent the second largest flow for all the macronutrients. In this sense, optimising the nutrient solution and maximising the solar radiation reaching the crop can help reduce the development of the stems and leaves of the plant. These two measures would restrain the biomass growth and improve the productivity of the crop because less resources would be used for biomass and more for fruits.

The concentration of nutrients in the produce and the biomass from the crops was included in Table 7.1 to provide reference values for future studies. Comparison with previous data is difficult due to the lack of scientific articles including these figures. The data shows that tomatoes hold higher concentrations of nitrogen and potassium, whereas in biomass calcium and sulfur also have significant concentrations.

In respect of the absorption of nutrients in the substrate (perlite), the results show that significant amounts of nitrogen, phosphorus and calcium are retained in the perlite after the crop, representing between 5 and 7% of the nutrient supplied. This is a substantial finding because this flow was not considered when assessing the efficiency of hydroponic crops until now. Future studies implementing nutrient dynamics should integrate this flow in the balance, which will help to close the balance of different elements. These results are further analysed in section 3.4.

As can be observed, most of the nutrients remain unbalanced, holding a percentage lower or higher than 100%. However, these balances are more closed than those found in previous literature, which range between 50 and 85% of the total (Bugbee 2004). Although these deviations might be due to the inherently limited accuracy that experimental measurements have, some factors affecting these balances should be assessed in future studies. For instance, the volatilization of nutrients was proven to represent a significant percentage of the nitrogen supplied (discussed above) but was out of the scope of this study. Moreover, contamination from other sources might influence the results, such as the application of phytosanitary products like wettable sulfur (2.4 kg were applied during the three crops), which might explain the high percentage of the sulfur balance. However, these issues are out of the scope of this study, which presents a first description of the metabolism of nutrients in hydroponic crops.

Regarding the water flows, the results are coherent with the water management along the crops, which aimed at maintaining the drainage between 30 and 40%. The evapotranspiration, which was calculated subtracting all the outflows to the irrigation, accounted for between 51 and 62% of the total. Although water is the main content of fruits (production) and biomass (between 90 and 96%), their moisture content represents less than 2% of the total. A possible measure to reduce the consumption of water would be adjusting the irrigation to keep it closer to 30%. However, if temperature rises drastically from one day to another, as usually happens in spring and autumn, there might be no time to adapt the irrigation. This can lead to an alteration of the drainage, which can derivate in losing part of the production. For instance, a sharp descent in the drainage during the pollination of flowers might imply the abortion of these flowers or might cause blossom in developing fruits.

Finally, the balance of the carbon fixed in the crop was analysed, given its relevance for climate change mitigation. It can be observed that during the three crops conducted 44 kg were fixed in the biomass and 48 kg in the production, being in total more than 90 kg of biogenic carbon. In the case of production, it will return to the atmosphere in a relatively short period, after being consumed. Regarding the biomass, its further use as a by-product might maintain the carbon fixed during a longer period. For instance, it can be used for the generation of biochar, which provides renewable energy and soil amendments (Llorach-Massana et al. 2017).

7.3.3 Balance of micronutrients

The nutrient dynamics was also conducted for some micronutrients (Na, Fe, Zn and Mn) for the third crop (S2). The results (Table 7.4) show that the final balance is much higher than 100% for all the micronutrients, indicating that there is more quantity of these elements in the outflows than in the incoming solution. As discussed in previous literature (Bugbee 2004), these results are typical in hydroponic systems and can be due to the contamination of the fertigation solution from elements of the irrigation system, such as plastic pipes (Zn) or pumps (Fe). This might explain the results found most of the micronutrients, but not for iron, whose outflows are 9 times the inflow. Although a significant part of the nutrients were retained in perlite, no clear patterns of retention were found for micronutrients (discussed in section 3.4). Between 35 and 90% of the sodium, iron and zinc was drained, and a significant part was retained in the biomass, especially in the case of manganese (56%). Balancing the micronutrients is difficult because quantities are small, which implies that more accurate measurement techniques are required, and the amounts in the flows can vary significantly with contamination.

Table 7.4 Flows of micronutrients in the third crop (S2) and water and carbon flows.

	Nutrient solution	Leachates		Biomass		Production		Perlite		Balance
	g	g	%[1]	g	%[1]	g	%[1]	g	%[1]	%[2]
Na	592.4	541.1	91%	61.8	10%	18	3%	68.1	11%	116%
Fe	30.3	19.0	63%	7.1	24%	0.3	1%	248.1	819%	906%
Zn	19.0	6.5	34%	1.6	9%	0.1	0%	23.1	121%	165%
Mn	12.5	0.4	3%	7	56%	0.1	1%	6.6	53%	113%

[1]*Percentage in relation to the incoming nutrients in the nutrient solution*
[2]*Total balance (addition of all the flows in relation with the incoming nutrients)*

7.3.4 Nutrient absortion in perlite

As explained in the methodology (section 2.3.2.), the concentration of nutrients in perlite was measured at the end of the second crop (samples of perlite used during 333 days for crops S1 and W) and at the end of the third crop (samples of perlite used during 466 days for crops S1, W and S2 and 133 days for crop S2). Thus, three points with different concentrations of nutrients were obtained (plus the blank) and possible correlations with different variables were assessed. Only the retention along the third crop was explicitly assessed replacing two bags at the beginning of the crop. As observed in Table 7.3, only the retention of the nutrients that showed a clear pattern and accounted for a significant percentage were estimated in crops S1 and W.

The results show that significant amounts of phosphorus and calcium are retained in perlite, and this retention is directly related to the duration of the period in which the perlite was used. The variable that provided a higher coefficient of determination (R^2) was the number of days of crop in which each sample had been used. Phosphorus accumulates in perlite following the linear regression model (1) (R^2=0.98) whereas calcium follows the regression model (2) (R^2=0.90).

$$P = 0.003 \text{ [g of P retained/day]} \cdot N \text{ days} \qquad (1)$$

$$Ca = 0.0068 \text{ [g of Ca retained/day]} \cdot N \text{ days} + 0.7803 \qquad (2)$$

Nitrogen also showed substantial accumulation in perlite, representing 6% of the nitrogen supplied for both the first (only nitrogen was measured at the end of this crop) and the third crop, which might indicate that perlite always retains this amount of N (around 0.1% of the dry substrate). However, perlite used during S1 and W showed no retention, probably because the measurement threshold of the analysis was 0.1% and the sample was slightly below this value. Thus, although a clear trend is observed, there is not sufficient evidence to confirm it.

In respect of magnesium and sulfur, its retention showed a linear correlation when contrasted with the concentration of these nutrients in the nutrient solution (for magnesium) and the leachtes (for sulfur) at the end of the crop. In other words, the higher the concentration of the nutrient, the higher the retention in the perlite. In the case of magnesium, around 0.22 mg/g of perlite were sorbed or 44 g in total (5% of the Mg supplied) during the third crop. In the case of sulfur, 0.26 mg/g of perlite was retained, being 53 g in total (only 2% of the S supplied). The problem with these correlations is that the scatter plot for both nutrients only includes three points (including the blank) because two of the samples had the same concentration (were collected at the same point in time) and the cases are close in the scatter plot. Thus, the trending line has low reliability and the tendency observed cannot be confirmed.

Regarding the potassium, although a relatively high quantity was retained during the third crop (0.51 mg/g of perlite, 105 g in total), its percentage in relation to the total supplied is only 1%. Moreover, no correlation was found with any of the variables with which these concentrations were contrasted.

Finally, the concentration of micronutrients in the perlite was also measured, but the results could only be contrasted with the duration of the crops because the nutrient dynamics of S1 and W do not include micronutrients, and thus the nutrient load and the concentration at the end of the crop could not be correlated. Although, as seen in Table 7.3, the concentration of certain micronutrients in perlite increased during S2, no clear correlation with the duration of the crops was observed. However, the nutrient solution included small quantities of these nutrients, which makes its presence in the flows prone to contamination, as discussed above.

7.4 Conclusions

This article tries to close the gap in previous literature regarding the study of the nutrient dynamics in hydroponic crops and opens new lines of research in the field. The study quantifies the nutrient flows in open hydroponic crops, representing the first comprehensive attempt to close the nutrient balance of these systems and providing new insights into the issue.

Optimising the use of nutrients in hydroponic crops is key, since the consumption of fertilisers is the most significant environmental hotspot of greenhouses. The study shows that 51% of nutrients are leached in average, which might be reduced or recirculated (closed hydroponic systems). The same goes for water, which could be adjusted to approach to 30% of drainage, improving the water use efficiency. However, the reduction of the nutrients and water supplied has limits and adjusting too much the supply might lead to agronomic problems and loss of produce.

The study reveals that significant amounts of nutrients remain sorbed or precipitated in the substrate (perlite) after the crop, representing between 3 and 7% of the incoming nitrogen, phosphorus and calcium. This finding is significant because this flow was not usually considered in previous studies, which measured the recovery considering only the nutrient supply (nutrient solution), the leachates and the plant uptake. Although the results for the retention of nitrogen, magnesium and sulfur show clear trends, further analyses are needed to verify the patterns observed. In the case of nitrogen, samples of perlite used in crops with different durations should be analysed using a more accurate measurement technique (with a measurement threshold lower than 0.1%). In the case of magnesium and sulfur, specific experiments should be conducted supplying different concentrations of these nutrients to perlite to observe the pattern of retention. Moreover, other substrates used in hydroponic crops should be assessed, such as rockwool or coir.

The retention of nutrients in perlite represents a loss of nutrients, that will be disposed of as a solid waste at the end of life of the perlite bags. From an industrial ecology perspective, using this perlite to amend soils might improve the utilisation of these nutrients and represents a more sustainable management of the waste in hydroponic crops.

The analysis of the micronutrients showed that it is complicated to close the balances due to the small quantities used in the nutrient solution (for crop S2, 30 g of iron were supplied, vs. 3.7 kg of nitrogen), which makes the concentration of these nutrients prone to contamination. However, the relevance of micronutrients from an environmental perspective is limited because small quantities are required, and the leachates hold low concentrations if compared with macronutrients such as nitrogen and phosphorus, which hold greater environmental impacts.

Chapter 8

Water, energy, air and food symbiosis between crops and buildings. Environmental assessment of an integrated rooftop greenhouse

Picture: integrated rooftop greenhouse (i-RTG)
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Chapter 8 Water, energy, CO_2 and food symbiosis between crops and buildings. Environmental assessment of an integrated rooftop greenhouse

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Abstract

Vertical farming is emerging as an effective measure to grow food in buildings and can increase food production in urban areas in a more sustainable manner. This study presents a comprehensive environmental assessment of food production in an integrated rooftop greenhouse (i-RTG) – an innovative vertical farm consisting of a rooftop greenhouse connected to a building – and considers rainwater, residual heat (energy), residual air (CO_2) and food from an industrial ecology perspective. This synergistic connection preserves resources and improves conditions in the greenhouse and the building. The goal of the study is to show the feasibility of the system and to calculate the environmental impacts from its whole life cycle, from infrastructure to end of life, by comparing these impacts with those of conventional production. The results show that the system is feasible and produced 30.2 kg/m^2 of tomato over 15.5 months. The synergy with the building allows the cultivation of winter-fall crops without supplying heating and maintained an average temperature 8 °C higher than that outdoors. Moreover, rainwater was used to irrigate the crops, reducing consumption from the water supply network by 80-90%. The environmental assessment showed that the operation of the i-RTG has more impacts than the infrastructure due to the use of fertilisers, which account for 25% of the impacts in four of the six impact categories studied. Regarding the infrastructure, the greenhouse structure and rainwater harvesting system of the building have substantial environmental impacts (over 30% in four of the six impact categories). Comparison with a conventional greenhouse demonstrates that the i-RTG has a better environmental performance, showing between 50 and 75% lower impacts in five of the six impact categories (for instance, 0.58 kg of CO_2 equivalent per kg of tomato vs. 1.7 kg), mainly due to the reduced packaging and transport requirements. From this study, it was concluded that optimisation of the amount of infrastructure material and management of the operation could lead to even better environmental performance in future i-RTG projects.

Keywords: food security, urban agriculture, vertical farming, LCA, water-energy-food nexus, industrial ecology

8.1 Introduction

Ensuring food security is a major concern worldwide (FAO et al. 2015). Providing enough nutritious food will likely become increasingly difficult due to the increasing world population and its concentration in cities (United Nations 2013). Innovative solutions are needed to address this problem.

In this context, urban agriculture is a growing trend that consists of growing food in and around cities and can contribute to food security in both developed and developing countries (Orsini et al. 2013; Mok et al. 2014). Additionally, urban agriculture has unique advantages, such as social education, the creation of local employment (reducing commuting), reduced food transportation distances and the development of local economies (Altieri et al. 1999; Bon et al. 2010; Kortright and Wakefield 2011; Nadal 2015).

An advanced type of urban agriculture is vertical farming, which is based on the production of food in buildings (Besthorn 2013; Thomaier et al. 2015). Similar concepts have been defined in previous literature, such as Z-Farming or Skyfarming (Despommier 2010b; Specht et al. 2013). Vertical farms are classified depending on the level of integration with the building, for example, by the placement (rooftop, facade), exposure (exposed, enclosed, closed), growth medium (aeroponic, hydroponic, aquaponic) and production purpose (educational, research, commercial) (Association for Vertical Farming 2016).

The concepts of highly technological systems for food production in buildings, completely isolated from nature, and establishing synergy between buildings and crops have been discussed by several authors (Hessel and Bar-On 2002; Fischetti 2008; Despommier 2010b, 2011; Germer et al. 2011). Nevertheless, pilot implementations of this technology in a research context are required to prove its feasibility, elucidate and resolve potential problems and assess its performance. Indeed, previous studies detected the need for scientific articles assessing vertical farming systems, highlighting the necessity of adopting a life cycle perspective in the analysis (Specht et al. 2013; Mok et al. 2014; Sanyé-Mengual et al. 2016).

In vertical farming, rooftop greenhouses (RTGs) are greenhouses located on top of buildings and can be either isolated from the building or integrated at several levels, in regard to water, energy and CO_2 flow (Pons et al. 2015). Occupying unused rooftops for agriculture has great potential for widescale implementation in urban areas, including major cities (Rodriguez 2009; Astee and Kishnani 2010). For instance, a city such as Bologna (Italy) could fulfil 77% of its vegetable requirements with rooftop farms with productivities of 15 kg/m^2 (Orsini et al. 2014). The short-term implementation of RTGs on available rooftops in a logistic park in Barcelona with 13 ha of suitable rooftop area could produce 2,000 tonnes of tomato annually, which would fulfil the demand of 150,000 people (Sanyé-Mengual et al. 2015a).

The concept of an integrated rooftop greenhouse (i-RTG) was proposed and discussed in previous literature (Caplow 2009; Cerón-Palma et al. 2012). i-RTGs share resources with the building and have the potential to increase both the productivity and the efficiency of crops using these synergies. This connection allows for optimisation of the energy behaviour of the building, reduction of CO_2 emitted by the building, increased crop yield and minimisation or elimination of external water use. Several rooftop greenhouse experiments have been reported worldwide (Wilson 2002; Engelhard 2010).

Nevertheless, to the best of our knowledge, no experimental case studies have been conducted integrating the greenhouse and the building. In addition to the advantages stated above, an i-RTG could potentially reduce the environmental impacts of vegetable production. Quantifying these environmental burdens of the pilot i-RTG is of interest to examine the potential for reducing the environmental impacts of food production (Sanyé-Mengual et al. 2012, 2015c).

The main objective of the study is to determine the feasibility of producing food in i-RTGs and examine possible problems. This study also aims to evaluate the environmental performance of the system and to analyse both the crop and its synergy with the building with respect to rainwater, residual heat (energy), residual air (CO_2) and food from an industrial ecology perspective.

The specific goals of the study are as follows:

- To assess an i-RTG with food production (tomato crops) over an extended period (more than a year) in a Mediterranean climate.
- To quantify the environmental impacts of the life cycle of the system and to detect environmental hotspots using the life cycle assessment (LCA) methodology.
- To compare the impacts of tomato consumption with respect to production in the i-RTG and a conventional greenhouse with similar theoretical conditions.
- To evaluate the feasibility of i-RTGs as food production systems and propose measures for optimisation in terms of resource efficiency and productivity.

8.2 Methodology

8.2.1 Description of the integrated rooftop greenhouse (i-RTG)

The ICTA-ICP building on the Universitat Autònoma de Barcelona campus (Spain) is a research centre designed with high standards of sustainability. The building is 7,500 m^2 (six floors) and contains a covered rooftop with four areas that can be used for vertical farming (Figure 8.1). This study analyses the food production in one of these four areas (marked in Figure 8.1) as a pilot i-RTG case study. As stated in the previous section, the main innovation of the i-RTG is that it is connected with the building from an industrial ecology perspective, as shown in the diagram of Figure 8.1.

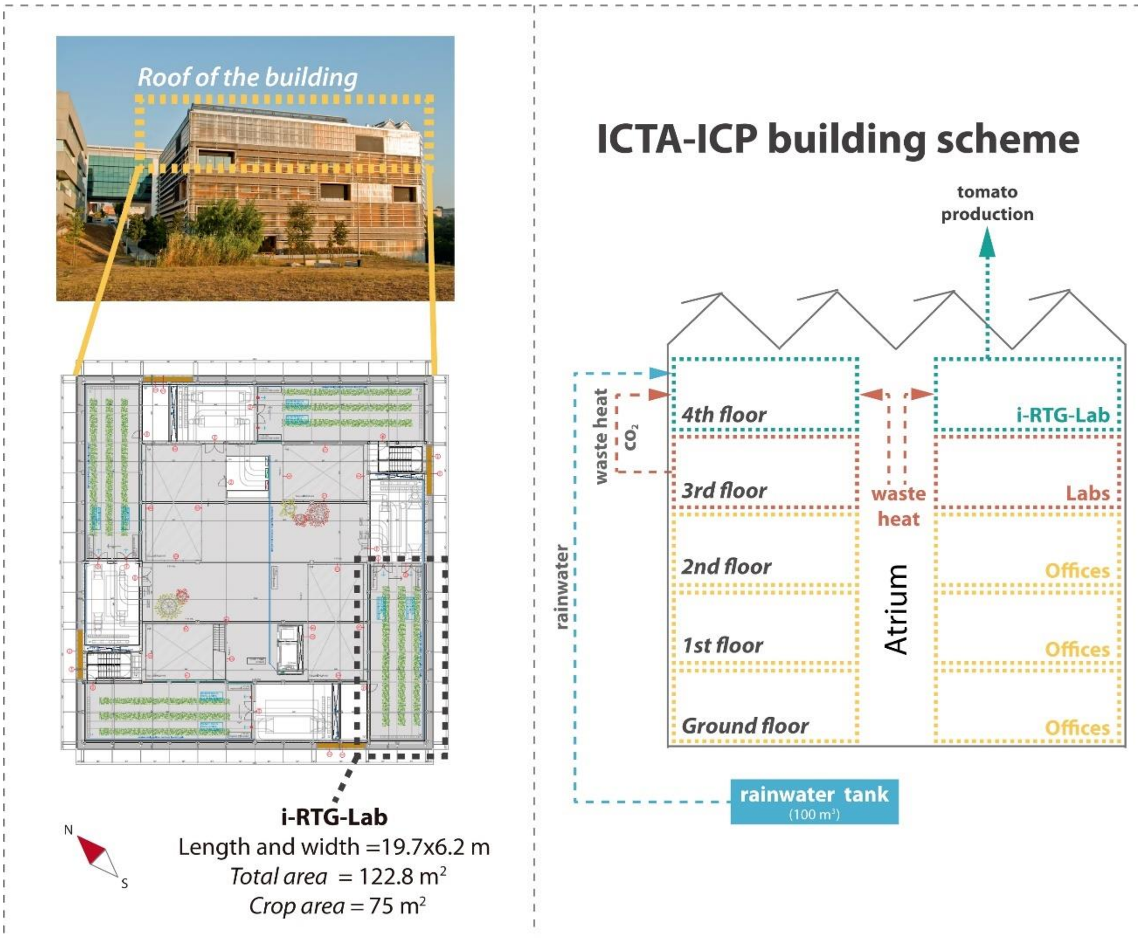

Figure 8.1 Diagram of the water, waste heat and CO_2 flows in the ICTA-ICP building and blueprint of the rooftop with the i-RTG.

The external structure of the ICTA-ICP building is composed of a metal frame with corrugated polycarbonate sheets that can be opened or closed to provide ventilation (Figure 8.2). This structure comprises the walls and the roof of the building and the i-RTG. The opening and closing of the sheets is automatic depending on the temperature and is controlled with specially designed software, following a protocol that can adapt to different external conditions. The greenhouse also contains internal polyethylene film curtains that can be rolled up or down to connect the greenhouse to the building or to isolate it. It should be highlighted that the i-RTG and the building were independently designed, and the greenhouse was adapted to the existing conditions on the rooftop. Residual air from temperature-controlled areas in the building (always between 20 and 24 ˚C) is injected into the i-RTG. This air flow improves the temperature of the greenhouse, cooling in summer and warming in winter, and provides higher CO_2 concentrations, which benefit the plants. The shared air not only benefits the i-RTG but also contributes to controlling the temperature of the building (synergistic conditions).

The building also contains a rainwater harvesting system that integrates water collected from the roof of the ICTA-ICP building and the roof of the nearest building (Eureka). Water passes through a primary filter to remove solids and is collected in a 100 m^3 water storage tank. This untreated rainwater is used in the i-RTG to irrigate the crops and water ornamental plants in the building, reducing the demand for potable water from the conventional distribution network. In total, the building has a harvesting surface of 900 m^2.

Figure 8.2 i-RTG with a crop of two weeks (top left), i-RTG with a crop of four months (top right), i-RTG from the atrium (bottom left), and polycarbonate sheets in the wall of the greenhouse (bottom right).

8.2.2 Plant materials and growth conditions

The pilot i-RTG has a total area of 122.8 m^2 (Figure 8.1) and a cropping area of 84.34 m^2. In total, 171 tomato plants were grown, 47 of which were perimeter plants with non-standard conditions.

A hydroponic system was used for irrigation to supply a nutrient solution (water plus fertilisers, also called fertigation) to plants located on an inert substrate. More specifically, the crop has an open hydroponic system, and thus, the leachates (excess nutrient solution) are disposed of. Two 300 litre tanks were installed for water storage in the greenhouse to avoid interruption in case of water supply failure. A pump propels water from the tanks, which replenish constantly, and the nutrients are injected from a concentrated nutrient solution to the water flow. Finally, water is applied to the plants through drippers with a flow of 2 L/h.

The substrate of the crop is composed of 57 perlite bags distributed in rows with a distance of 1.2 m between them. Each of these bags measures 1 m long, contains 40 L of perlite and provides a substrate for three plants.

The crops were beef tomato varieties (*Lycopersicon esculentum*, *Arawak* for spring crops and *Tomawak* for winter crops). Seedlings grown in peat for 4 to 6 weeks (at a local garden centre) were transplanted to the perlite bags in the greenhouse. Three crops were grown from February 2015 to July 2016. Table 8.1 shows the specific cultivation periods. The third crop was interrupted due to a critical condition (affected by plagues). Produce was harvested when there was a significant amount of ripe fruits (daily during the peak of production). A follow-up of the state of the plants was carried out by agronomy experts twice per month to prevent or treat possible plagues and plant diseases.

Table 8.1 Characteristics of tomato cultivation.

Cultivation	Season	Starts	Harvest starts	Finishes	Days (n)
S1	Spring-summer	10/02/2015	20/04/2015	23/07/2015	164
W	Fall-winter	15/09/2015	17/12/2015	04/03/2016	169
S2	Spring-summer	08/03/2016	23/05/2016	20/07/2016	133

S=spring crop, W=winter crop

8.2.3 Experimental analyses

The concentration of nutrients was measured periodically to ensure adequate nutrient supply. Samples were collected once per week from the nutrient solution and three times per week from the leachates (during S2, both were collected daily). The concentrations of Cl^-, NO_2^-, NO_3^-, PO_4^{3-}, SO_4^{2-}, Ca^{2+}, K^+ and Mg^{2+} were measured using ionic chromatography. Additionally, the pH and EC were measured daily for both the nutrient solution and the leachates. According to the results of these analyses, adjustments were made to tailor the nutrient solution to the requirements of the crops.

A protocol was defined to evaluate the quality of the tomatoes produced by the W and S2 crops. This assessment considered the size, weight and sugar content of the tomatoes. Three rows of plants were selected, and ten representative tomatoes were collected, excluding perimeter plants and exceptionally large or small fruits. The diameter and weight were measured for all the tomatoes collected. For each of the rows, the degrees Brix (sugar content) was measured for six of the ten tomatoes. For each crop, the average values of all implemented protocols were considered.

8.2.4 Life cycle assessment (LCA)

The LCA methodology was used to quantify the environmental impacts of the system following ISO 14040 and 14044 (ISO 2006a, b).

8.2.4.1. Goal and scope

The whole system was considered for the LCA, from the materials to the end of life of the i-RTG, including all elements. Figure 8.3 shows the diagram of the i-RTG life cycle, distinguishing between the infrastructure (when the lifespan of the element is more than five years) and operation (the lifespan is less than five years).

The inventory for the LCA was elaborated by collecting data during the construction of the rainwater harvesting system and the auxiliary equipment and the operation (inputs-outputs) of the i-RTG during the experiment. Additionally, the inventory for the greenhouse structure was compiled using data from Sanye-Mengual et al. (2015).

The functional unit selected for assessment is 1 kg of tomato delivered for consumption. To calculate the impacts of the functional unit, all edible produce was considered, only excluding tomatoes affected by blossom or plagues (which represent less than 2% of the total produce). All the environmental impacts reported in the study refer to this functional unit.

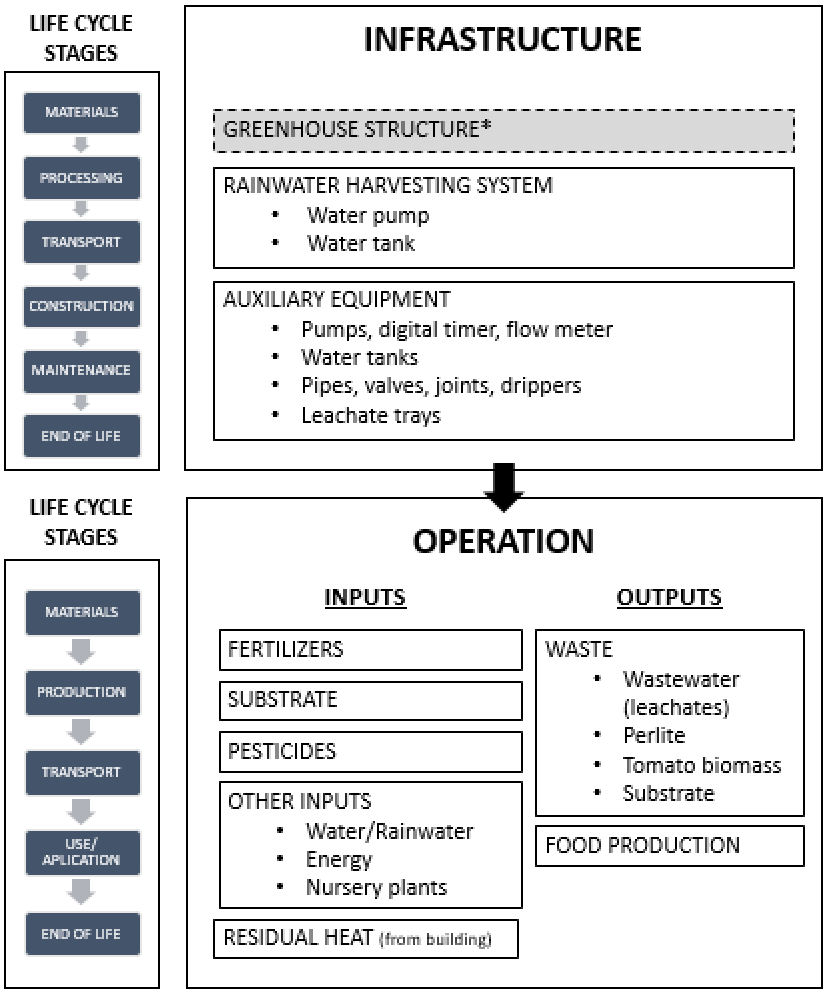

Figure 8.3 Diagram of the i-RTG and system boundaries of the assessment.

**Data for the inventory of the greenhouse structure was obtained from Sanye-Mengual et al. (2015).*

The environmental impacts of tomato production in the i-RTG were compared with those of conventional production in a standard multi-tunnel greenhouse. For this, a scenario for conventional food production was defined, considering the same system boundaries. Table 8.2 gives the scientific articles used as data sources for the LCA, all of which were published by the Sostenipra research group.

Table 8.2 Summary of the data sources considered for the life cycle inventory.

	i-RTG	Conventional greenhouse	Environmental information
Greenhouse infrastructure			Ecoinvent 3
Greenhouse structure	BL (a)	BL (b)	
Auxiliary equipment	OD	BL (b)	
Rainwater harvesting system	OD	-	
Management of the greenhouse			
Use of water and fertilisers	OD	BL (c,d)	
General management	OD	BL (b)	
Agricultural data			
Crop yield	OD	BL (c)	
Water consumption	OD	BL (c)	
Compost biomass	BL (e)	BL (f)	
Packaging and distribution			
Packaging of the product	-	BL (a)	
Distribution distances and losses	-	BL (a)	

(a) Sanye-Mengual et al. (2015), (b) Martínez-Blanco et al. (2011), (c) Muñoz et al. (2015), (d) Muñoz et al. (2008), (e) Martínez-Blanco et al. (2010) (f) (Colón et al. 2012). OD=own data, BL=based on the literature.

8.2.4.2. Life cycle inventory of the i-RTG

This section presents the relevant assumptions and data sources considered for the inventory of the i-RTG LCA.

Infrastructure

The corresponding impacts of the rainwater harvesting system were allocated to the i-RTG according to its consumption. For the allocation, the lifespan and the rainwater supplied to the system were used to calculate the impacts per cubic metre of rainwater.

According to the expertise of the authors and similar to previous studies, a 50 year lifespan was assumed for the rainwater harvesting system (Vargas-Parra et al. 2013; Sanjuan-Delmás et al. 2015a) and the greenhouse structure (Sanye-Mengual et al. 2015), and a ten year lifespan was assumed for the auxiliary equipment (Hoffman et al. 2007).

The detailed inventory for the infrastructure and its description can be found in section 3.2 and Appendix VII.I.

Operation

The assessment of the fertilisers and pesticides used in this work includes impacts of the emissions to air generated during application, which were estimated in accordance with Montero et al. (2011). The impacts derived from the generation of leachates, which were discharged to the sewer network, were considered emissions to water (into nature) provided there was no guarantee that these contaminants were removed in the municipal wastewater treatment plant. Furthermore, the waste biomass was composted in the greenhouse, and the impacts were calculated according to Martínez-Blanco et al. (2010).

The electricity required for opening and closing the walls and roof was estimated using data from the building software, and the electricity consumed by water pumps was estimated considering the characteristics of the pumps and the amount of water pumped. The Spanish 2015 electricity mix (Red eléctrica de España 2015) was used.

Transport

The database used to acquire environmental information included transport to markets based on average values. Additionally, transportation from the market to the i-RTG was included. This distance was 35 km for fertilisers, pesticides and auxiliary equipment; 60 km for rainwater harvesting construction materials; and 850 km for substrate bags (the bags were not available locally and had to be imported from Almeria). All distances covered during transport were doubled because the vehicle was empty on the trip back.

End of life

For the end of life assessment, the impacts of materials that were disposed of were included, but possible impacts of recycling were considered to be charged to the subsequent systems. Auxiliary equipment was assumed to go to the landfill, while all pumps and tanks (including the rainwater tank) were assumed to be recycled. A distance of 30 km was assumed for travel from the i-RTG to the landfill or the recycling station.

Comparison with the reference scenario

In the reference scenario, the packaging and distribution required to reach the consumer's home and the product loss (17%) were determined according to Sanye-Mengual et al. (2015). None of these elements were found in the i-RTG, where the produce was taken by the users of the building using their own bags and without extra transport. Details of the inventory for the definition of this scenario can be found in Appendix VII.II.

Unlike this study, previous studies did not include the impacts of the residual nutrient solution used for irrigating the soil-based crops. To maintain the same system boundaries, the impact of these leachates was not included in the comparison between i-RTGs and conventional greenhouses.

8.2.4.3. Environmental information and calculation method

The Simapro 8.2 software was used along with the ReCiPe method (Hierarchist; H) to calculate the environmental impacts. The environmental information was acquired from the Ecoinvent 3 attributional database.

According to the expertise of the authors and previous literature (Brentrup et al. 2004), the following impact categories from the ReCiPe method (H) were selected as indicators: climate change (CC), ecotoxicity (ET), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME) and fossil fuel depletion (FD). For ET, the addition of three ReCiPe impact categories (terrestrial, freshwater and marine ecotoxicity) was considered.

8.4 Results and discussion

8.4.1 i-RTG: a new urban food production system

The system produced 30.1 kg of tomato per square metre over 15.5 months, providing a total of 2,540 kg of food (Table 8.3). For reference, the system could grow approximately 1,660 kg of tomatoes per year, whereas the annual consumption in Spain is 13.5 kg of tomatoes per capita (Ministerio de Agricultura 2016), which means that the i-RTG could supply tomatoes to 110 people. This figure proves that the i-RTG has the potential to produce a significant amount of food throughout the year.

The productivity was found to be on average three times higher for the spring crops (S1/S2) than for the winter crop (W). Moreover, tomatoes grown in winter are smaller and have a slightly lower sugar content (Table 8.3). This difference in productivity is a result of the relatively lower solar radiation and temperature during winter. Although in absolute terms the consumption of resources (water, fertilisers) is lower due to the reduced evapotranspiration, the decrease in the productivity makes winter crops less efficient. However, tomatoes hold a significant added value in winter, because winter is not their natural growing season in the Mediterranean region.

The i-RTG makes cultivation easier during the winter because the system takes advantage of warm air from the building, affording milder temperatures (on average, between 5 and 8 Celsius degrees higher than that outdoors; Table 8.3), which improves the growing conditions considerably and avoids the necessity for heating. Nadal et al. (2017) estimated that to achieve these temperatures in a similar greenhouse located on the ground would require 341.9 kWh of thermal energy/m^2/year, generating between 5.5 and 113.8 kg CO_2 eq/m^2/year (depending on the heating system and type of fuel). This heating would increase the carbon footprint of production by several times its current value.

Table 8.3 Agronomic data for spring and winter crops in the integrated rooftop greenhouse (i-RTG).

		Units	S1	S2	W
Food	**Total yield**	kg of tomato/m^2	15.3	10.5	4.4
	Tomato average diameter	mm	-	78.3	57.9
	Tomato average weight	g	176	188	119
	Degrees Brix	^{0} Bx	-	5.1	4.7
Water	**Water use efficiency**	L/kg of tomato	63.8	47.3	103.8
	Percentage of rainwater used	%	82	90	88
Energy	**Average temperature i-RTG**	^{0} C	21.3	21.2	19.5
	Average temperature outside	^{0} C	16.2	16.1	11.8
	Maximum temperature i-RTG	^{0} C	34.6	29.2	26.0
	Minimum temperature i-RTG	^{0} C	11.8	13.9	14.6

S1=spring crop 1, S2=spring crop 2, W=fall/winter crop.

It is important to highlight that shading from some elements of the building structure (ventilation conduit, inner wall; Figure 8.4) diminished productivity in the i-RTG. This shading is a common problem affecting vertical farming systems because the systems are usually adapted to existing structural conditions. As is well known in agriculture, the productivity of a greenhouse is strongly influenced by the total solar radiation reaching the crop. For tomato, between 2 and 2.65 kg per of produce square metre is accumulated for every 100 additional MJ/m^2 of solar radiation incident on the crop (Papadopoulos and Pararajasingham 1997). Thus, minimising the influence of shading elements on solar radiation can help significantly improve the crop yield.

Figure 8.4 i-RTG with a two-week crop and the ventilation conduit (top left), inner wall of the i-RTG (top right), tomatoes on the crop (bottom left) and tomatoes produced in the i-RTG (bottom right).

The water use efficiency (WUE), i.e., the water consumed for irrigation per unit produce, was better for the spring crops, which was more than double that of the winter crop. The lower productivity of W compared with S1 and S2 implies higher water consumption per unit produce. The WUE values reported for beef tomato crops in standard greenhouses are lower, 33.3 and 63.5 L/kg of tomato for the spring and winter crops, respectively (Muñoz et al. 2015). This higher efficiency is due to the lack of optimisation in the management of crops grown in the i-RTG. Moreover, a more efficient mechanism to evacuate heat in the summer would reduce temperature and hence diminish evapotranspiration. However, it should be highlighted that most of the water consumed in the i-RTG was rainwater collected from the building (80-90%). The remaining 10 to 20% was tap water, which was on average approximately 1.6 m^3 per month during the cropping period. Thus, the final external demand of water for the i-RTG is even lower than that for conventional greenhouses due to its high self-sufficiency. Moreover, the implementation of improvements for the optimisation of the system in future crops might also significantly reduce the WUE.

8.4.2 Life cycle inventory of the i-RTG crops

Table 8.4 shows the inventory of the operation phase for the spring (S1, S2) and winter (W) crops grown in the i-RTG. The data are given as per kg of tomato produced and per square metre of cultivation area. The inventory of the i-RTG infrastructure can be found in Appendix VII.I.

Table 8.4 Inventory of the operation life cycle phase for the spring (S1, S2) and winter (W) crops grown in the i-RTG.

Element	Material	Units	S1		W			S2		
			per crop	per kg tomato	per crop	per kg tomato	Ratio W/S1	per crop	per kg tomato	Ratio S2/S1
Substrate*	Perlite	kg	71.8	5.6E-02	74.0	2.0E-01	3.6	58.2	6.6E-02	1.2
	HDPE	kg	1.9	1.5E-03	1.9	5.3E-03	3.6	1.5	1.7E-03	1.2
Fertilisers	KNO_3	kg	18.6	1.4E-02	11.6	3.1E-02	1.6	12.7	1.4E-02	0.7
	KPO_4H_2	kg	11.2	8.7E-03	5.2	1.4E-02	2.2	5.7	6.4E-03	1.0
	K_2SO_4	kg	26.9	2.1E-02	10.0	2.7E-02	1.3	10.9	1.2E-02	0.6
	$Ca(NO_3)_2$	kg	34.6	2.7E-02	12.5	3.4E-02	1.3	13.7	1.6E-02	0.6
	$CaCl_2$	kg	10.9	8.4E-03	4.2	1.2E-02	1.4	4.6	5.3E-03	0.6
	$Mg(NO_3)_2$	kg	22.9	1.8E-02	8.5	2.3E-02	1.3	9.3	1.1E-02	0.6
	Hortilon / Tradecorp	kg	0.8	6.4E-04	0.4	1.0E-03	1.6	0.4	4.7E-04	0.7
	Sequestrene	kg	0.8	6.4E-04	0.4	1.0E-03	1.6	0.4	4.7E-04	0.7
Pesticides	Potassium soap	kg	1.2	9.3E-04	2.4	6.5E-03	7.0	1.2	1.4E-03	1.5
	Wettable sulphur	kg	0.2	1.2E-04	0.8	2.0E-03	17.5	1.5	1.7E-03	14.6
	Costar (80% bacillus thuringiensis)	kg	0.0	0.0E+00	0.1	1.6E-04	-	0.2	2.4E-04	-
	MeemAzal (10 g/L $C_{35}H_{44}O_{16}$)	kg	0.0	0.0E+00	0.0	4.9E-05	-	0.1	8.2E-05	-
Water	Tap water	m^3	14.9	1.2E-02	4.2	1.1E-02	1.0	5.2	5.9E-03	0.5
	Rainwater	m^3	67.2	5.2E-02	38.1	1.0E-01	2.0	36.6	4.1E-02	0.8

Processes										
HDPE	Extrusion, plastic film	kg	1.9	1.5E-03	1.9	5.3E-03	3.6	1.5	1.7E-03	1.2
Energy - opening/closing slabs	Electricity, Spanish mix 2015	kWh	4.7	3.7E-03	4.4	1.2E-02	3.3	4.0	4.5E-03	1.2
Energy - rainwater pump	Electricity, Spanish mix 2015	kWh	1.5	1.1E-03	0.8	2.1E-03	1.8	0.8	8.5E-04	0.7
Energy - nutrient solution Pump	Electricity, Spanish mix 2015	kWh	16.8	1.3E-02	9.5	2.6E-02	2.0	9.1	1.0E-02	0.8
Nursery plants**	Diesel	kWh	0.0	2.3E-05	0.0	7.9E-05	3.5	0.0	3.3E-05	1.5
	Electricity, Spanish mix 2015	kWh	0.2	1.5E-04	0.2	5.3E-04	3.5	0.2	2.2E-04	1.5
	Transport, passenger car	km	14.0	1.1E-02	14.0	3.8E-02	3.5	14.0	1.6E-02	1.5
Leachates (emission to water)	Cl^-	kg	5.7	4.4E-03	2.6	7.2E-03	1.6	0.5	5.6E-04	0.1
	NO_3^-	kg	23.7	1.8E-02	4.9	1.3E-02	0.7	7.3	8.3E-03	0.5
	PO_4^{3-}	kg	2.2	1.7E-03	0.8	2.1E-03	1.2	1.0	1.1E-03	0.7
	SO_4^{2-}	kg	11.0	8.6E-03	3.4	9.3E-03	1.1	4.2	4.8E-03	0.6
	K^+	kg	13.1	1.0E-02	4.1	1.1E-02	1.1	4.9	5.5E-03	0.5
	Mg^{2+}	kg	1.4	1.1E-03	0.6	1.7E-03	1.6	0.6	6.4E-04	0.6
	Ca^{2+}	kg	7.0	5.4E-03	2.1	5.7E-03	1.1	2.5	2.8E-03	0.5
Waste – biomass	Biomass	kg	383.2	3.0E-01	345.6	9.4E-01	3.2	300.3	3.4E-01	1.1
Waste – substrate*	Sanitary landfill	kg	73.7	5.7E-02	75.9	2.1E-01	3.6	59.8	6.8E-02	1.2
Transport fertilisers	Transport, van	tkm	8.9	6.9E-03	3.7	1.0E-02	1.5	4.0	4.6E-03	0.7
Transport pesticides	Transport, van	tkm	0.1	7.3E-05	0.2	6.2E-04	8.4	0.2	2.4E-04	3.2
Transport perlite*	Transport, lorry	tkm	125.3	9.7E-02	129.1	3.5E-01	3.6	101.6	1.2E-01	1.2

*HDPE=high density polyethylene, *Allocated according to the duration of the crops, **Retrieved from Antón (2004)*

As seen in Table 8.4, water and fertilisers are the largest material inputs in the i-RTG. This consumption is linked to the WUE because both water and fertilisers are supplied through the fertigation system. In this sense, the spring crops were more efficient than the winter crop, as mentioned above. The use of pesticides is a sensitive issue in vertical farming due to the proximity to people's living or work places. For this reason, only small quantities were used when necessary, always selecting the mildest available option for environmental and health reasons.

The substrate for cultivation and waste biomass from the crop are also significant elements of the i-RTG operation. Substrate bags lead to materials and waste that must be landfilled and imply transport at the beginning and end of the life cycle. Biomass from the crop plants was composted in the greenhouse, avoiding transport and landfilling, although certain materials were required for the installation of the composter, and emissions were generated during the composting process.

8.4.3 Environmental performance of the i-RTG

The environmental impacts of tomato production in the i-RTG are shown in Table 8.5. The complete results obtained from the LCA can be found in Appendix VII.III.

The spring crops showed better environmental performance than the winter one, where S2 had the least impact with between 50 and 60% lower environmental impacts than W. These impacts are clearly affected by key factors such as the WUE, the season and the productivity. A higher WUE not only implies a larger water demand but also a larger quantity of fertilisers, which have significant influences on the environmental impacts. Moreover, S2 showed better environmental performance than S1, with 30 and 40% less impact by freshwater and marine eutrophication, respectively. The higher impact of S1 is also derived from a greater consumption of water due to the occurrence of exceptionally high temperatures that spring and summer. Another reason that must be highlighted is the lack of experience of the staff running the system during S1, which improved during the crop cycle and in the following cycles (W, S2).

Table 8.5 Total environmental impacts per kg of tomato crops grown in the i-RTG.

		CC	ET	TA	FE	ME	FD
		kg CO_2 eq	kg 1,4-DB eq	kg SO_2 eq	kg P eq	kg N eq	kg oil eq
S1	**Spring crop 1**	6.10E-01	1.37E-02	3.11E-03	6.65E-04	6.52E-03	1.50E-01
W	**Winter crop**	1.41E+00	3.01E-02	7.29E-03	3.05E-03	1.20E-02	3.78E-01
	Ratio W/S1	2.31	2.20	2.34	1.36	1.10	2.52
S2	**Spring crop 2**	5.60E-01	1.22E-02	2.93E-03	4.60E-04	3.75E-03	1.52E-01
	Ratio S2/S1	0.92	0.89	0.94	0.69	0.58	1.01

CC=climate change, ET=ecotoxicity, TA=terrestrial acidification, FE=freshwater eutrophication, ME=marine eutrophication, FD=fossil fuel depletion.

The contribution of each element in the i-RTG to the total environmental impacts is shown in Figure 8.5. The results show that most of the environmental impacts are generated during the operation of the i-RTG, especially for freshwater and marine eutrophication (FE, ME), in which operation contributed over 90% to these impact categories. In contrast, infrastructure has a larger impact on fossil fuel depletion (FD), contributing between 55 and 60% of the impact.

During the operation of the greenhouse, the use of fertilisers has the most impact, accounting for more than 25% in four of the six impact categories considered. The impacts of fertilisers are higher in S1 due to the higher WUE (mentioned above) and account for more than 30% in five of the six impact categories. The environmental impacts of fertilisers are generated during their production due to the high quantities of chemicals, such as sulphuric acid and nitric acid, and the large amounts of energy (heat and electricity) required in the process. Prior studies assessing the life cycle of conventional greenhouses have concluded that the use of fertilisers was critical from an environmental perspective (Muñoz et al. 2008a, 2015).

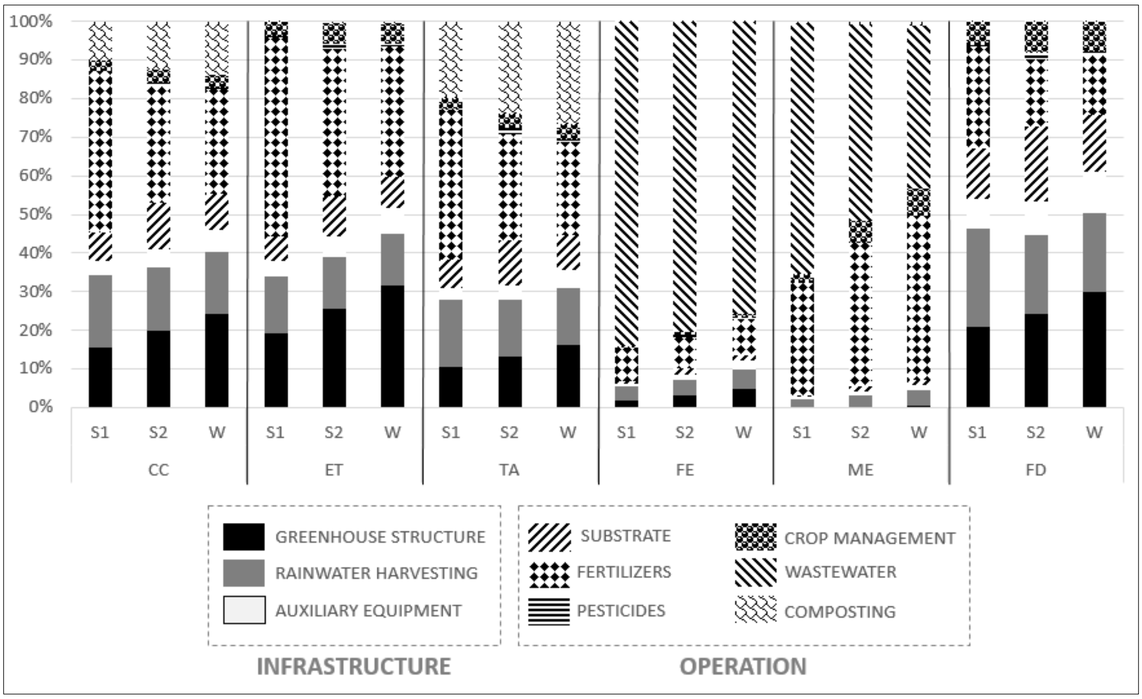

Figure 8.5 Contribution of system elements to the total environmental impacts of the spring (S1/S2) and winter (W) crops.

CC=climate change, ET=ecotoxicity, TA=terrestrial acidification, FE=freshwater eutrophication, ME=marine eutrophication, FD=fossil fuel depletion.

Wastewater (leachates from the crop) sent to the sewer contributes between 40 and 85% of the environmental impacts of freshwater and marine eutrophication (FE, ME). These impacts are caused by the nitrates and phosphates contained in the leachates of the crops, which are discharged into the sewer network and sent to a wastewater treatment plant. Nevertheless, as stated in the methodology section, the most extreme case was considered in the assessment, assuming that all nitrates and phosphates discharged into the sewer remained after treatment in the wastewater treatment plant and eventually arrived in the environment. For instance, if the treatment plant included a denitrification process, the amount of nitrates discharged into the environment would be lower, although other impacts would result from the denitrification processes. The reuse of leachates for watering ornamental plants in the building would significantly reduce the environmental impacts and at the same time increases the overall efficiency of the building (reducing the amount of water and fertilisers used for ornamental plants). Another option would be to use the leachates to irrigate ground-based crops, reducing the impacts and utilising the nutrients. All these are options to be considered for implementation in future crops.

Composting biomass is another environmental hotspot of i-RTGs. Composting generates between 20 and 30% of the impact on terrestrial acidification (TA) and 10 to 15% of the impact on climate change (CC) due to the release of gases during the composting of organic matter. Ammonia (NH_3) emissions have great potential for terrestrial acidification, whereas nitrous oxide (N_2O) affects climate change. To a lesser extent, the substrate bags also generate substantial impacts, accounting for 10 to 20% of fossil fuel depletion (FD) and between 5 and 12% of the other three impact categories. Most of these environmental impacts are generated during the production of the substrate.

Regarding the infrastructure of the i-RTG, the environmental impacts of the greenhouse structure (including the steel framework and the polycarbonate sheets) allocated to each of the crops is the most important contributor. This greenhouse structure produces between 10 and 30% of the impacts in four of the six impact categories. The steel used for construction has the most impact due to the manufacturing processes and the resultant emissions of mercury to air and manganese and arsenic to water. Another important environmental hotspot is the construction of the rainwater harvesting system allocated to the i-RTG, which represents between 10 and 25% of the impact in four of the six categories. These impacts are generated during the manufacture of the 100 m^3 water tank, which requires a significant amount of glass fibre-reinforced polyester.

8.4.4 i-RTG vs. standard greenhouse

The environmental impacts of tomatoes from the i-RTG and a conventional greenhouse were compared, as shown in Figure 8.6. It can be observed by comparing spring and winter crops separately that the i-RTG has lower environmental impacts in five of the six impact categories analysed. For instance, spring crops in the i-RTG generate on average 0.58 kg of CO_2 equivalent per kg of tomato, while conventional greenhouses generate 1.7 kg, which is consistent with previous literature (Payen et al. 2015). For the winter crops, the i-RTG generates 1.4 kg of CO_2 equivalent per kg of tomato, whereas conventional production generates 2.0 kg. Packaging and distribution of the produce have the most impact in the conventional system. In this scenario, the produce was assumed to travel 500 km from the south (Almeria) to the north of Spain (Barcelona), but this distance could be larger because fruits are often imported from other countries and continents. Production from the i-RTG does not require packaging or distribution. For this reason, the environmental impacts of conventional production are more than double those of i-RTG in some impact categories (and would be higher if they came from distant regions).

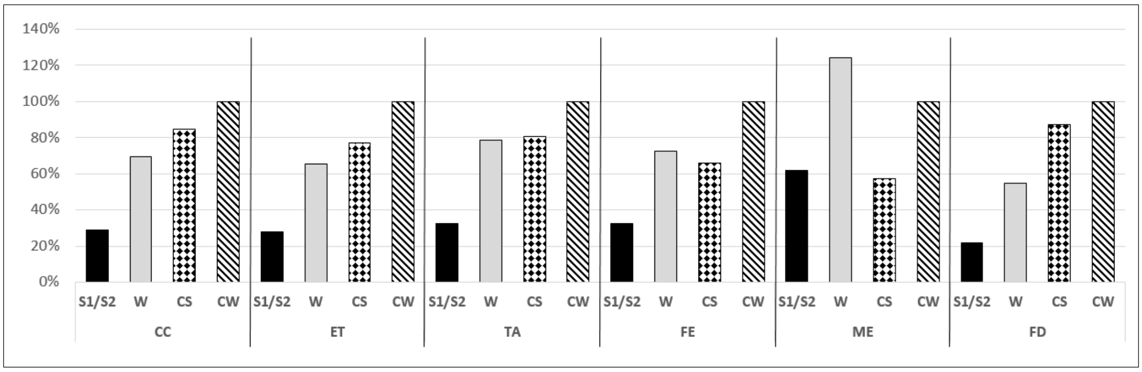

Figure 8.6 Comparison of the environmental impacts of crops grown in the i-RTG and a conventional greenhouse.

S1/S2=average values for spring crops, W=winter crop, CS=spring crop in conventional greenhouse, CW=winter crop in conventional greenhouse, CC=climate change, ET=ecotoxicity, TA=terrestrial acidification, FE=freshwater eutrophication, ME=marine eutrophication, FD=fossil fuel depletion.

Comparison between the performance of the pilot i-RTG and a standard greenhouse with similar conditions is complex. Conventional production systems are expected to be more efficient in the use of resources because they benefit from the economy of scale and because their main purpose is economic benefit. In contrast, research i-RTGs have different priorities and are usually small installations. For instance, they may provide potential positive social impacts if they become educational centres or if they are used for community agriculture, as discussed in the previous literature (Caplow 2009; Sanyé-Mengual 2015). As the case under assessment is a small pilot facility for research purposes and is not optimised regarding management, there is significant potential for improvement, which may increase productivity and reduce environmental impacts.

Another complex issue regarding the comparison between i-RTGs and standard greenhouses is the construction of the infrastructure for the i-RTG. Vertical farming systems are usually conditioned by the existing structure of the building, which has drawbacks, such as reduced space for the production area and shading from some building elements. In this specific case study, the roof and walls of the i-RTG belonged to the building structure but were considered in the calculation of the environmental impacts. However, it could be argued that these impacts should not be included because they were not installed for the greenhouse. Excluding this element for the calculation of the i-RTG environmental impacts would significantly improve the environmental performance of the system (see the contribution from the greenhouse structure in Figure 8.5). In this respect, different assumptions can be considered depending on the situation. For instance, an existing building adapted for a rooftop greenhouse can have different allocation criteria than a building originally designed with a rooftop greenhouse.

8.4.5 Improving i-RTGs: towards an industrial scale

Future applications of this technology should consider the environmental hotspots detected in this study and the provided recommendations to reduce the environmental impacts of i-RTGs. One of the most significant issues in i-RTGs and hydroponic crops, in general, is the use of fertilisers. The nutrient solution should be adjusted according to the requirements of the plants to avoid the leaching of excess nutrients. Implementing closed hydroponic systems (with recirculation of the leachates) could save significant quantities of water and fertilisers. However, this technology has a more complex mechanism in comparison with open hydroponic systems (without recirculation), requiring devices for filtering and disinfecting the leachates before recirculation, as well as more pumps, pipes and tanks for recirculation. Further studies should assess the payback time of this technology in environmental terms. In other words, it should be assessed whether the savings in fertilisers and water compensate for the extra expenditures in energy and auxiliary equipment.

Another issue that should be considered in the design of an i-RTG is the optimisation of the infrastructure, which can substantially reduce the environmental impacts. The structure of the greenhouse was exaggerated in terms of the size and the quantity of steel to ensure its security. More experience is required in the construction of these structures to provide the same function with a lower use of resources. Reducing the amount of steel or changing the material or global design could be beneficial due to the high environmental burden of steel. Similarly, optimisation of the rainwater harvesting infrastructure can be achieved by reducing the size of the water storage tank, which would significantly reduce the amount of material required for its manufacture. A preliminary assessment to optimise the rainwater tanks was carried out using the software Plugrisost® (Morales-Pinzón et al. 2012; Morales-Pinzón et al. 2015). Applying the software to the case study showed that 90% of the rainwater used for the crops during the assessment period could have been covered with a 20 m^3 tank instead of the current 100 m^3 tank. The reason for this is that the limiting factor in the system is the harvesting surface, not the tank size. Thus, an estimation of the optimum tank size while designing the greenhouse may significantly reduce the environmental impacts.

8.5 Conclusions

This study has proven the feasibility of utilising i-RTGs for food production in urban areas by taking advantage of synergies between the building and the rooftop greenhouse to produce 19.6 kg of tomato/m^2·year. The synergy with the building afforded significant resource savings, for example, 80 to 90% of the water used for the crop was rainwater collected from the building. These figures mean that to fulfil the average consumption of tomato per person in Spain only 0.7 m^2 of productive area in the i-RTG are required, along with 7.5 m^2 of catchment area to collect rainwater. This system can be an alternative to conventional production and an opportunity to improve food security and self-sufficiency in cities. Moreover, the i-RTG has lower environmental impacts than conventional production in all the impact categories analysed (except marine eutrophication). For instance, a summer crop in the i-RTG generates 0.58 kg of CO_2 equivalent per kg of tomato, while a conventional greenhouse generates 1.7 kg, which proves that i-RTGs can contribute to climate change mitigation.

The ultimate purpose of this study is to foster the application of i-RTGs in urban systems on an larger scale. The industrial application of this technology with larger crops and better conditions would be a crucial step to enhance food production in urban areas. In this context, it is important to provide clear recommendations capturing the lessons learned in this pilot application. For large-scale implementation, improving the management of the system is key to reduce the consumption of fertilisers and generation of leachates. The use of rainwater must be implemented when possible to avoid impacts from transportation and to increase self-sufficiency. Moreover, the infrastructure (greenhouse structure, rainwater storage tanks) should be optimised to reduce the amount of materials used, which can substantially reduce the environmental impacts. Available software and methodologies must be applied to conduct this optimisation.

Future research efforts should focus on improving the efficiency of i-RTGs without increasing the complexity of the system and its management. An example is the implementation of closed hydroponic systems for irrigation, which recirculate water and nutrients in the leachates (open hydroponic systems dispose of the leachates). This technology would allow for substantial quantities of water and nutrients to be saved, but the auxiliary equipment required is more complex and expensive, requiring further knowledge for its operation and additional environmental impact. Moreover, comparison between the i-RTG and conventional production should be expanded to include other perspectives, such as nutritional aspects, reduction of food waste and food security. Food produced in i-RTGs can be more fresh and nutritious due to the proximity to the consumption point and the optimal timing of collection.

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Final remarks and future research

Part IV

Chapter 9

Discussion of the main contributions

Picture: Donation of food rejected from Mercabarna at FADfest (summer 2017)

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Chapter 9 General discussion and main contributions

This chapter discusses the main contributions of the dissertation and the implications that these contributions will have for urban areas from a scientific perspective.

Within the urban water cycle (UWC), this dissertation has focused on the transport and consumption of water in cities, which is the main topic connecting all the research carried out. The approach adopted includes the assessment of water supply networks and the water consumption in innovative buildings to reduce the demand for water and to maximise the utilization of rainwater and greywater. In this context, whereas the water demand in cities is usually associated with domestic uses and the service sector, this research adopted a wider approach integrating food production from the perspective of the water-food-energy nexus. With this purpose, a vertical farm was analysed as an innovative water-demanding activity, quantifying the flows of nutrients and water and its environmental impacts.

9.1 Discussion on the environmental assessment of water supply networks

The sustainability of water supply networks will be a major issue in the near future since new infrastructures for water supply are expected to be built. Firstly, 10% of the world population do not have access to water supply (The World Bank 2017b). Secondly, the population growth in cities will imply the construction of new urban areas. Moreover, old networks will be replaced and refurbished to improve its efficiency and to reduce the water loss in networks, which reaches 50% of the water supply in some European countries (European Environmental Agency 2008). The results from the dissertation provide useful information for the sustainable planning of these infrastructures, which can help to prevent significant environmental impacts.

Previous studies analysing the environmental impacts of water supply networks had focused on the assessment of isolated case studies, considering the water supply network (Venkatesh and Brattebø 2011b, 2012b; Piratla et al. 2012b) or the whole urban water cycle (Lemos et al. 2013b; Amores et al. 2013b). The results from these studies showed considerable variations among them because the impacts of the water supply network depend on its specific characteristics. In this context, this dissertation aimed at conducting a complete and comprehensive assessment of water supply networks.

With this purpose, a general perspective has been adopted aiming at obtaining results that could be useful for its management. Regarding the application of the LCA methodology to constructive solutions for the networks and municipal water tanks, the results obtained can be used by constructors and municipal managers to estimate the environmental impacts of the construction of the network and to select the less impacting options. This can help in decision-making processes, as well as to monitor the evolution of the environmental impacts of networks. Indeed, selecting the less impacting options for the construction of the network in a case study has shown a potential to reduce the environmental impacts between 6 to

16% (results from Betanzos, Spain). For municipal water tanks, the potential to reduce the environmental impacts was between 10 and 40% (case studies from Calafell, Spain). These examples show how the results presented can help to prevent environmental impacts.

The operation phase of the water supply network was the element that presented the higher dispersion in previous literature. In this sense, the contribution of the dissertation is the adoption of a top-down approach to understanding which are the factors affecting the environmental impacts of the operation of networks. The results obtained are useful for urban and regional planners, who will be able to focus on the factors of the networks that are more linked to their environmental impacts. On this regard, electricity consumption was identified as the main contributor to the impacts of the network, and thus the environmental action of these managers should focus on designing the networks to reduce this consumption. Moreover, the results presented show which networks might have larger demands for electricity, which might help prioritising the worst cases from an environmental perspective.

9.2 Discussion on the water use and vertical farming in buildings

The efficiency in the use of water at the consumption point is key because, considering the whole urban water cycle, it can affect the environmental impacts of the supply and the wastewater transport and treatment. In this context, the research presented in Chapter 6 provides useful information to optimise the application of innovative technologies for saving water and reducing the wastewater generation. This issue is of general interest, especially in Mediterranean areas where the occurrence of drought is expected to increase in the following years because of climate change.

The results show that water-saving technologies require a proper planning to be effective, and the water flows in the building should be estimated during the phase of design. These results might have an impact on the perception of these technologies, whose effectiveness should no longer be assumed without adequate analysis. For instance, certifications awarding sustainable buildings should consider not only the application of these technologies but also the volume of water (and wastewater) saved. Moreover, the application of similar analyses to other buildings with water-saving technologies can improve the utilisation of water in the system.

The production of food is the largest water-demanding activity, accounting for 70% of the global water consumption (WBCSD 2005), and part of this water is transported to cities contained in the food. Thus, the innovative system for food production presented in this dissertation, the i-RTG, represents an opportunity to improve the efficiency in the use of water for agriculture and reduces the needs for transportation.

In this context, several studies can be found in previous literature analysing from a conceptual and theoretical perspective vertical farming systems in buildings, but there are few articles assessing real case studies. This is particularly the case for vertical farming systems integrated with the building, which were proposed as an innovative alternative in previous literature (Caplow 2009; Despommier 2010b; Cerón-Palma et al. 2012) and evaluated in terms of potential environmental impacts and productivity (Sanyé-Mengual et al. 2015a, b), but the operation phase was not analysed in a real installation. This dissertation has covered this gap providing information of the operation phase of the i-RTG.

The system presented should be considered by urban planners as a feasible option to boost food production in cities and, at the same time, reduce the water demand and the environmental impacts of agriculture at the regional level.

9.3 Other contributions of the dissertation

Implementing a life cycle perspective

The studies conducted in this dissertation have considered the whole life cycle of the water supply network and the integrated rooftop greenhouse.

- Water supply network
    - Construction: The analysis of the network (pipe, trench, appurtenances) and the water storage tanks (cylindrical tanks) using the LCA methodology revealed which were the best available alternatives to reduce the impacts of its construction.
    - Operation: The top-down statistical study provided insights on the variability of the impacts of the operation phase.
- Integrated rooftop greenhouse (i-RTG)
    - Construction: The LCA methodology revealed that the rainwater harvesting system and the structure of the infrastructure were significant contributors to the environmental impacts, in contrast with the impacts of the auxiliary equipment.
    - Operation: This phase was the main contributor to the impacts of the i-RTG due to the use of nutrients for fertigation. The assessment of the nutrient flows in hydroponic crops will contribute to improve the efficiency of these systems.

Analysis at different scales of the water cycle

Another particularity of this research has been the consideration of the urban water cycle at different scales of analysis:

- City
- Building
- Rooftop

Regarding the city scale, the statistical analysis for the operation of the network presented in Chapter 4 allowed comparing various types of cities according to with variables such as population (small, medium), climate (Mediterranean, Atlantic) or location (coastal, inland). This scale of assessment revealed the trends of different types of cities regarding the factors influencing the environmental impacts of the network. Also in the case of the infrastructure of the network, the results were applied at municipal scale, estimating the environmental impacts of the network for a municipality. The results provided the environmental impacts of the construction of these infrastructures, as well as the potential for improvement.

The assessment at building scale provided information regarding the use of water in cities and the effectiveness of existing technologies to reduce it. Buildings are significant focuses of water consumption, and thus the assessment of its efficiency in the use of water is of interest. The results allowed proposing recommendations for the future application of water-saving technologies.

Finally, the i-RTG was analysed as a specific subsystem within the building. This scale of analysis allowed obtaining information regarding the potential of vertical farming for food production in cities.

Methodological contributions

The research concerning the i-RTG involved the development of new methodologies that had not been used before in the research group. In order to facilitate the continuation of the research lines started, the functioning of the procedures and the techniques developed during the thesis were compiled in reference documents for future researchers.

For instance, all the necessary information for the operation of the i-RTG was written in standard work procedures (Appendix I). Similarly, a guide was elaborated with all the procedures and supporting information required to use the ion chromatography system (Appendix I.II).

9.4 Dissemination of the results

As discussed, the research conducted is of interest to improve the environmental performance of urban areas. An effort was made for the dissemination of the results to maximise the impact of the research.

The results of this research were used as the framework for the development of open tools and databases for the calculation of the environmental impacts in decision-making processes. This is the case for the results from Part I, which were used at the end of the LIFE+ Aquaenvec project to develop the web-based software Aquaenvec tool (http://tool.life-aquaenvec.eu/en) for the calculation of the environmental impacts of the UWC. This tool allows constructors and managers of the UWC to easily calculate the eco-efficiency of the system for a sustainable design or redesign.

The tool considers four section of the UWC: drinking water treatment, water supply network, sewer network and wastewater treatment. This dissertation contributed to the section of water supply network providing the environmental impacts of the different elements of the network, including the operation phase and water storage tanks. The tool enables the assessment of the UWC or a part of it from data such as the pipe diameters, the length of the network or the electricity consumption during the operation. The results from the tool are presented in eco-efficiency indicators, combining environmental indicators (global warming, ozone depletion, eutrophication and cumulative energy demand) and the costs. The interphase of the tool can be observed in Figure 9.1, along with an example of the data that must be fulfilled for its application.

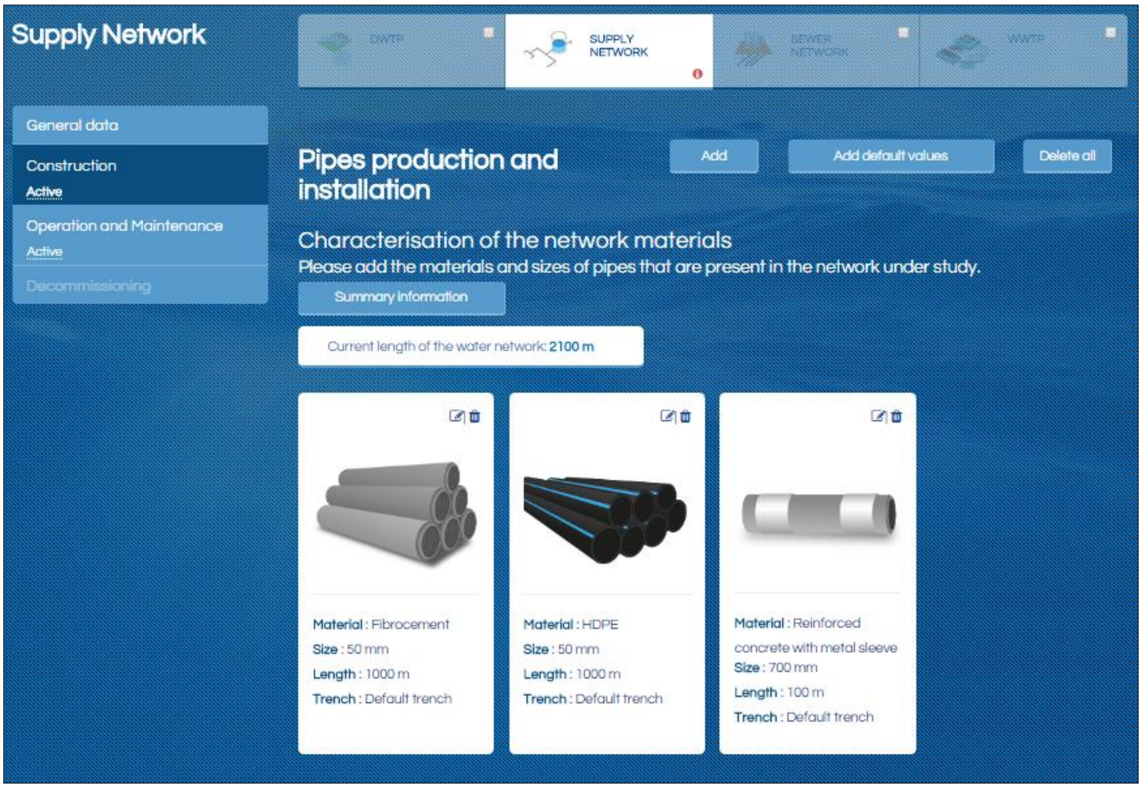

Figure 9.1 Interface of the web-based Aquaenvec tool at http://tool.life-aquaenvec.eu/en.

Most of the life cycle inventories presented in the dissertation were submitted, validated and published at the LCADB.sudoe database (http://lcadb.sudoe.ecotech.cat). This is an open database for the implementation of LCA studies that focuses on the South of Europe. The contributions in the framework of this research will contribute to increasing the pool of LCA-related data and will be available for future studies for research and companies. Figure 9.2 shows the interface of the web application for the introduction of the inventories in the database.

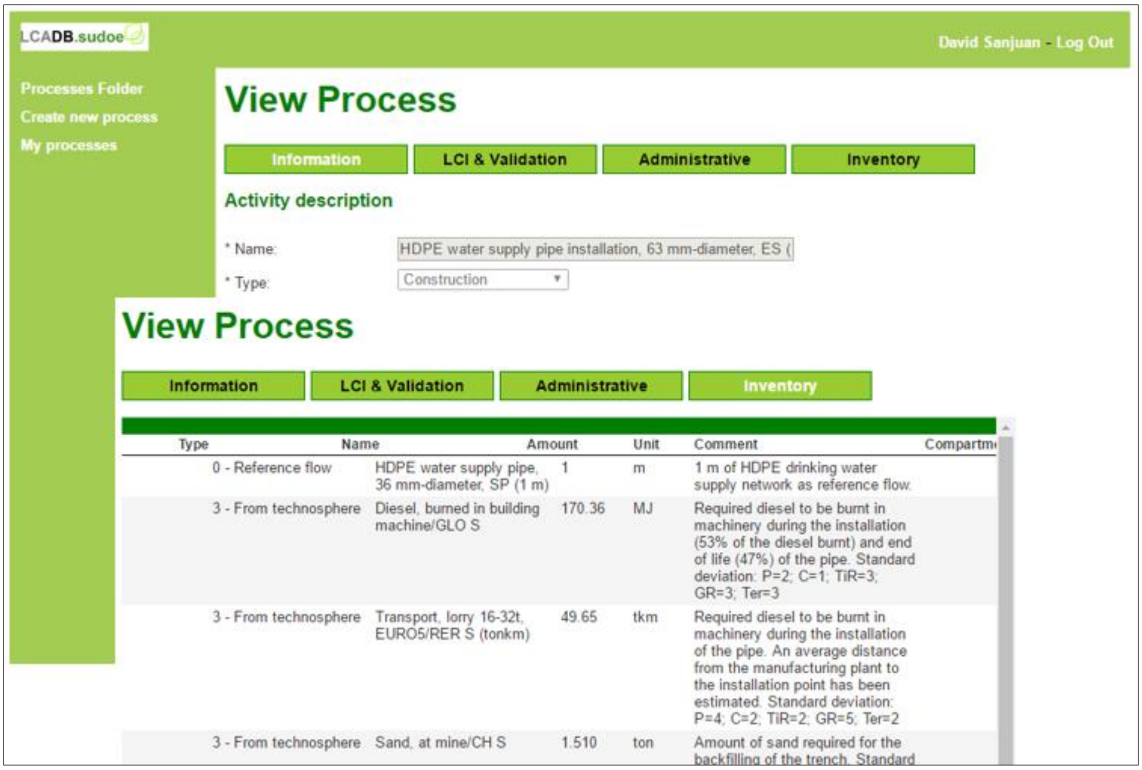

Figure 9.2 An example of the introduction of a process (installation of a high-density polyethylene pipe) in the LCADB.sudoe database.

Chapter 10

General conclusions

Picture: Mandeo River in Betanzos (Galicia)

Retrieved from: http://www.herculestours.com/rutas-por-galicia/desde-coruna/rutas-por-galicia-coruna-betanzos/

Chapter 10 General conclusions

This chapter presents the general conclusions of the dissertation, providing adequate answers to the research questions defined in Chapter 2.

- **Research Question 1**: What are the main factors affecting the environmental impacts of water supply networks in cities and which improvements should be implemented?

The environmental analysis of the water supply networks was done differentiating two parts of the life cycle: the construction and the operation.

Construction of water supply networks: pipe and appurtenances

One of the relevant factors affecting the environmental impacts of the construction of the network is the pipe diameter of the constructive solution. For constructive solutions with smaller pipe diameters, the installation of the network is the largest contributor. Thus, optimising the dimensions of the trench and the processes of the installation will be key for the reduction of the environmental impacts. In contrast, for constructive solutions with larger diameters, the pipe (its production) accounts for the highest percentage of the environmental impacts. In this case, using less impacting materials will allow the maximum reduction of the impacts.

Therefore, the pipe material is another relevant factor affecting the environmental impacts, and the selection of less impacting pipes can prevent a significant part of these impacts. The constructive solutions were assessed for the pipes made of the most common materials. The results revealed that plastic pipes (HDPE, PVC and LDPE) are more sustainable than pipes made of ductile iron and glass fibre reinforced polyester, which have between 3 and 11 times more environmental impacts than the prior ones, depending on the impact category (Table 10.1). However, there is an existing gap regarding the variation of the lifespan of the pipes depending on its pipe material. Future findings in this regard would be of interest, but the lifespan should be significantly different to affect these conclusions because the impacts of glass fibre reinforced polyester and ductile iron are several times that of plastic pipes.

Table 10.1 Comparison of the environmental impacts of constructive solutions with different pipe materials and diameters.

	Eutrophication	Global warming	Ozone layer depletion	Cummulative energy demand
	kg PO4--- eq	kg CO_2 eq	kg CFC-11 eq	MJ
HDPE, 90 mm	3.34E-02	2.53E+01	3.25E-06	5.12E+02
HDPE, 200 mm	4.28E-02	3.67E+01	3.79E-06	8.96E+02
DI, 200 mm	4.98E-01	1.61E+02	1.16E-05	2.77E+03
Ratio HDPE 90/200	1.3	1.5	1.2	1.8
Ratio DI/HDPE (200)	11.6	4.4	3.1	3.1

HDPE=high density polyethylene, DI=ductile iron, 90/200 mm=pipe diameter of the constructive solution

At the city scale, the selection of the less impacting materials for the construction of the network has proven to be a simple but effective measure to reduce the environmental burdens. This analysis can be applied to new urban areas or for the redesign of old networks. The construction of the water supply network of Betanzos (Spain) with plastic pipes (the least impacting material) instead of ductile iron and cement pipes would have generated between 6 and 16% less environmental impacts.

Construction of water supply networks: municipal water tanks

The environmental impacts of municipal water tanks, more specifically cylindrical water tanks, are affected by three variables: position (buried, partially buried, superficial), storage capacity (cubic meters) and dimensions (radius and height).

For the position, superficially placed tanks are preferable from an environmental perspective because its construction requires less reinforcing steel and less soil needs to be excavated and transported, reducing the environmental impacts between 15 and 35%. In respect of the dimensions, the less impacting water tanks are the tallest ones, which also have the smallest diameter, because these dimensions imply a more optimised geometry and a limited use of steel.

Regarding the water storage capacities, tanks with volumes ranging between 1,000 and 2,500 m^3 are environmentally preferable, as these cases hold a better relation of steel and concrete per volume of water stored. Volumes smaller than 500 m^3 hold between 5 and 30% higher impacts and volumes larger than 5,000 m^3 are between 5 and 20% more impacting.

Applying the less impactful options for each of these variables in the construction of water storage tanks is key for the reduction of its environmental impacts. However, this is not always possible due to specific conditions of the installation points. For instance, superficial tanks cannot be installed in some densely populated urban areas. The application to real case studies shows that selecting the less impacting option for the construction of the tanks would have prevented between 10 and 40% of the environmental impacts in the specific case studies assessed.

Operation of the water supply network

Regarding the operation, the consumption of electricity for the transportation of water is the most relevant factor to consider. This consumption varies from one municipality to another according to with some key variables that affect it.

A relevant variable affecting the relative consumption of electricity and hence the environmental impacts is the size of the municipality. Small-sized municipalities (<10,000 inhabitants) tend to have larger electricity consumptions than medium-sized ones (10,000-50,000 inhabitants). In the sample analysed, the prior ones show nearly 14 times larger electricity consumption (1.15E-2 as opposed to 8.3E-4 kWh/m^3 registered water·km of network).

Another significant variable is the density of the population (inhabitants/km^2). Water needs to cover relatively longer distances in less densely populated municipalities (<90 inhabitants/km^2) and thus present a higher electricity consumption in comparison with more densely populated municipalities (>90 inhabitants/km^2). In this case, municipalities with lower population density show approximately 7 times higher electricity consumption.

The location of the municipality (cost or inland) and the climate (Mediterranean or Oceanic) might be linked to the electricity consumption of the network, as well as the seasonality. However, the relation found was not robust enough to reach solid conclusions, and further studies with a larger sample should be implemented.

The correlation between some of the variables considered in the study was analysed, and the results are represented in Figure 10.1. As seen, the size of the city is clearly related to the length of the network and the water consumption, but not with the electricity consumption, which was not related with any of the variable (only holds a relation in terms of kWh per m^3 of water and km of network, as discussed above).

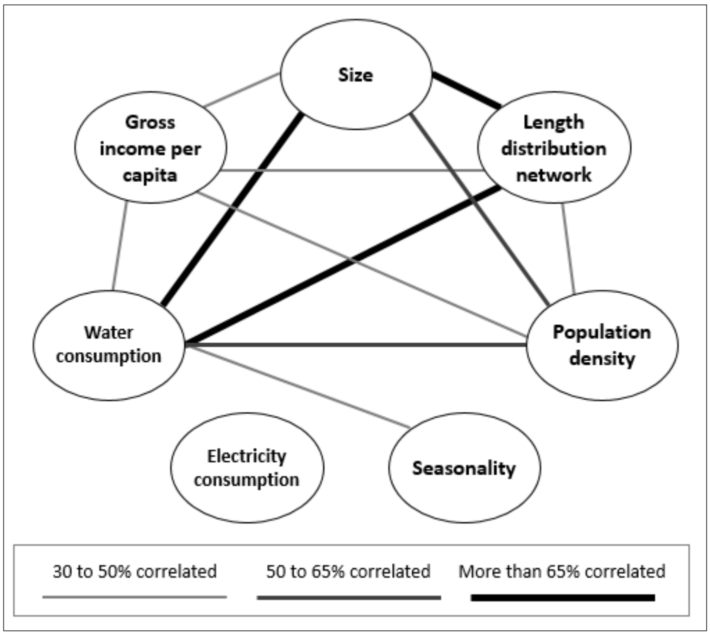

Figure 10.1 Diagram of the relations found between some of the variables analysed for the operation of the network.

Another important factor to consider is the loss of water, which should be assessed in a more thorough bottom-up study, as it is believed that external factors stated in IWA (2003), such as un-metered connections, dilute the measurement of the water losses.

Although specific measures to reduce the environmental impacts of networks were not considered in the dissertation, any reduction of the electricity consumption and the water losses would be helpful. A proper urban and regional planning to optimise the water transportation might be effective to reduce the electricity consumption. Another relevant measure would be increasing the share of renewable energies in the electricity mix of the country. Finally, the reduction of the water losses along the network would also reduce these environmental impacts.

These measures should preferably be implemented in municipalities from the clusters holding the higher electricity consumption. Small-sized municipalities with a low density of population are prone to have higher electricity consumption.

- **Research Question 2**: How effective are water-saving technologies used at the building level in urban areas?

Based on previous literature, there is strong evidence showing that rainwater harvesting and greywater reclamation have a significant potential to save water in urban areas (Farreny et al. 2011b; Angrill et al. 2012, 2017b, Vargas-Parra et al. 2013, 2014). Nevertheless, an appropriate application and planning of these technologies in buildings is required for their effectiveness. Otherwise, their efficacy can be limited, and they might even increase the overall environmental impacts and costs of the system.

The assessment of the ICTA-ICP building has shown being more efficient in the use of water than a reference office building from the same area, consuming 18% less water per user. However, these savings might be low when considering all the measures undertaken in the building for the efficiency in the consumption of water. The research conducted revealed that although the water-saving technologies are working properly, their effectiveness is limited due to a lack of planning during the design phase.

The rainwater harvesting system of the building holds a 35 m^3 tank, whose rainwater might partially cover the large demand for toilets. However, this rainwater is filtered and chlorinated for its used in washbowls, generating further impacts with this additional treatment. Moreover, the rainwater collected in this tank is underused due to the low demand generated in washbowls.

The most significant water demand of the building is the flushing of toilets (90% of the drinking water consumed). In contrast with the rest of the water-consuming devices, toilets hold a conventional mechanism with a discharge volume of 7 and 9 L/discharge and no double-discharge option. The greywater reclamation, which collects greywater from washbowls and uses it for flushing toilets, only covers 6% of this demand because the volume of water used in washbowls is substantially smaller than the volume required for flushing toilets.

The water use efficiency of the building might improve if certain low-cost measures were applied. Firstly, the discharge volume of toilets in the building should be reduced. If a device for the regulation of the discharge was installed, or simply a 2 L volume that sinks was introduced into the toilet tank the discharge could be reduced by 30% for 7 L cisterns and by 20% for 9 L cisterns. Another effective measure would be using the rainwater collected directly for flushing toilets, increasing the utilisation of this resource and eliminating the need for treatment (filtration and chlorination). Washbowls would use regular water from the water supply network, which has the adequate quality without additional treatment. The implementation of these measures might reduce by 75% the external water demand of the building, improving the water efficiency and the self-sufficiency of the building significantly.

Figure 10.2 shows the diagram of the current system and the potential improvements that could be implemented.

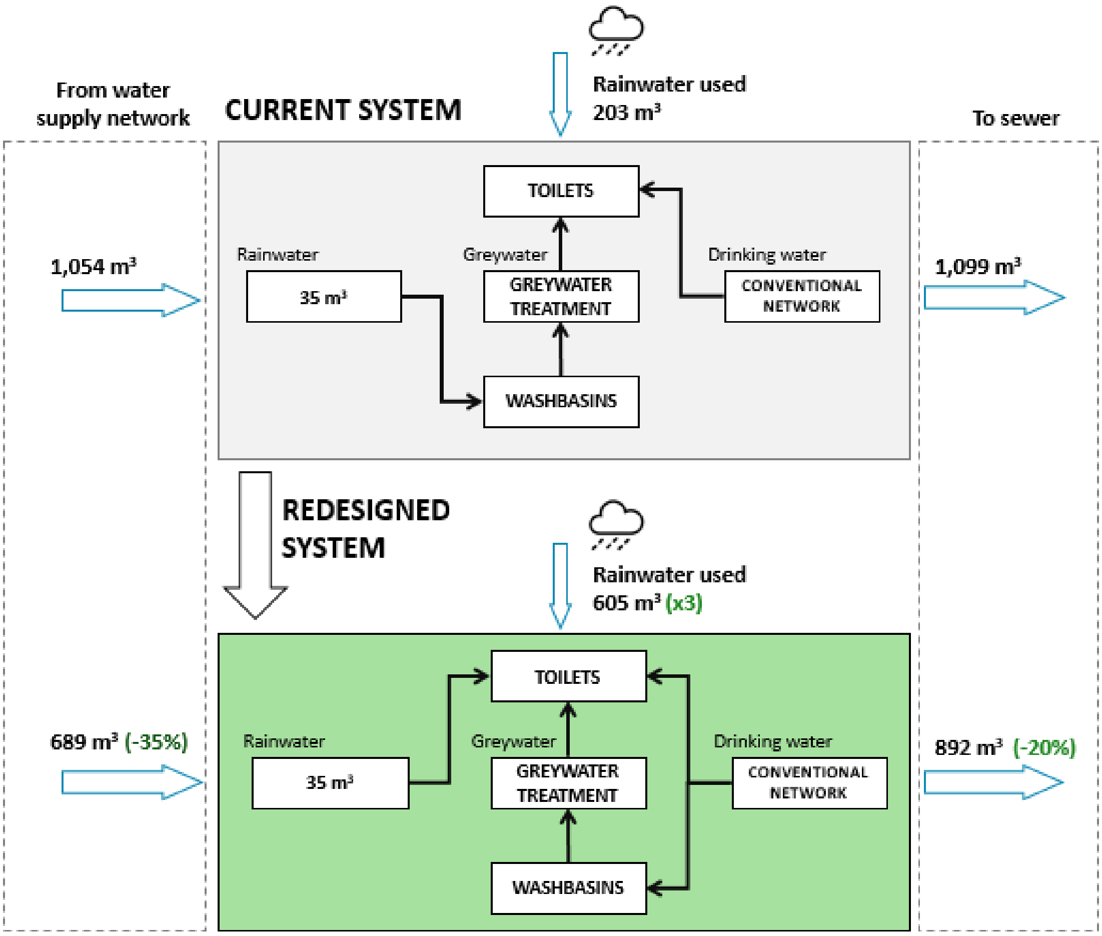

Figure 10.2 Diagram with the quantification of the water flows in the ICTA-ICP and the preliminary data for the potential redesign.

- **Research Question 3:** Are integrated rooftop greenhouses an efficient and sustainable alternative for food production in cities?

This research has proven that the i-RTG is feasible and can boost the production of food in urban areas. From an urban perspective, this new system represents a new use for water in cities, providing agricultural services to buildings.

The system can grow 19.6 kg of tomato/m^2·year, being in total 1,650 kg of tomato for the 85 m^2 of productive area analysed. Thus, the i-RTG is an alternative to conventional production that can provide fresh and nutritious food and improve food security and self-sufficiency in cities.

The symbiosis with the building allows reducing the use of resources significantly. Between 80 and 90% of the demand for water during the crops was covered with rainwater from the rainwater harvesting system of the building. This symbiosis also allows cultivating during both summer and winter with significant savings in the use of energy, as demonstrated in previous studies (Nadal et al. 2017). Winter crops have shown being less efficient than summer ones in the use of resources due to the lower production (increasing the use per kg of product). For instance, the winter crop conducted consumed 104 L/kg of tomato whereas summer crops consumed 47 and 64 L/kg.

The i-RTG can contribute to reduce the environmental impacts of food production. The environmental performance of the system is better than that of conventional production for all the impact categories analysed (except marine eutrophication) thanks to the lower needs for packaging and transportation. For instance, a summer crop in the i-RTG generates 0.58 kg of CO_2 eq per kg of tomato whereas a conventional greenhouse generates 1.7 kg of CO_2 eq, which proves that it can contribute to climate change mitigation.

The most important contributors to the environmental impacts of the i-RTG are the use of fertilisers, accounting for more than 25% in four of the six impact categories, and the infrastructure of the i-RTG (structure and rainwater harvesting system), accounting for between 30 and 60% of the impact. In this sense, the application of this technology to an industrial scale should consider the optimisation of the infrastructure and the adjustment of the fertilisers used to improve the environmental performance of such systems. For instance, applying available software for the optimisation of the size of the rainwater storage tank might prevent significant environmental impacts. Moreover, a proper follow-up of the concentration of nutrients in the nutrient solution and the leachates can allow adjusting the nutrients supplied to improve the efficiency of the crops.

Thus, the analysis of the nutrient flows of the crops (Chapter 7) is a central issue for improving the efficiency of the i-RTG and hydroponic crops in general. In average, 51% of the nutrients supplied to the crops end up in the leachates, whereas a significant part is uptake by plants and remains in the biomass (26%) and the fruits (production) (11%). However, these percentages are very different depending on the specific nutrient.

The perlite used for cultivation of hydroponic crops retains substantial amounts of nutrients, in particular for nitrogen (in average, 6% of the incoming nutrient), phosphorus (7%) and calcium (5%). This factor must be considered when evaluating the nutrient balance and for the management of the substrate, which could be a potential by-product at the end of life (for instance, for amending soil-based crops). Other substrates such as rockwool or coir are pending to be assessed, but they might have similar retention rates.

Although the balances for the different nutrients were not completed, a significant improvement was observed in relation to recovery values seen in the previous literature, representing the first comprehensive attempt to close the nutrient balances in open hydroponic crops. The measures that should be undertaken in future projects according to the research conducted are summarized in Table 10.2. Future studies should provide further insights in this regard and try to get closer to a full balance.

Table 10.2 Summary of the measures proposed for future i-RTG projects.

Subsystem	Measures
Nutrient solution and leachates	• A periodic follow-up should be conducted to adjust the nutrient solution to the requirements of the crop. • Recirculating or reusing the leachates utilising the nutrients and avoiding the discharge to nature.
Biomass and production	• Maximise the solar radiation reaching the crop to improve productivity and reduce biomass. • To compost bio-waste generated in the crop. • To fix the biogenic carbon in biomass using it as a by-product for manufacturing goods.
Infrastructure	• Optimising the dimensions of the infrastructure, for instance, the size of the rainwater tank.
Nutrient retention in perlite	• Reusing the substrate as a byproduct, for example for the amendment of soil-based crops.

Chapter 11

Future research

Picture: Tasting of vertical farming lettuce at FADfest (summer 2016)

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Chapter 11 Future research lines

This chapter proposes new lines of research that can complete and complement the results obtained in this dissertation.

The following main lines are proposed:

(i) Environmental and economic assessment of the water supply network
(ii) Assessing rainwater harvesting and greywater reclamation
(iii) Assessing nutrient flows in hydroponic crops
(iv) Implementing the i-RTG technology at industrial scale

(i) Environmental and economic assessment of the water supply network

In respect of the construction of the water supply network, the most significant issue that needs further research is the **definition of the lifespan of pipes depending on its material**. As discussed in Chapter 3, the lifespan of the alternative constructive solutions analysed might significantly affect the results obtained.

Regarding the construction of municipal water storage tanks, the **environmental assessment of rectangular tanks** would be of interest. Although cylindrical water tanks have an optimised geometry and thus require less steel and concrete for its manufacture, these tanks might be not suitable for some locations, such as densely populated urban areas with rectangular urban forms.

Additionally, the **assessment of the water supply network from an eco-efficiency perspective** might be of interest to integrate environmental and economic factors of its construction. This analysis might be applied to both the network (pipe plus appurtenances) and water storage tanks.

Assessing the **construction of the network in other municipalities** might be useful to study tendencies and obtain average impact values. The **Aquaenvec tool** presented in Chapter 9 might be used for this purpose. For instance, applying the tool to a sample of municipalities might provide data to study the variation of the environmental impacts of the network construction depending on the typology of the municipality.

Further statistical studies of the operation of the network are required to check the trends observed. Some of the trends presented in the dissertation are not robust enough to be confirmed or discarded. Analysing these trends might provide useful complementary insights on the factors affecting the environmental impacts of the network. The analysis of a larger sample of municipalities might provide useful information in this regard.

Another significant issue of the operation that should be covered is the **water loss along the network.** As discussed in Chapter 5 more sophisticated methods are required to quantify the water loss, which can be key for the reduction of its environmental impacts.

The **development and application of a protocol for the collection of data of the operation** of the network might be key for conducting future studies. The lack of data or reliability in the databases consulted limited the available municipalities that could be considered for the study.

(ii) Assessing rainwater harvesting and greywater reclamation

After implementing the improvements proposed in the dissertation for the ICTA-ICP building, it would be of interest to conduct a balance of the water flows. The improvements would require little resources and would be useful to check the preliminary results analysed and provide information about the potential for improvement of the system.

Analysing the **water flows in other buildings with rainwater harvesting and greywater reclamation systems** might also be useful to assess the efficiency of these water-saving technologies in urban areas.

However, new innovative projects should be developed **implementing the water-energy-food nexus from the design phase and propose further improvements to increase the efficiency** in the use of water. These new building designs should adopt an integrative approach to make compatible the use of water for food production and services by improving the efficiency and maximising the utilisation of local resources like rainwater and greywater.

(iii) Assessing nutrient flows in hydroponic crops

On the subject of nutrient and water flows, **applying the nutrient dynamics methodology to other hydroponic crops** might provide helpful information to improve the efficiency in the use of nutrients. For instance, a description of the nutrient flows in conventional hydroponic crops is still lacking in previous literature. Future studies should cover different crops and types of greenhouses, both in conventional agriculture and in i-RTGs. Moreover, the productivity of other types of crops in the i-RTG should be assessed to increase productivity during the winter season, which was observed low.

Future studies should also **implement this methodology with more detail** to approach a full balance (100% inputs-output) of the main macronutrients.

In this sense, the research on the nutrient retention in perlite should be developed and extended to **other substrates, such as rockwool or coir.** The trends observed in this dissertation for the different nutrients should be checked and the relation between the retention of nutrients and different variables (nutrient load, duration of the crop, etc.) should be assessed **to define models for the estimation of this retention in conventional crops**.

Moreover, research should be undertaken regarding the **volatilization of nutrients in hydroponic crops**, which might be a crucial element to contribute closing the balance.

Finally, the **recirculation of nutrients using closed hydroponic crops should be environmentally and economically assessed from a life cycle perspective**. This technology can bring significant advances to the efficiency in the use of nutrients and water, but it implies the use of more complex equipment, energy and auxiliary equipment.

(iv) Implementing the i-RTG technology at industrial scale

Concerning the application of the i-RTG at a larger scale, further research should be conducted to **analyse the full potential of the system.** For instance, the i-RTG technology could be implemented in other buildings with optimal solar radiation conditions and a larger cropping area, which would probably improve the productivity of the crops and reduce the environmental impacts.

Improving the efficiency of the system during the management of crops would also be of interest. Future research should focus on **simplifying this management without increasing the complexity** to run the system. For instance, procedures should be defined to use closed hydroponic systems without the need for highly specialised staff.

Another issue that remains uncovered is the **economic study of the i-RTG system** with real data from its operation, which might provide useful insights into the payback time of this technology. The life cycle costing (LCC) methodology might be suitable for this purpose.

In respect of the comparison between the i-RTG and conventional production, different aspects of the production might be compared. For instance, the **nutritional value of the food** from the i-RTG might be higher due to the longer maturation in the plant and the proximity and freshness of production.

Social issues should also be considered in future studies, analysing the **social impact of i-RTGs**. For instance, the system might have a major role as an educational centre or promote social interaction if it is community-based.

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Fecha de emisión	Fecha de aplicación
24/11/2014	**08/07/2015**
Elaborado por	**Revisado y aprobado por**
Cargo: Doctorando **Nombre y apellido:** David Sanjuan	<u>**REVISADO**</u> **Cargo:** Investigador Senior **Nombre y apellido:** Xavier Gabarrell <u>**APROVADO**</u> **Cargo:** Investigador Senior **Nombre y apellido:** Pere Muñoz

II) RELACIONES

PNT y otros documentos asociados	Apartado
PNT-1: Seguimiento de los cultivos PNT-7: Cromatografía iónica	**1. Introducción** **2. Ámbito de aplicación** **3. Definiciones** **4. Cualificación del personal** **5. Responsabilidades** **6. Nivel de riesgo** **7. Descripción del proceso** **8. Residuos** **9. Referencias** **10. Esquema**

IV) CONTROL DE CAMBIOS

Control de cambios			
1. Núm.	2. Punto	3. Cambio	4. Justificación

1. INTRODUCCIÓN

El presente procedimiento normalizado de trabajo (PNT) tiene como objetivo establecer unas pautas que aseguran el buen funcionamiento de los flujos de agua y la medida de los parámetros necesarios para su seguimiento. Este documento se tendrá en cuenta conjuntamente con el resto de PNTs que hacen referencia a los diferentes flujos, utensilios y al funcionamiento general del invernadero.

2. ÁMBITO DE APLICACIÓN

Este procedimiento normalizado de trabajo se aplicará al cultivo en cubierta del invernadero SO y SE del edificio "Z" (ICTA-ICP) de la UAB. Los métodos indicados están pensados para ser aplicados en el marco del proyecto *Fertilecity* o personal vinculado/contratado con la cualificación y conocimientos necesarios.

3. DEFINICIONES

- **Sistema de los flujos de agua**: Solución nutritiva (agua de entrada + nutrientes) y lixiviados (agua residual) del cultivo y toda la infraestructura necesaria para su funcionamiento.
- **Agua fría sanitaria (AFS)**: Agua proveniente de la red convencional de abastecimiento.
- **Agua pluvial para riego**: Agua procedente del sistema de recogida de aguas pluviales. Se almacena en el depósito de 100 m^3 situado delante del edificio ICTA-ICP y se bombea para ser utilizada en los cultivos de la cubierta y en las plantas ornamentales del edificio.
- **Cultivo hidropónico:** Método de cultivo que utiliza soluciones químicas de nutrientes minerales dentro del agua para nutrir las plantas a través de un suelo inerte, en lugar de suelos agrícolas fértiles.
- **Saco de perlita:** Substrato inerte de perlita utilizado para fijar las raíces de las plantas y aportar las soluciones nutritivas a las plantas proporcionadas a través del agua de riego.
- **Equipo:** Partes o módulos necesarios para el desarrollo de la tarea, incluyendo las partes o módulos de adquisición y/o procesamiento de dadas, etc.
- **Programador de riego:** Aparato electrónico para definir y controlar la intermitencia y durada del riego.
- **Sistema de goteo:** Parte extensiva del riego para alcanzar a la planta de manera individual.
- **Dosatron:** Aparato para la dosificación de la solución nutritiva que permite mezclar las soluciones químicas de nutrientes con el agua de riego.

4. CUALIFICACIÓN DEL PERSONAL

Sólo queda autorizado para realizar el control y seguimiento del cultivo el personal que se haya leído este PNT o bien los expertos de soporte del IRTA. El personal encargado del control de los cultivos quedará registrado al Registro de Usuarios en la libreta de seguimiento del cultivo.

Es necesario que el personal:

- Conozca el funcionamiento del sistema del cultivo y los flujos principales.
- Conozca el funcionamiento de los equipos que se tenga que utilizar.
- Disponga de la acreditación y permisos adecuados en caso de que sea necesario.

5. RESPONSABILIDADES

a) *Es responsabilidad del usuario hacer un uso correcto de los equipos e instalaciones.*
b) *Es responsabilidad del usuario registrar todas las dadas especificadas en el apartado 7 para su posterior estudio.*
c) *Es responsabilidad del usuario disponer de los conocimientos necesarios especificados en el apartado 4 antes de realizar las tareas pertinentes.*
d) *Los usuarios tendrán cuidado y custodiaran los documentos y manuales necesarios para el uso y gestión del invernadero y los proporcionaran a nuevos usuarios.*
e) *Los usuarios tendrán cuidado y mantendrán en buen estado el material y equipos, así como la infraestructura del cultivo.*
f) *El Director del proyecto será el responsable de la difusión del PNT entre los miembros que deban seguirlo.*

6. NIVEL DE RIESGO

Las tareas de recogida de muestras y mantenimiento de los sistemas de cultivo implican un nivel bajo de riesgo. Con tal de minimizar los riesgos, los análisis y tareas a realizar al laboratorio sólo se llevarán a cabo con el material y equipamiento adecuado y habiendo recibido la formación previa necesaria para cada equipo.

7. DESCRIPCIÓN DEL SISTEMA Y PROCEDIMIENTOS:

7.1. Observaciones generales.

El sistema incluye dos tipos de flujos de agua para la irrigación del cultivo: el agua fría sanitaria (AFS) y el agua pluvial para riego (APR). De esta manera, hay dos tuberías que aportan agua al invernadero, una para cada tipo de agua. Cada una de estas dos tuberías se encuentra conectada a un depósito de 300 L, y ambos depósitos están conectados a una misma bomba que envía el agua al equipo de regulación de riego con la presión necesaria. No obstante, con tal de evitar mezclar aguas de diferentes calidades (ya que la solución nutritiva es específica en función de la calidad), sólo uno de estos depósitos estará lleno y proveyendo agua a la vez. El otro se encontrará inactivo.

Este equipo, por un lado, dispensa el riego necesario en función de lo que se especifica en el programador. Por otro lado, 2 dosatrones inyectan los nutrientes para la fertilización del cultivo con la proporción que se haya especificado. Hay 2 depósitos de nutrientes de 80 L que inyectan solución nutritiva a la vez, cada uno con una composición diferente. La solución nutritiva del depósito 1 contiene K_2SO_4, KPO_4H_2 y KNO_3; y la solución nutritiva del depósito 2 contiene $CaCl_2 \cdot 2H_2O$, $Mg(NO_3)_2$, $Ca(NO_3)_2$, Hortrilon y Sequestrene.

La Figura 1 muestra un esquema de todo el sistema.

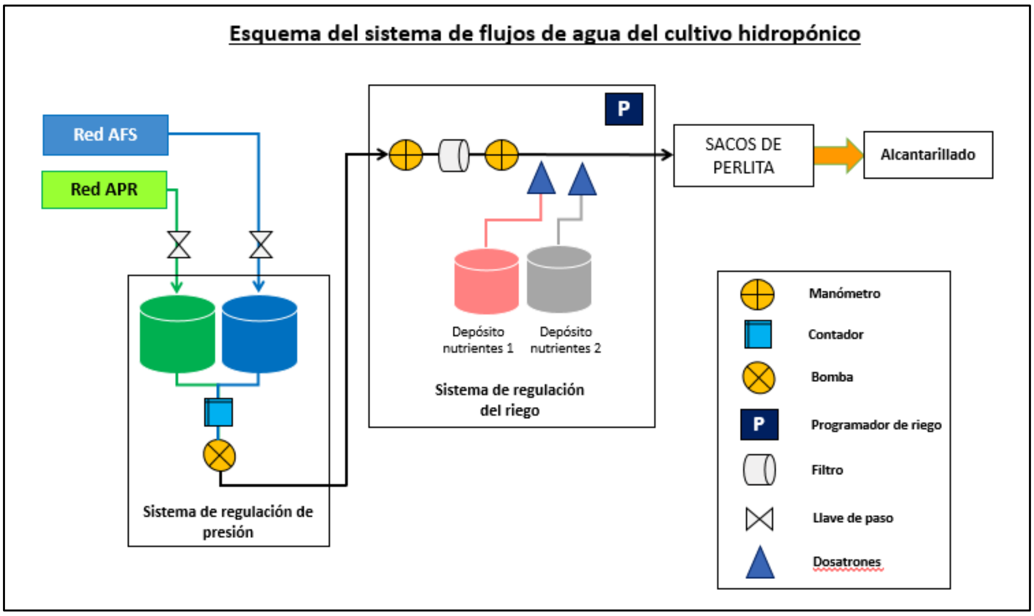


Figura 1. Esquema del sistema de flujos de agua del invernadero.

Se distinguen los siguientes subsistemas dentro del sistema general de flujos de agua:

- Regulación de la presión.
- Regulación de riego.
- Sacos de perlita (cultivo en sí).
- Lixiviados del cultivo.

El mantenimiento y seguimiento de estos sistemas es relevante y se detalla en las siguientes secciones.

7.2. Regulación de la presión

Habitualmente, se utilizará agua de lluvia para el riego de los cultivos hidropónicos. En caso de sequía severa podría agotarse el agua del depósito. Por este motivo es necesario tomar las medidas necesarias para evitar daños al cultivo. Los 300 L de agua que hay en el depósito dan un margen de, como mínimo, un día para hacer los preparativos pertinentes para el cambio de agua.

Acciones de seguimiento a llevar a cabo:

- Seguimiento del nivel de agua al depósito de pluviales a través del **software** de SIEMENS (semanalmente).
- Comprobación del buen **funcionamiento** del sistema: depósito regulador lleno, bomba y contador funcionando (diariamente).
- Anotación flujo de agua consumido mirando el **contador** entrante (diariamente).

Acciones a llevar a cabo en caso de previsión de agotamiento del agua de lluvia:

- Rellenar el depósito de AFS y, antes del agotamiento del agua del depósito de 100 m^3, cerrar el grifo y el mecanismo del depósito de regulación de agua pluvial y abrir el grifo del otro depósito.

7.3. Regulación del riego

El agua entrante al sistema de regulación de riego pasa primero por un filtro. Posteriormente, se le añade el flujo de solución nutritiva a través de los dosatrones. La solución nutritiva proviene de dos depósitos de 80 L cada uno, con dos soluciones diferentes.

Acciones de seguimiento a llevar a cabo:

- Comprobar que el **filtro** no esté obturado. Es necesario que la presión de los dos manómetros (antes y después del filtro) sea similar (diariamente).
- Comprobar el buen funcionamiento de los **dosatrones**: tienen que estar graduados por 1:100 partes por litro, el nivel del agua de los depósitos con solución nutritiva tiene que ser similar (sino, uno no está funcionando correctamente) (diariamente).

Acciones a llevar a cabo en caso de previsión de agotamiento del agua de lluvia:

- Vaciar los depósitos con las soluciones nutritivas para el agua pluvial y rellenarlos con las soluciones nutritivas adecuadas para a AFS, teniendo en cuenta el factor de dilución. Se planteará rellenar sólo medio depósito en función de las previsiones meteorológicas.
- Realizar la operación inversa para devolver al agua de lluvia una vez el depósito de almacenamiento disponga de agua pluvial suficiente.

7.4. Sacos de perlita y lixiviados del cultivo

La solución nutritiva final saliente del sistema de regulación del riego llega a los sacos de perlita a través de los goteros. La solución pasa a través de los sacos de perlita, hidratando y nutriendo el cultivo. Finalmente, los sacos de perlita drenan el agua que no es retenida por la perlita y ésta es recogida a cada una de las hileras a través de un canalón. El canalón va a parar al desagüe, que después se junta con la red de aguas residuales amarillas.

Acciones de seguimiento a llevar a cabo:

- Comprobar que los **goteros** no estén obturados: es necesario comprobar que todos los goteros funcionen, sobretodo prestando atención a las plantas que no crezcan correctamente (muy pequeñas o marchitas) (revisión plantas diariamente).
- Comprobar que los **canalones** de recogida de lixiviados de cada hilera funcionen correctamente: se tiene que comprobar que la lona no se haya movido y que se esté drenando el agua a las hileras (diariamente).

Recogida de muestras y medida de parámetros:

- Anotar los datos de todos los contadores del sistema de riego, los volúmenes de los dos depósitos de solución nutritiva, y los volúmenes de lixiviados recogidos en las bandejas de las hileras 3 y 7 para, posteriormente, calcular el drenaje.
- Tomar **pH** y **conductividad** de la solución nutritiva de los goteros y del lixiviado (una sola medida para el agua recogida en los canalones de las hileras 3 y 7) (diariamente).
- Tomar **muestras de solución nutritiva y lixiviada** para su análisis con cromatografía iónica. En función del estudio se determinará la regularidad de la recogida de muestras, así como el protocolo (se organizará con el técnico de laboratorio). Es importante etiquetar bien las muestras (fecha, iniciales de quien las recoge, descripción muestra, **filtrada o no**). Todas las muestras han de filtrarse

con un filtro de 0,22 µm para pasarlas por el cromatógrafo. Se acordará si se filtra antes o después de la recogida y se especificará en la etiqueta.

- Posteriormente, las muestras deben ser guardadas, según convenga, en la nevera, cámara de frío o congelador.

8. RESIDUOS

Cuando se realice el cambio de solución nutritiva en los depósitos de 80 L, la solución nutritiva se verterá al desguace. No obstante, en caso de que se disponga de dos depósitos adicionales, se podrá guardar la solución sobrante con tal de utilizarla una vez se restablezca el riego con aguas pluviales.

Appendix I.II Standard work procedure 7 (PNT – 7). Ion chromatography.

Fecha de emisión	Fecha de aplicación
30/09/2016	**19/11/2016**
Elaborado por	**Revisado y aprobado por**
Cargo: Doctorando **Nombre y apellido:** David Sanjuan	**REVISADO** **Cargo:** Investigador Senior **Nombre y apellido:** Xavier Gabarrell **APROVADO** **Cargo:** Investigador principal del proyecto **Nombre y apellido:** Joan Rieradevall

II) RELACIONES

PNT y otros documentos asociados	Apartado
PNT-1: Seguimiento de los cultivos PNT-2: Seguimiento de flujos de agua	**1. Introducción** **2. Ámbito de aplicación** **3. Definiciones** **4. Cualificación del personal** **5. Responsabilidades** **6. Nivel de riesgo** **7. Conceptos básicos y puesta en marcha** **7.1. Principales componentes** **7.2. Purga básica y completa** **7.3. Puesta en marcha básica** **8. Preparación de eluyente, patrones y muestras** **8.1. Preparación y conservación de eluyente** **8.1.1. Explicación general** **8.1.2. Preparación de eluyente** **8.1.3. Conservación** **8.2. Preparación y conservación de patrones** **8.2.1. Explicación general** **8.2.2. Preparación de patrones** **8.2.3. Conservación** **8.3. Preparación y conservación de muestras** **8.3.1. Muestreo de flujos de agua** **8.3.2. Preparación de muestras** **8.3.3. Conservación** **9. Montaje y desmontaje del equipo** **9.1. Montar los componentes del cromatógrafo** **9.2. Desmontar los componentes** **9.3. Cambio aniones/cationes** **10. Uso de Chromeleon** **10.1. Generalidades** **10.2. Secuencias** **10.2.1. Explicación general** **10.2.2. Crear secuencia a partir de secuencia anterior** **10.2.3. Crear secuencia de nuevo** **10.2.4. Pasar una secuencia (hacer un BATCH)** **10.3. Calibrado** **10.3.1. Explicación general** **10.3.2. Calibrar a partir de un calibrado anterior** **10.3.3. Calibrar sin partir de calibrado previo** **10.4. Backups** **11. Residuos** **12. Consideraciones finales** **12.1. Puntos importantes** **Resolución de problemas**

1. INTRODUCCIÓN

Actualmente, la cromatografía iónica es una herramienta básica para el análisis de aniones y cationes en bajas concentraciones. Para hacer un buen uso de la técnica se deben tener ciertos parámetros bien controlados para que todo funcione a la perfección. El presente documento presenta una guía para dar soporte al usuario del cromatógrafo iónico, incluyendo las pautas para realizar las principales operaciones para su funcionamiento.

2. ÁMBITO DE APLICACIÓN

Este procedimiento normalizado de trabajo se aplicará al cromatógrafo iónico ICS 1000 de DIONEX de la tercera planta del edificio ICTA-ICP (campus UAB). Los métodos indicados están pensados para ser aplicados en el marco del proyecto *Fertilecity* o personal vinculado/contratado con la cualificación y conocimientos necesarios.

3. DEFINICIONES

- **Agua Ultra pura:** agua de tipo Milli-Q con mínimo de 18,2 MΩ de resistencia.
- **Columna:** componente del cromatógrafo iónico de forma cilíndrica que se sirve per a poner en contacto dos fases con tal que se produzca una transferencia de una fase a la otra, i así obtener una separación de los componentes de la mezcla alimentadora en dos fracciones o más.
- **Cromatografía:** método de análisis inmediato basado en la percolación de una fase líquida o gaseosa (mezcla problema) a lo largo de una fase estacionaria, que puede ser sólida o bien líquida fija impregnando un soporte inerte. Los componentes de la mezcla se separan de acuerdo con su distinta velocidad de migración a lo largo de la fase estacionaria.
- **Eluyente:** fase móvil líquida.
- **Equipo:** partes o módulos necesarios para el desarrollo de la tarea. Incluyendo partes o módulos de adquisición y/o procesamiento de datos, etc.

4. CUALIFICACIÓN DEL PERSONAL

Queda autorizado para utilizar el equipo el personal que haya pasado un período de formación para aprender a utilizar el equipo i haya leído este PNT. La lectura del documento no cualifica por sí misma para el uso del cromatógrafo. Deberá igualmente registrarse en el registro de usuarios en la libreta del equipo.

5. RESPONSABILIDADES

a) *Es responsabilidad del usuario hacer un uso correcto de los equipos e instalaciones.*

b) *Es responsabilidad del usuario registrar todas las dadas especificadas en el apartado 7 para su posterior estudio.*

c) *Es responsabilidad del usuario disponer de los conocimientos necesarios especificados en el apartado 4 antes de realizar las tareas pertinentes.*

d) *Los usuarios tendrán cuidado y custodiaran los documentos y manuales necesarios para el uso y gestión del invernadero y los proporcionaran a nuevos usuarios.*

e) *Los usuarios tendrán cuidado y mantendrán en buen estado el material y equipos, así como la infraestructura del cultivo.*

f) *El Director del proyecto será el responsable de la difusión del PNT entre los miembros que deban seguirlo.*

6. NIVEL DE RIESGO

El uso del cromatógrafo implica un nivel de riesgo bajo. Los compuestos químico que se utilizan tienen una peligrosidad baja. En caso de que ocasionalmente se requiera el uso de un compuesto peligroso, se tendrá en cuenta las precauciones indicadas en su etiqueta y se tomarán las precauciones necesarias.

7. CONCEPTOS BÁSICOS Y PUESTA EN MARCHO

7.1. Principales componentes

Hay tres elementos principales a tener en cuenta en el uso del cromatógrafo iónico: cromatógrafo (equipo), autosampler (equipo para el pase automático de muestras), software *Chromeleon* (Figura 1).

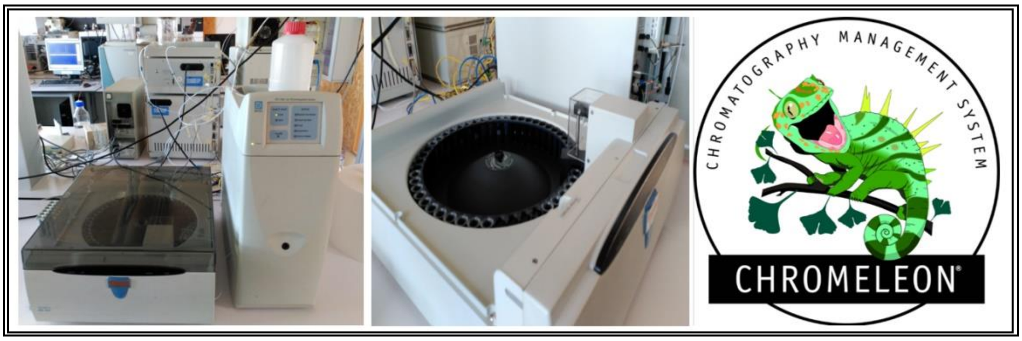


Figura 1 Imágenes de los tres componentes del equipo de cromatografía: cromatógrafo, autosampler y software Chromeleon

<u>CROMATÓGRAFO IÓNICO</u>

La Figura 2 muestra los principales componentes del cromatógrafo iónico, que se describen someramente a continuación:

A. <u>Botella de eluyente</u>: Recipiente que contiene el eluyente que el cromatógrafo utiliza. Presenta un tubo por el cual se aporta el eluyente al cromatógrafo.
B. <u>Bomba</u>: Dispositivo para el bombeo de la fase móvil (eluyente).
C. <u>Válvula de inyección</u>: Conecta la entrada del eluyente, el tubo de dosificación de la muestra, el Loop, la pre columna y el residuo. Tiene dos posiciones: cargar e inyectar. En la posición cargar (en la que está de forma normal) el flujo de eluyente pasa de la bomba a la pre columna, mientras que el Loop está conectado con la dosificación de muestra y el residuo. Es decir, la muestra puede ser inyectada, ya que llenará el Loop. En la posición de inyectar, el eluyente sigue el mismo recorrido, pero pasando por el Loop, de forma que si ha sido cargado con una muestra esta será arrastrada.
D. <u>Loop</u>: Tubo que sale de la válvula y vuelve a entrar, de forma que almacena 25 µL. Su función es cargar la muestra para que posteriormente sea arrastrada hacia las columnas.
E. <u>Pre columna</u>: Pieza cilíndrica similar a la columna de separación (más pequeña) que cumple la función de protegerla.
F. <u>Columna de separación</u>: Pieza cilíndrica que permite separar los elementos de la muestra problema de forma que sus conductividades se puedan identificar y cuantificar.
G. <u>Supresora</u>: Pieza en forma de prisma por la que pasa el eluyente (y la muestra) antes de llegar a la celda de conductividad y posteriormente para regenerar la propia

supresora. Tiene la función de reducir la conductividad de fondo del cromatograma y minimizar el "ruido" de la línea base.

H. Celda de conductividad: Componente que mide la conductividad del flujo entrante de eluyente y muestra. A partir de esta medición se generan los cromatogramas.
I. Residuo: Recipiente en el que se almacena el líquido de deshecho.
J. Panel indicador: Muestra el estado (LED encendido=activo, LED apagado=inactivo) de los diferentes componentes del cromatógrafo.

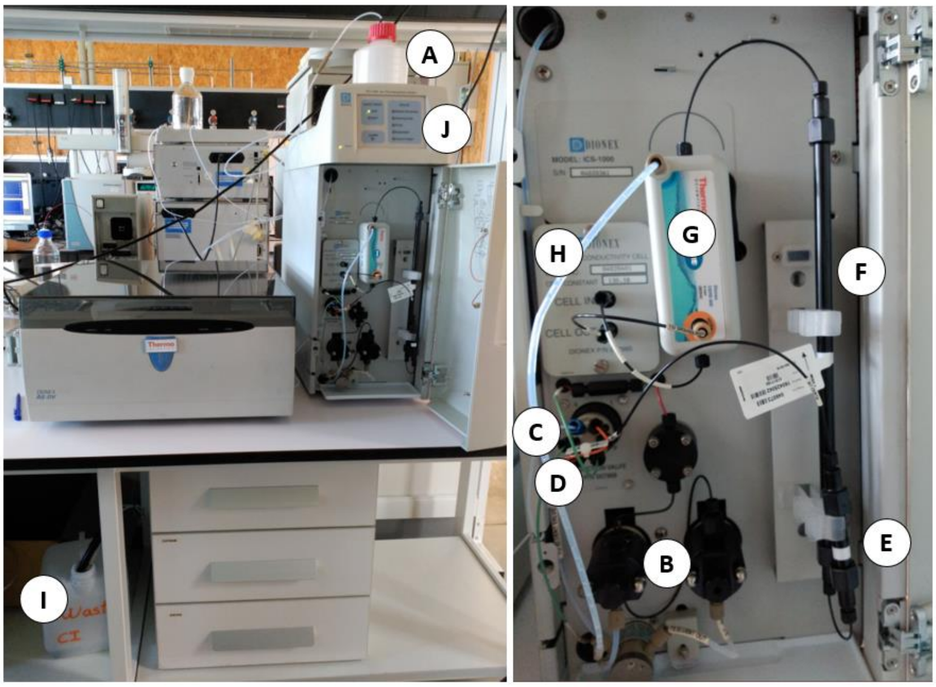


Figura 2 Cromatógrafo iónico con cada uno de sus componentes etiquetados

AUTOSAMPLER

La Figura 3 muestra los principales elementos del autosampler AS-DV, que se describen a continuación de forma breve:

A. Carrusel de muestras: Componente circular en el que se colocan los viales. Permite desplazar los viales hasta el punto donde debe ser tomada la muestra.
B. Émbolo: Pieza que penetra el vial para recoger la muestra y enviarla hasta el cromatógrafo
C. Panel indicador: Muestra el estado (LED encendido=activo, LED apagado=inactivo) de los diferentes componentes del autosampler.

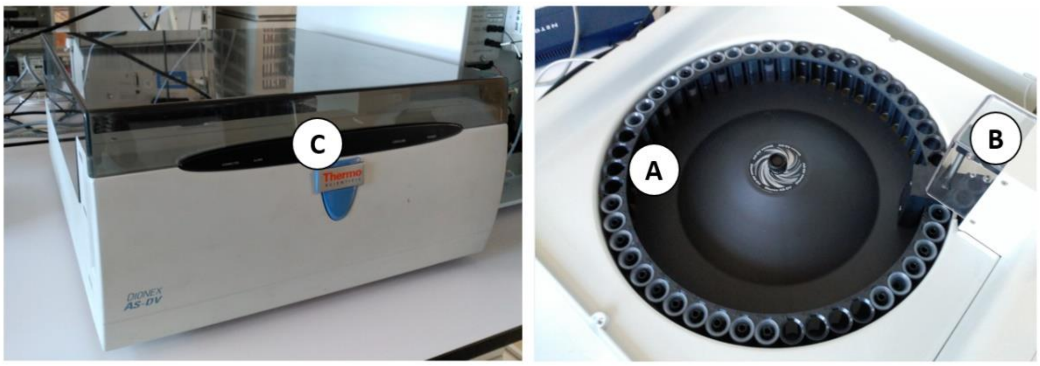


Figura 3 Autosampler AS-DV con cada uno de los componentes etiquetados

CHROMELEON

La Figura 4 muestra las pantallas que principalmente se utilizan en el programa.

A. Monitor/*Panel Tabset* (cromatógrafo): Muestra las condiciones actuales del cromatógrafo, incluyendo el estado de la bomba, la válvula de inyección y la celda de conductividad, la presión y la conductividad actuales del cromatógrafo, los últimos comandos ejecutados y el gráfico de la conductividad. También permite modificar la configuración del bombeo y de la supresora
B. Monitor/*Panel Tabset* (autosampler AS-DV): Muestra el estado actual del autosampler: condiciones del vial actual, configuración de la dosificación de muestra, panel de comandos manuales, reseteado de la memoria, diagrama actual del autosampler y últimos comandos ejecutados.
C. Directorio raíz/*browser*: Permite visualizar la programación de pase de muestras.

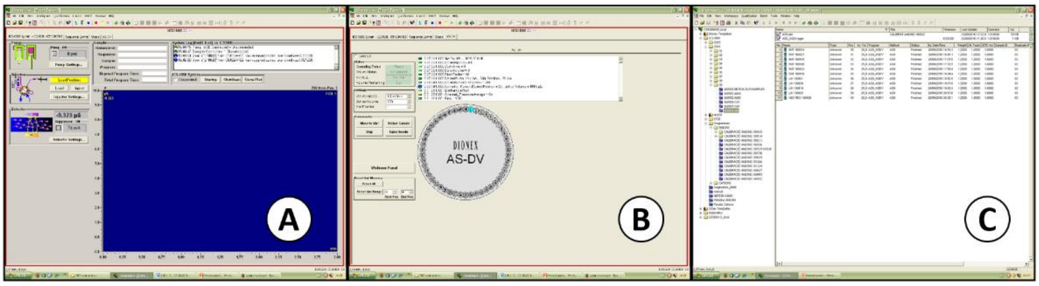


Figura 4 Pantalla del monitor del cromatógrafo y del autosampler y del directorio raíz en el software Chromeleon

7.2. Purga básica y completa

Antes de poner en marcha el cromatógrafo (iniciar la circulación de eluyente por el circuito completo con columnas y supresora), es vital realizar una purga, que consiste en la eliminación de burbujas de aire del circuito de tubos. Hay dos tipos de purga, la básica y la completa. La básica se realizará siempre que se abra la botella de eluyente para añadir eluyente, de forma que entrará aire en el tubo (no hacerlo con la bomba funcionando). La completa se realizará siempre que se realice el montaje del equipo.

Purga básica

1. En el monitor, abrimos la configuración de la bomba (*Pump settings…*).
2. Pulsamos comando *Prime.*
3. Abrimos la válvula de residuo en la bomba.
4. Aceptamos el mensaje de advertencia.
5. Dejamos circular suficiente agua para asegurarnos de que no hay aire en el tubo de la botella a la bomba (puede seguirse la burbuja y ver cómo sale hacia residuo).
6. Apagamos la bomba en la configuración (*Off*).
7. Cerramos la válvula de residuo.

Purga completa

La purga completa consiste en hacer circular agua por el circuito desconectando cada uno de los tubos (hay que parar la bomba con cada desconexión) para sacar posibles burbujas de aire retenidas.

1. Realizar una purga básica.
2. Desconectar el tubo que entra al pre columna.
3. Activar la bomba (*Pump Settings*… → *On*).

4. Esperar unos segundos (a que salga el aire, en caso de que lo haya) (Figura 4).
5. Desactivar la bomba (*Pump Settings… → Off*).
6. Volver a conectar el tubo al pre columna.
7. Repetir pasos 2 a 6 para la conexión a la columna separadora.
8. Repetir pasos 2 a 6 para la conexión a la supresora.

Figura 5 Desconexión del tubo del pre columna y de la columna de separación para purgar

7.3. Puesta en marcha básica

Cuando todo el equipo está montado (columnas y supresora; Figura 1), los pasos a seguir para ponerlo en marcha son los siguientes:

1. Encendemos el equipo (interruptor está detrás).
2. Encendemos el autosampler (interruptor está detrás).
3. Abrimos en el ordenador el software *Chromeleon.*
4. Aparecerá un mensaje de advertencia, aceptamos.
5. Aparecerá una pantalla con información que no hace referencia al cromatógrafo, se corre hacia la derecha y desaparecerá (Figura 6).
6. En el monitor (Figura 6), marcamos la casilla *Connect* para conectar el equipo al ordenador.
7. En la cuarta pestaña del monitor (monitor del autosampler; Figura 6) activamos la casilla *Connect* para conectar el autosampler y clicamos *Reset all* para borrar memoria que se haya podido guardar de muestras pasadas.
8. Realizar purga básica o completa si conviene (leer sección 8.2).
9. Comprobar que los valores especificados para la supresora son correctos y convenientes con lo que se esté pasando (aniones o cationes).
10. Encender la bomba (Pump on) y posteriormente la supresora (Supresor on) o las dos simultáneamente con *Start up.*
11. Esperar a que el valor de conductividad se estabilice (segunda cifra no varía en 10 segundos).
12. Una vez estabilizado, pueden pasarse las muestras pertinentes.

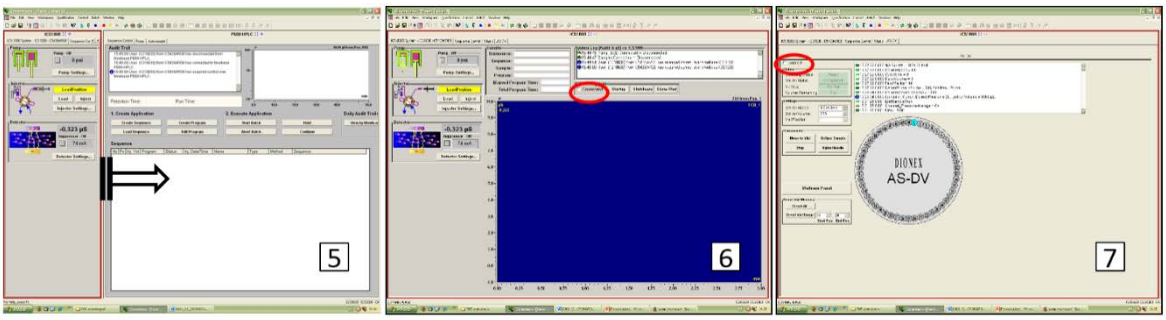


Figura 6 Indicaciones para la puesta en marcha básica del equipo

La Tabla 1 muestra los valores estándar del cromatógrafo, que son los que deberían observarse en un funcionamiento normal. Valores alterado pueden indicar avería, mal funcionamiento o mala gestión del equipo.

Tabla 1 Resumen de los valores del equipo durante un funcionamiento normal

CATIONES Supresora: **CSRS_4 mm** Temperatura de la celda: **40ºC** Corriente de la supresora*: **59 mA** Valores de conductividad*: **2 µS** Presión en funcionamiento*: **1,150 psi**
ANIONES Supresora: **ASRS_4 mm** Temperatura de la celda: **35ºC** Corriente de la supresora*: **45 mA** Valores de conductividad*: **23.6 µS** Presión en funcionamiento*: **2,070 psi**

*Estos valores pueden variar en función del tipo de componentes del equipo y de la antigüedad. Habrá que tener presente de forma constante cuales son los valores habituales del equipo para detectar anomalías.

8. PREPARACIÓN DE ELUYENTE, PATRONES Y MUESTRAS

8.1. Preparación y conservación de eluyente

8.1.1. Explicación general

El eluyente es la fase móvil que circula por el sistema cuando el cromatógrafo está en funcionamiento. Esta fase móvil será distinta en el caso de analizar aniones al de cationes. Es muy importante suministrar el eluyente adecuado y, sobre todo, no confundir aniones con cationes. Es importante también tener en cuenta que todos los reactivos para la preparación de eluyente deben ser de un pureza mínima para análisis (PA).

Para preparar el eluyente, se consultará qué solución y con qué concentración se debe preparar en el informe de la columna de separación de cationes o aniones en cuestión.

8.1.2. Preparación de eluyente

A continuación se indica el procedimiento para la preparación de eluyente.

CATIONES (para columna IonPac CS12A)

Eluyente: Solución de ácido metanosulfónico (AMS) 20 mM.

Preparación:

1. Pipetear la cantidad necesaria de AMS y verter en un matraz aforado, de acuerdo con el volumen a preparar (ejemplo: para 1 L de eluyente, se pipetearan 1,286 µL de AMS en un matraz de 1 L).
2. Enrasar con agua MilliQ y homogenizar.
3. Volcar en recipiente no volumétrico.
4. Desgasificar en ultrasonidos (o método alternativo) durante 15 minutos.

ANIONES (para columna IonPac AS9-HC)

Eluyente: Solución de carbonato de sodio (Na_2CO_3) 9 mM.

Se recomienda disponer de solución madre para una preparación más fácil y rápida de eluyente. Por ejemplo, preparando una solución madre de carbonato de sodio 9 M, para preparar 1 L de eluyente solamente habrá que pipetear 10 mL de solución madre.

Preparación de solución madre:

Para evitar tener que pesar cantidades de reactivo muy pequeñas (error alto) se hará una solución más concentrada sin filtrar, de la cual se filtrará y diluirá una parte en otro recipiente. Una opción para la preparación de solución madre seria: solución madre concentrada (no filtrada) y solución madre (filtrada) de 9 M de Na_2CO_3.

1. Pesar la cantidad necesaria de reactivo (Na_2CO_3) en una balanza analítica (ejemplo: 0,5 L).
2. Añadir agua MilliQ necesaria para disolver (será bastante) con cuidado de no superar el volumen del matraz.
3. Disolver el soluto con un agitador magnético.
4. Volcar en matraz aforado y enrasar.
5. Volcar la solución madre de alta concentración no filtrada en recipiente no volumétrico.
6. Rotular indicando que no está filtrada.
7. Filtrar un volumen superior al necesario (en relación a la cantidad para hacer la dilución) de solución concentrada con filtro de 0.2 µm.
8. Pipetear el volumen necesario de la solución filtrada en un matraz aforado y enrasar.
9. Volcar en un recipiente no volumétrico y rotular indicando que está filtrada.

Preparación eluyente:

1. Pipetear la cantidad necesaria de solución madre a un matraz aforado, de acuerdo con el volumen a preparar.
2. Enrasar con agua MilliQ y homogenizar.
3. Volcar en recipiente no volumétrico.
4. Desgasificar en ultrasonidos (o método alternativo) durante 15 minutos.

8.1.3. Conservación

En caso de querer guardar eluyente, ya sea porque no se va a utilizar después de prepararlo o porque no se ha consumido todo el que se ha puesto en la botella, se recomienda guardarlo en la nevera o cámara de frío (4º). En caso que al volver a usarse hayan pasado algunos días, se volverá a desgasificar el eluyente. De igual forma, la solución madre se guardará en la nevera una vez preparada, pudiéndose guardar hasta 6 meses.

Tanto el eluyente en conservación como la solución madre deberán estar bien rotulados con tal de no generar confusiones. El rotulado deberá incluir: tipo de eluyente (aniones/cationes), componente y concentración (ej. Na_2CO_3, 9 mM), fecha de preparación del eluyente, persona o grupo (ejemplo: Sostenipra o David). Para la solución madre de eluyente, es muy importante indicar si está o no filtrada.

8.2. Preparación y conservación de patrones

8.2.1. Explicación general

Las soluciones patrón son necesarias para el funcionamiento del cromatógrafo iónico, ya que a partir de estas se calibra el aparato, realizando las rectas de calibración que permiten cuantificar los diferentes elementos en las muestras. Los patrones de cationes y aniones se prepararán e inyectarán por separado.

Se preparará previamente una solución madre disolviendo los reactivos convenientes en agua MilliQ. Esta se diluirá posteriormente en los viales para los patrones de concentraciones diferentes. Es importante tener en cuenta que todos los reactivos para la preparación de eluyente deben ser de un pureza mínima para análisis (PA).

Para determinar las concentraciones de los diferentes elementos en la solución madre habrá que tener en cuenta qué rango de concentraciones se quiere obtener para cada elemento en los patrones. No es necesario que los diferentes elementos tengan igual concentración ni que se hagan conjuntamente. No obstante, lo más práctico es hacer una solución madre con todos los elementos (de aniones o de cationes). De esta forma, pueden considerarse diferentes concentraciones para los elementos, pero se diluirán todos en la misma proporción.

8.2.2. Preparación de patrones

Preparación de solución madre para patrones:

1. Decidir las concentraciones para los diferentes componentes de la solución madre, así como el volumen a preparar.
2. Pesar uno a uno los componentes en una balanza analítica, y volcarlos en un vaso de precipitados, pasando unas gotas de agua MilliQ por el soporte para arrastrar los restos de la sal con una pipeta Pasteur.
3. Una vez se tienen todos los componentes pesados y en el vaso, añadir el agua MilliQ necesaria para disolver.
4. Disolver las sales manualmente o con la ayuda de una mosca.
5. Filtrar todo el volumen de la solución con filtro de 0.2 µm.
6. Volcar toda la solución filtrada en un matraz aforado y enrasar.
7. Volcar en un recipiente no volumétrico y rotular indicando que está filtrada.

A continuación se incluyen las cantidades de reactivo a pesar para preparar una solución madre de 500 ppms para todos los elementos a analizar.

ANIONES (500 ppm)

Componente	mg/L
NaCl	828.36
$NaNO_2$	757.42
$NaNO_3$	688.82
Na_2SO_4	746.78
KH_2PO_4	720.06

CATIONES (500 ppm)

Componente	mg/L
$CaCl_2 \cdot 2\ H_2O$	1,856
$MgCl_2 \cdot 6\ H_2O$	4,224
KCl	963

Preparación de los patrones:

1. Preparar en un soporte adecuado los viales donde se vayan a preparar los patrones y rotularlos: aniones o cationes, concentración, factor de dilución
2. Pipetear el volumen de solución madre necesario en función de la concentración. Por ejemplo si no diluimos, llenaremos el vial (5 mL), si diluimos 1:2 llenaremos la mitad (2.5 mL).
3. Pipetear un volumen de agua MilliQ necesario para acabar de llenar el vial (en total son 5 mL)
4. Tapar los viales bajando el tape con la herramienta hasta abajo (no dejar el saliente fuera del tubo) y homogenizar los patrones

8.2.3. Conservación

En caso de no pasar los patrones después de prepararlos, se recomienda guardarlo en nevera o cámara de frío (4ºC). De igual forma, la solución madre se guardará en la nevera una vez preparada, pudiéndose guardar hasta 6 meses.

La solución madre deberá estar correctamente rotulada, incluyendo: aniones o cationes, concentración (ej. 500 ppm), fecha de preparación, persona o grupo (ejemplo: Sostenipra o David), filtrada o no.

8.3. Preparación y conservación de muestras

8.3.1. Muestreo de flujos de agua

Durante el cultivo deben tomarse las muestras convenidas para hacer un seguimiento de la concentración de nutrientes en los principales flujos de agua. Estas muestras sirven para gestionar los nutrientes en la solución nutritiva del cultivo y para controlar los flujos de nutrientes en caso que se quiera estudiar. En un cultivo sin recirculación deberán tomarse muestras de entrada y lixiviados, si hay recirculación deberán decidirse los puntos a muestrear del cultivo. Las muestras recogidas deben rotularse y conservarse debidamente (subapartado 9.3.3.).

En la recogida de muestras hay que tener en cuenta que los viales a utilizar son de 5 mL, con lo cual deberá cogerse suficiente muestra, especialmente en caso de que la muestra tenga concentraciones muy bajas y no se pueda diluir. Habrá que considerar si diluir la muestra en caso de que las concentraciones sean elevadas y no se pueda cuantificar bien. Una muestra piloto puede ayudar a aclarar cuál es la mejor forma de pasar las muestras.

8.3.2. Preparación de muestras

1. Preparar en un soporte adecuado los viales donde se vayan a preparar las muestras y rotularlos: aniones o cationes, tipo de muestra (lixiviados, agua, solución nutritiva), factor de dilución.
2. Pipetear el volumen de cada muestra en su vial (5 mL si no hay dilución).
3. En caso de diluir la muestra, pipetear agua MilliQ para completar los 5 mL.
5. Tapar los viales bajando el tape con la herramienta hasta abajo (no dejar el saliente fuera del tubo) y homogenizar las muestras.

8.3.3. Conservación

Las muestras recogidas en el cultivo deben estar rotuladas correctamente: tipo de muestra (lixiviados, solución nutritiva, agua de lluvia, etc.), fecha, filtrada o no, iniciales de quien las recogió (ejemplo: DSD). Posteriormente deberán ser guardadas en la nevera o cámara de frío (4ºC) hasta que se vayan a preparar para el cromatógrafo. De igual forma, si las muestras ya preparadas en viales no se van a utilizar en unos días deben guardarse en la nevera hasta que se vayan a pasar.

En caso de que las muestras no vayan a analizarse durante un período prolongado de tiempo, deben guardarse en el congelador o cámara de frío (-15ºC). El rotulado de las muestras debe cubrirse con cinta adhesiva con tal de que no se borre. A la hora de disponer de ellas, habrá que prever su descongelación.

9. MONTAJE Y DESMONTAJE DEL EQUIPO

9.1. Montar los componentes del cromatógrafo

1. Partiendo del equipo apagado y todos los tubos conectados en un circuito sin columnas ni supresora (Figura 8).
2. Desatornillar todas las conexiones de los tubos y guardar los conectores.
3. Hidratar la supresora de acuerdo con las instrucciones que se indican en el manual de hidratación (documento en papel dentro de la caja)* (Figura 7).
4. Conectar la supresora al cable de corriente, guardar el cable dentro del hueco y encajar la supresora en su sitio.
5. Quitar los tapones a la columna y la pre columna y colocarlas en su sitio, asegurando que la orientación es correcta (mirar flecha en la etiqueta de la columna).
6. Conectar todos los cables en sus respectivas uniones (4 conexiones en la supresora y 2 en cada columna).
7. Vaciar el eluyente en caso de tener agua MilliQ y rellenar con el eluyente pertinente.
8. Encender el cromatógrafo y conectar al monitor de Chromeleon.
9. Realizar purga completa.
10. Queda listo para iniciar la estabilización.

*El punto 3 aplica a supresora de hidratación manual. Si la supresora debe hidratarse usando el flujo de la bomba, saltarse el paso 3 y, después del paso 9 realizar la hidratación pertinente habiendo colocado en la botella de eluyente el eluyente con la concentración adecuada.

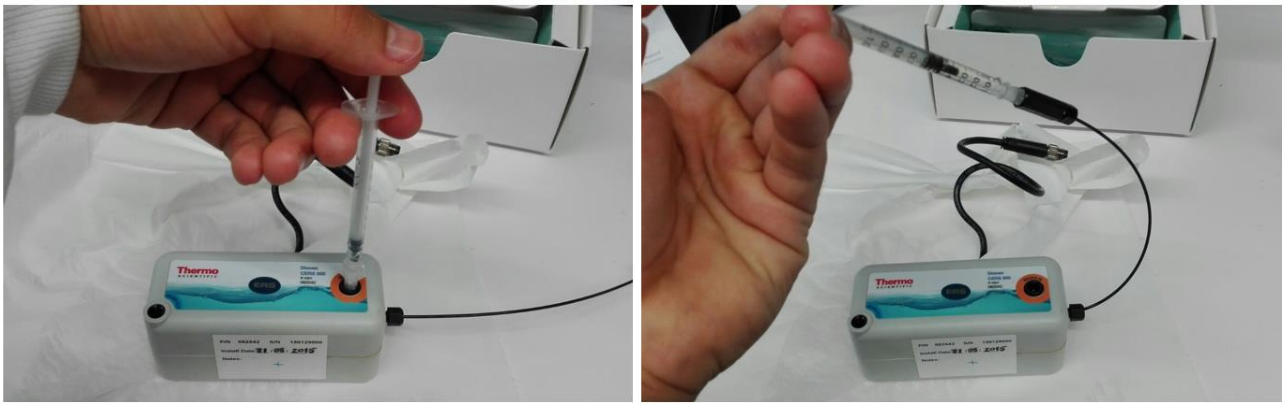


Figura 7. Fotografía de la hidratación manual de la supresora (inyección de agua por los canales)

9.2. Desmontar los componentes

1. Asegurar que el equipo y el autosampler están apagados*.
2. Desatornillar todas las conexiones de las dos columnas y la supresora.
3. Poner los tapes a las dos columnas y guardar en sus cajas.
4. Descolgar con cuidado la supresora, desconectar el conector e hidratarla de acuerdo con las instrucciones que se indican en el manual de hidratación (documento en papel dentro de la caja)* (Figura 7).
5. Una vez hidratada, enroscar los tapes y guardar en su caja. Tendremos todos los componentes guardados y nos quedarán fuera los tubos que los unían.
6. Unir todos los cables de 4 mm (negros) que han quedado con los conectores adecuados (negros) de manera que formen un circuito desde la válvula de inyección hasta la celda de conductividad (Figura 8).
7. De igual forma, unir los dos cables transparentes de la supresora con un conector adecuado (marrón), de forma que quedará un circuito de CELL OUT al residuo (Figura 8).
8. Desechar o guardar el eluyente sobrante, enjuagar la botella con agua MilliQ.
9. Rellenar la botella con unos 300 mL de agua MilliQ e instalar en el cromatógrafo.
10. Encender el cromatógrafo y conectar al monitor de Chromeleon.
11. Realizar purga básica (*Prime).*
12. Realizar purga en la última junta antes de la celda de conductividad.
13. Hacer circular agua por este circuito hasta que quede limpio de eluyente (conductividad debe ser aproximadamente 1 µS).
14. Apagar el equipo.

*El punto 4 aplica a supresora de hidratación manual. Si la supresora debe hidratarse usando el flujo de la bomba, la hidratación deberá realizarse en primer lugar (previo al punto 1), siguiendo las instrucciones del manual de la supresora.

Figura 8. Circuito cerrado de tubos para la limpieza en el cambio de aniones a cationes (o viceversa)

9.3. Cambio aniones/cationes

El cambio de aniones a cationes consiste en desmontar el equipo de acuerdo con lo indicado en el subapartado 10.2 y en volverlo a montar con los componentes adecuados de acuerdo con el subapartado 10.1.

Se pondrá especial atención en limpiar bien el circuito de cualquier resto de eluyente así como de no confundirse a la hora de colocar los diferentes componentes y preparar el eluyente.

10. USO DE CHROMELEON

10.1. Generalidades

Chromeleon es un software específico para cromatografía iónica. Este permite utilizar el cromatógrafo iónico, cuantificar los elementos en las muestras a partir de los cromatogramas y programar el pase de muestras, entre otras cosas.

En la sección 8 del documento, se han presentado las características más básicas del programa, necesarias para poner en marcha el cromatógrafo. Concretamente, se ha presentado lo referente al monitor (*Panel Tabset*), desde el que se ve en tiempo real las condiciones y mediciones del cromatógrafo y se puede controlar directamente.

En la presente sección se muestra lo referente al directorio raíz (*Browser)* de Chromeleon, desde donde se programa el pase de muestras, se realiza la cuantificación y se extraen los resultados obtenidos.

10.2. Secuencias

10.2.1. Explicación general

La secuencia es la "unidad básica" del directorio raíz de Chromeleon, y consiste en un conjunto de muestras para ser pasadas por el cromatógrafo. Las secuencias permiten organizar las muestras a pasar y programar en qué orden se va a realizar el pase.

Las secuencias también son la interfaz a través de la cual cuantificamos las muestras y realizamos el calibrado. Generalmente, las secuencias se crean a partir de una secuencia anterior similar a la que queremos crear, de forma que se mantienen las características básicas y se modifica solo lo necesario.

10.2.2. Crear secuencia a partir de secuencia anterior

1. Clic en la secuencia de la que queramos partir en la columna de la izquierda, de forma que se nos muestre la secuencia en la derecha (escoger la secuencia más parecida a la que se quiera crear).
2. Ir a *FILE → SAVE AS → ICS 1000 → AÑO → MES → Ponemos fecha (ej. 161003) seguido de letra (A, B, C, etc) si hay más de una secuencia el mismo día.*
3. Modificamos, en caso de ser necesario, el programa y el método de cuantificación. Esto es, en la parte de arriba, borrar los archivos .pgm y .qnt y copiar los archivos correctos (arrastrándolos hasta la secuencia en el menú de la izquierda o copiando y pegando).
4. Borrar o añadir las muestras que queramos (botón derecho y *Delete, Append sample o insert sample).* Revisar los siguientes elementos de la muestras en nuestra secuencia (se modifican haciendo clic encima):

    a. <u>NOMBRE</u>: Poner el nombre de la muestra: tipo de muestra (lixiviado, etc.), fecha

    b. <u>TIPO DE MUESTRA</u>: Básicamente hay dos tipos:

        i. Unknown: Desconocido, es lo que pondremos cuando pasemos una muestra problema

ii. Standard: Cuando pasamos un patrón para hacer el calibrado

c. POSICIÓN: Indicar la posición de cada una de las muestras en el autosampler. Posiciones 45 a 50 (incluidas) están destinadas a viales de agua MilliQ para rinse.

d. PROGRAMA: Revisamos que se indica el programa que hemos puesto arriba.

e. MÉTODO: Revisamos que se indica el método que hemos puesto arriba.

f. ESTADO: Escogemos para cada muestra el estado adecuado entre los siguientes:

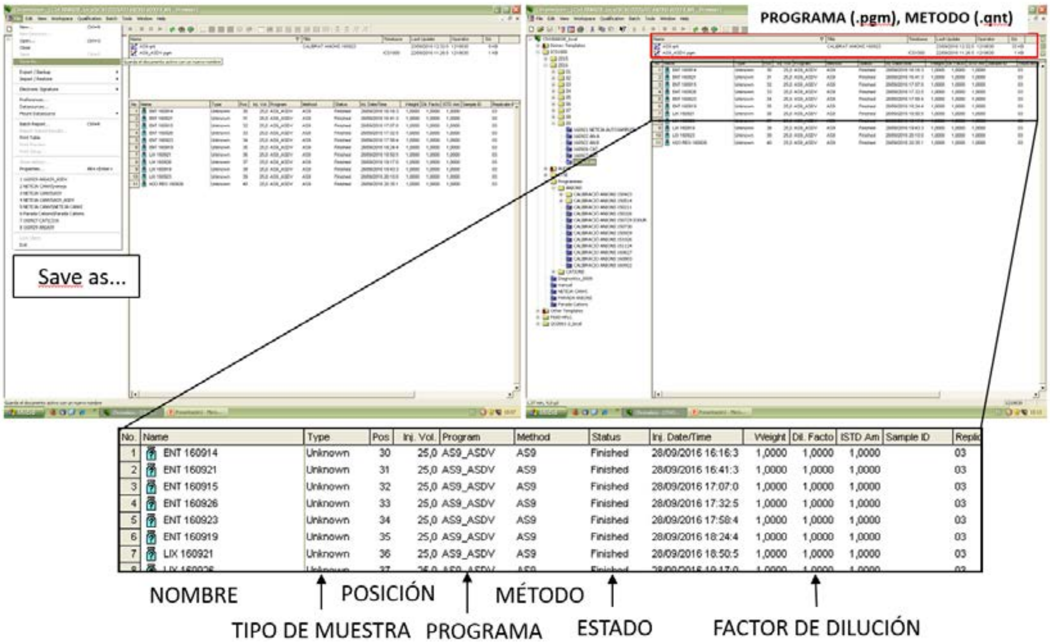
   i. Single: Muestra sin pasar, es el que ponemos cuando queremos pasar una muestra.

   ii. Finished: Muestra finalizada, aparecerá cuando ya se haya pasado una muestra. Podemos ponerlos manualmente cuando no queremos que se pase una muestra en concreto.

   iii. Interrupted: Aparecerá cuando una muestra se haya empezado a pasar y se haya interrumpido el pase.

g. FACTOR DE DILUCIÓN: Se indica el factor de dilución. Por ejemplo, una muestra diluida a la mitad (2.5 mL muestra, 2.5 mL agua MilliQ) tendría factor de dilución 2.

5. Una vez se ha revisado todo, la secuencia está lista para ser pasada.

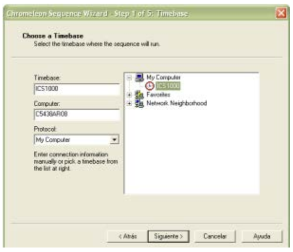


10.2.3. **Crear secuencia de nuevo**

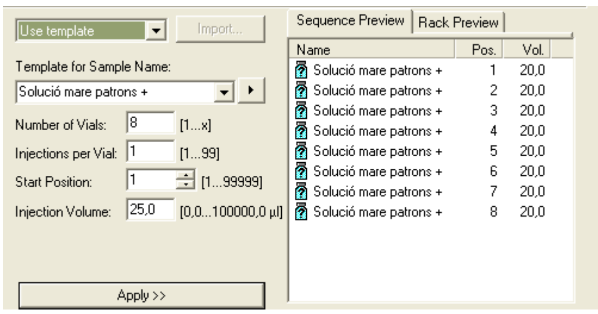
1. Ir al directorio raíz (Browser)
2. Ir a la pestaña FILE → NEW → SEQUENCE (USING WIZARD) → OK

3. En la primera pantalla clicar *Siguiente*

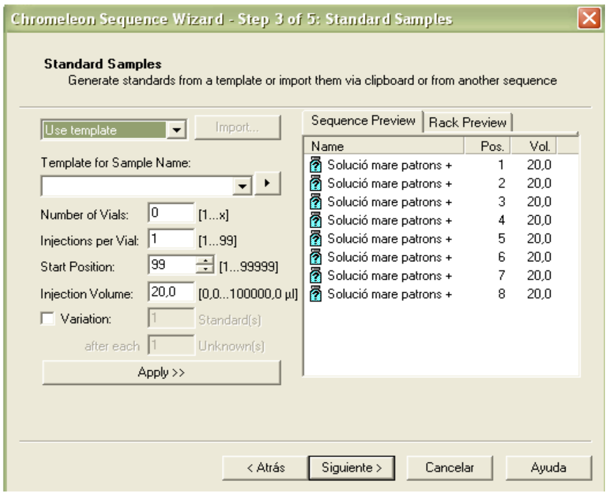
4. En la siguiente hay que tener:
   a. Time base: **ICS 1000**
   b. Computer: **C5438AR08**
   c. Protocolo: **My Computer**
   d. Clicar *Siguiente*



5. En la pantalla Step 2 of 5: Unknown Samples debemos poner:
   a. *Template for Sample Name:* Ponemos el nombre de nuestra muestra, con la flecha que señala a la derecha (al lado) tenemos la lista desplegable de opciones para nombrar o numerar las muestras
   b. *Number of Vials:* se introduce el número de viales que se quiere
   c. *Injections per Vial:* **SIEMPRE 1**
   d. *Start Position:* Se introduce la posición del autosampler a partir de la cual se colocan los viales
   e. *Injection Volume:* **SIEMPRE 25,0** (corresponde al volumen de nuestro loop).
   f. Clicamos *Apply* para visualizarlo todo en la pantalla de la derecha
   g. Clicamos *Siguiente*

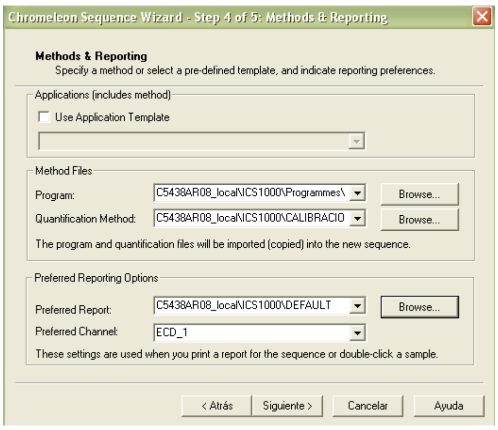


6. En la siguiente pantalla no tocamos nada, pero debemos tener algo parecido a lo que se ve en la imagen y nada más. Clicamos *Siguiente*.



7. En pantalla *Step 4 of 5* hemos de vincular el nuestro programa, método de cuantificación i report. Para hacerlo en cada apartado vamos a:
   a. *Programe: BROWSE* hay que buscar en *ICS 1000* → *PROGRAMES* → *ANIONS* → *AS9* (por ejemplo para aniones) 

   b. *Quantification Method: BROWSE* buscamos el método de cuantificación siguiendo el mismo camino que para el programa i seleccionamos también el AS9
   c. *Preferred Report: BROWSE* y buscamos el report en *ICS 1000 DEFAULT*.
   d. *Preferred Channel:* **SIEMPRE *ECD_1***
   e. Clicamos *Siguiente*
8. Estamos en el paso 5 de 5. Vamos a poner el título en la secuencia i la fecha i vincularlo a una carpeta de año/mes.
   a. *Sequence name:* ponemos el nombre (siempre al revés). Ejemplo: 150320A. Detrás pondremos A, B, C… por si pasamos diferentes secuencias en un día.
   b. *Title:* podemos poner nuestro nombre i qué estamos pasando
   c. *Datasource:* **SIEMPRE C5438AR08_local** (no se cambia nunca).
   d. *Directory: BROWSE* y vamos dentro de *ICS 1000* → *AÑO* → *MES* → *OK*
   e. Clicar *Finalizar.*
   f. Clicar *Done.*



10.2.4. **Pasar una secuencia (hacer un *BATCH*)**

Una vez nuestra secuencia está lista, la pasaremos haciendo un *batch*, que es un "pase" de una o más secuencias. Con el *batch* programamos el pase de las secuencias que deseemos, de forma que podemos irnos y dejar el equipo trabajando. Es importante calcular que el eluyente disponible es suficiente para el pase y el nivel de eluyente esté actualizado en el monitor.

De igual forma, es importante incluir en el *batch* una secuencia de parada (*ICS 1000 → PROGRAMES → PARADA ANIONS / PARADA CATIONS)*, configurada previamente para que apague la bomba y la supresora. Si no se incluye la secuencia de parada, el equipo continuará funcionando hasta que se quede sin eluyente.

1. Asegurar que el botón de *Aquiring data* del monitor está apagado y que hay suficiente eluyente para pasar las muestras.
2. En la secuencia que queremos pasar, vamos a *BATCH → START*.
3. Aparecerá la secuencia creada en una pantalla. Clic en READY CHECK.
4. Si todo es correcto damos a *START.*
5. Las secuencias programadas empezarán a pasarse.

10.3. Calibrado

10.3.1. Explicación general

El calibrado es una parte esencial de la cromatografía iónica, ya que nos permite cuantificar las concentraciones de los diferentes elementos de la muestra a partir del cromatograma.

Se recomienda realizar, como mínimo, un calibrado mensual. Adicionalmente, se pasará una muestra patrón (de concentración conocida) cada vez que vayan a pasarse muestras (aniones o cationes). En caso que este patrón no se cuantifique adecuadamente, se recomienda realizar entonces un calibrado. También es conveniente pasar un patrón a partir de una solución estándar para evaluar la exactitud de las mediciones.

Generalmente, cuando realizamos un calibrado lo hacemos a partir del calibrado anterior (subapartado 10.3.2). Esto es, aprovechando el archivo previo y solamente actualizando lo que es necesario. En caso que no se disponga de ningún archivo, habrá que hacer un nuevo calibrado (subapartado 10.3.3).

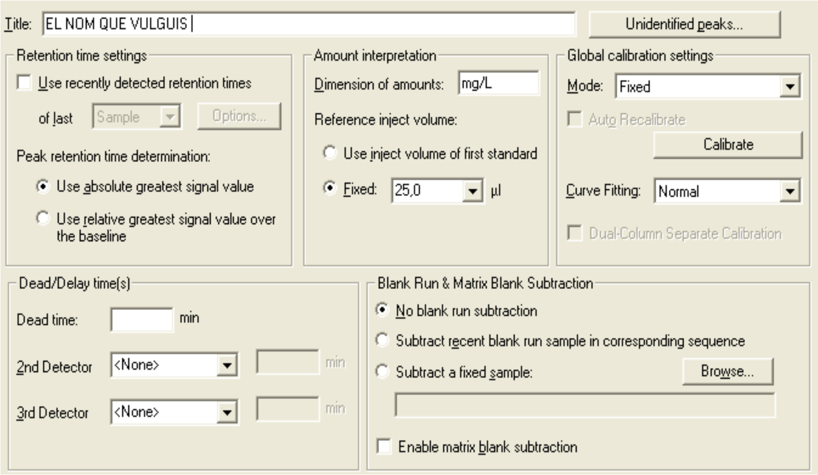
10.3.2. Calibrar a partir de un calibrado anterior

Este subapartado indica solo lo que hay que modificar para hacer un calibrado de forma sencilla a partir de un calibrado anterior. Para ver con más detalle los elementos del QNT ver subapartado 10.3.3.

1. Crear una secuencia a partir de la secuencia del último calibrado (subapartado 10.2.2). Los calibrado se guardan en (*ICS 1000 → PROGRAMES → ANIONS / CATIONS)*
2. Modificar las muestras de acuerdo con los patrones que vayamos a pasar (cambiar nombre, estado y eliminar o añadir muestras si es necesario) (subapartado 10.2.2). Los patrones deben estar marcados como *Standard.*
3. Cuando la secuencia está preparada y el estado en *Single* corremos la secuencia.
4. Una vez se ha pasado, hacemos doble clic en una muestra y vamos a *QNT-Editor*. 
5. Entramos en una pantalla grande donde se ve el cromatograma. Abajo vemos diferentes pestañas:

a. En la pestaña de *General,* solo habrá que modificar*:*

   - *Title*: El nombre que demos a l secuencia (mínimo fecha y aniones/cationes)
   - Todo lo que se ve en la pantalla de abajo lo dejaremos igual.



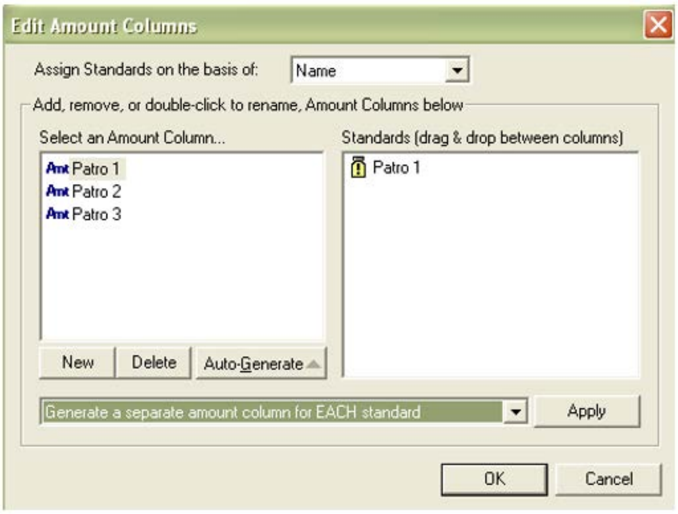
b. En la pestaña *Peak Table*:

   - *Ret.Time,* miraremos en una de las muestras de la secuencia cual es el tiempo de retención (en que minuto sale cada elemento) y actualizaremos los tiempos de retención de cada uno.

No.	Peak Name	Ret.Time	Window	Standard	Int.Type	Cal.Type	Peak Type	Group	Comment
1	Clorur	7,160 min	5,000 RG	External	Area	LOff	Auto		Autogenerated
2	Nitrit	9,157 min	5,000 RG	External	Area	LOff	Auto		Autogenerated
3	Nitrat	14,653 min	5,000 RG	External	Area	LOff	Auto		Autogenerated
4	Fosfat	19,458 min	5,000 RG	External	Area	LOff	Auto		Autogenerated
5	Sulfat	21,546 min	5,000 RG	External	Area	LOff	Auto		Autogenerated

c. En la pestaña Amount table:

   - Botón derecho en cualquier fila.
   - Vamos a *EDIT → COLUMNS → EDIT AMOUNT COLUMNS*
   - Saldrá una ventana nueva
   - Eliminamos una por una todas las muestras de la ventana de la izquierda
   - Clicamos en *Auto-Generate*
   - Clicamos en *Apply*
   - En el mensaje que sale le damos a **Sí.**
   - En las columnas que hemos generado introducimos manualmente la concentración de cada patrón **para cada elemento**. Si por ejemplo tenemos un elemento con otra concentración dentro del patrón, lo cambiamos. (en nuestro ejemplo todos tienen igual concentración).



d. En la pestaña *Calibration*:

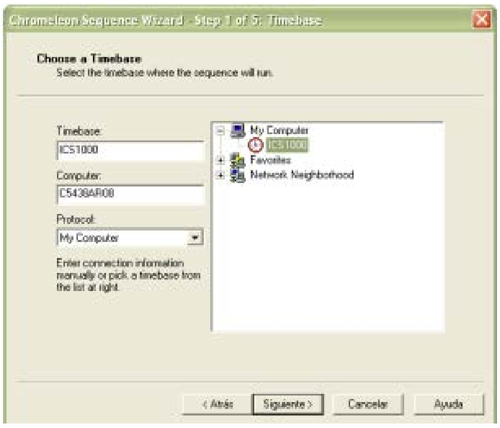
- Nos ponemos encima de la línea, clicamos con el botón derecho.
- Seleccionamos Append Standard.
- Buscamos nuestros patrones uno a uno y los añadimos

e. Finalmente, guardamos nuestro Calibrado

10.3.3. Calibrar sin partir de calibrado previo

El ejemplo que a continuación se muestra está hecho con los datos de aniones. Para cationes, el procedimiento es exactamente igual cambiando lo que hace referencia a aniones así como los componentes a analizar.

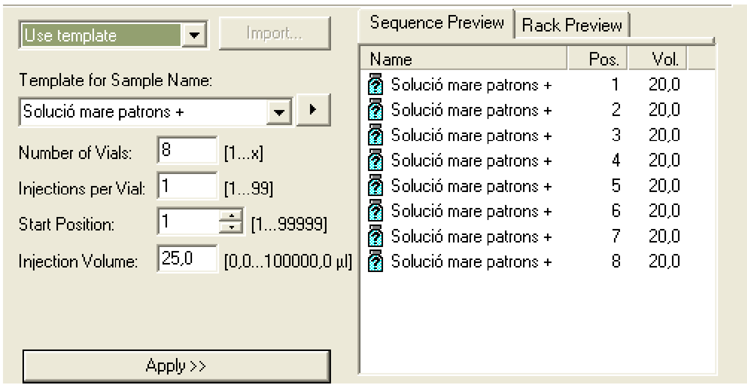
1. Ir a directorio raíz (Browser)
2. Pestaña FILE → NEW → SEQUENCE (USING WIZARD) → OK
3. En la primera pantalla clicar *Siguiente*
4. En la siguiente debemos poner en la casillas:
   a. Time base: **ICS 1000**
   b. Computer: **C5438AR08**
   c. Protocolo: **My Computer**
   d. Clicar *Siguiente*



5. En la pantalla Step 2 of 5: Unknown Samples tiene que haber:

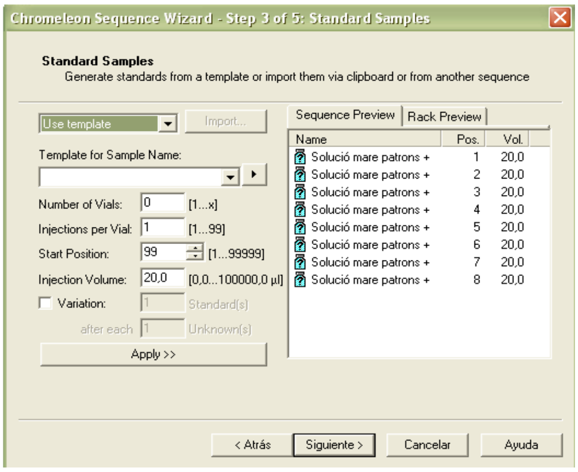
   a. *Template for Sample Name:* Ponemos el nombre de nuestra muestra, con la flecha que señala a la derecha (al lado) tenemos la lista desplegable de opciones para nombrar o numerar las muestras.

b. *Number of Vials:* se introduce el número de viales que se quiere
c. *Injections per Vial:* **SIEMPRE 1.**
d. *Start Position:* Se introduce la posición del autosampler a partir de la cual se colocan los viales.
e. *Injection Volume:* **SIEMPRE 25,0** (corresponde al volumen de nuestro loop).
f. Clicamos *Apply* para visualizarlo todo en la pantalla de la derecha.

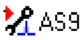


g. Clicamos *Siguiente.*

6. En la siguiente pantalla no tocamos nada, pero debemos tener algo parecido a lo que se ve en la imagen y nada más. Clicamos *Siguiente.*
7. En pantalla *Step 4 of 5* hemos de vincular el nuestro programa, método de

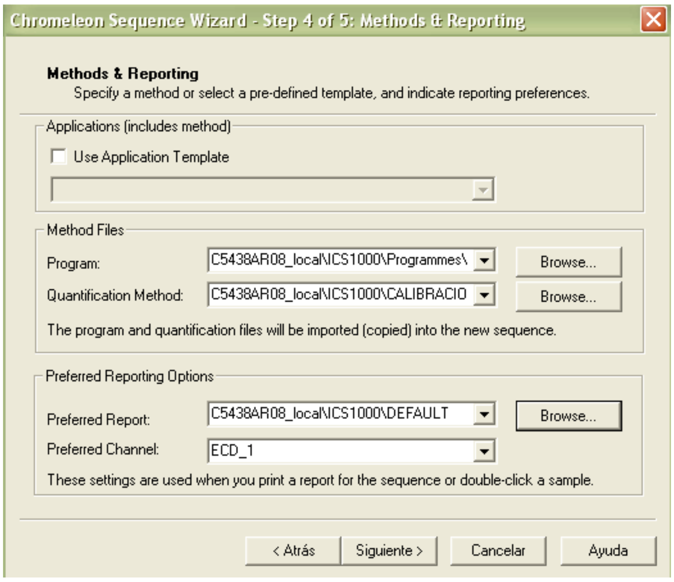


cuantificación i report. Para hacerlo en cada apartado vamos a:

a. *Programe: BROWSE* hay que buscar en *ICS 1000* → *PROGRAMES* → *ANIONS* → *AS9* (por ejemplo para aniones). 

b. *Quantification Method: BROWSE* buscamos el método de cuantificación siguiendo el mismo camino que para el programa i seleccionamos también el AS9.
c. *Preferred Report: BROWSE* y buscamos el report en *ICS 1000 DEFAULT*.
d. *Preferred Channel:* **SIEMPRE *ECD_1.***

e. Clicamos *Siguiente.*



8. Estamos en el paso 5 de 5. Vamos a poner el título en la secuencia i la fecha i vincularlo a una carpeta de año/mes.

a. *Sequence name:* ponemos el nombre (siempre al revés). Ejemplo: 150320A. Detrás pondremos A, B, C… por si pasamos diferentes secuencias en un día.

b. *Title:* podemos poner nuestro nombre i qué estamos pasando

c. *Datasource:* **SEMPRE C5438AR08_local** (no se cambia nunca).

d. *Directory: BROWSE* y vamos dentro de *ICS 1000 → PROGRAMES → ANIONS → CALIBRACIÓ ANIONS* (DATA)

e. Clicar *Finalizar.*

f. Clicar *Done.*

9. Vamos a la secuencia que hemos creado y cambiamos el tipo de muestra de *UnKnow* a *Standard*. Para hacerlo más deprisa, clicar encima de Standard, botón derecho i *Fill Column*.
10. Pasamos el batch en *BATCH → START*
11. Aparecerá la secuencia creada en una pantalla. Hacemos READY CHECK, si todo es correcto damos a *START*
12. Se pasan las muestras
13. Cuando han acabado, hacemos doble clic en una y vamos a *QNT-Editor*. 
14. Entramos en una pantalla grande donde se ve el cromatograma. Abajo vemos diferentes pestañas:

a. En la pestaña de *General:*

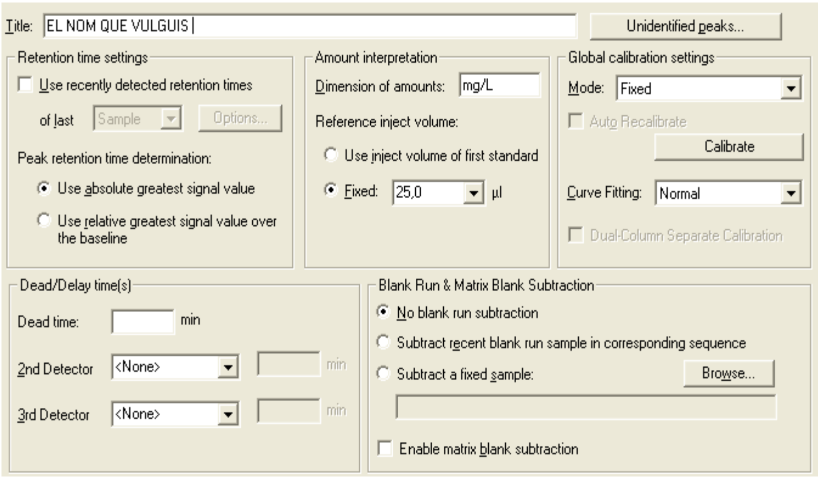
- *Title*: El nombre que demos a l secuencia (mínimo fecha y aniones/cationes)
- *Amount interpretation*: en *Dimension of amount* las unidades que se quiera (generalmente mg/L o ppm)
- *Reference inject volume*: *Fixed,* pondremos **SIEMPRE** 25 µl (volumen de nuestro Loop)

- *Global calibration settings*: *Fixed* (si primero hacemos la recta patrón y después pasamos las muestras para cuantificar). Si pasamos las muestras primero (antes de tener una recta decente) tendremos que copiar los patrones dentro de nuestra secuencia y **cambiar de *Fixed* a *Total*** en *Global calibration settings*, dentro de AS9.qnt. El cambio solo afectará a esta secuencia.

Name	Title	Timebase	Last Update	Operator	Siz
AS9.pgm	Proba David analits	ICS1000	26/03/2015 13:04:5	1218630	1 KB
AS9.qnt	Anions formació		26/03/2015 13:03:2	1218630	22 KB

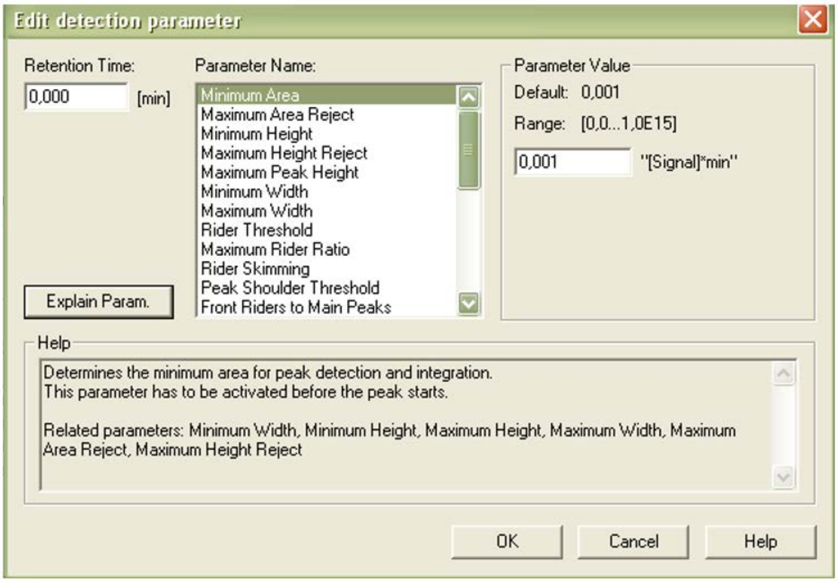
No.	Name	Type	Pos	Inj. Vol.	Program	Method	Status	Inj. Date/Time	Weight	Dil. Facto	ISTD Am	Sample ID	Replicate ID	Comment
1	Patro 1	Standard	99	25,0	AS9	AS9	Finished	11/02/2015 16:39:2	1,0000	1,0000	1,0000		99	
2	Patro 2	Standard	100	25,0	AS9	AS9	Finished	11/02/2015 17:10:4	1,0000	1,0000	1,0000		100	
3	Patro 3	Standard	101	25,0	AS9	AS9	Finished	11/02/2015 17:43:2	1,0000	1,0000	1,0000		101	
4	Patro 1	Standard	102	25,0	AS9	AS9	Finished	12/02/2015 8:57:46	1,0000	1,0000	1,0000		101	
5	Patro 2	Standard	103	25,0	AS9	AS9	Finished	12/02/2015 9:28:27	1,0000	1,0000	1,0000		101	
6	Patro 3	Standard	104	25,0	AS9	AS9	Finished	12/02/2015 9:59:39	1,0000	1,0000	1,0000		101	
7	seq.	Unknown	1	25,0	AS9	AS9	Finished		1,0000	1,0000	1,0000		01	
8	seq.	Unknown	2	25,0	AS9	AS9	Finished		1,0000	1,0000	1,0000		02	
9	seq.	Unknown	3	25,0	AS9	AS9	Finished		1,0000	1,0000	1,0000		03	
10	seq.	Unknown	4	25,0	AS9	AS9	Finished		1,0000	1,0000	1,0000		04	
11	seq.	Unknown	5	25,0	AS9	AS9	Finished		1,0000	1,0000	1,0000		05	
12	seq.	Unknown	6	25,0	AS9	AS9	Finished		1,0000	1,0000	1,0000		06	
13	seq.	Unknown	7	25,0	AS9	AS9	Finished		1,0000	1,0000	1,0000		07	
14	seq.	Unknown	8	25,0	AS9	AS9	Finished		1,0000	1,0000	1,0000		08	

- Todo lo que se ve en la pantalla de abajo lo dejaremos igual.



b. En la pestaña *Detection*:
   - Introducimos los parámetros necesarios para que la integración se haga correctamente.
   - Doble clic en alguna línea de *Param Name.*
   - Seleccionamos la más adecuada para nuestras necesidades i clicamos OK
   - Con el botón *Explain Param*. tenemos la explicación de qué hace el parámetro.
   - Podemos poner tantos parámetros como queramos.

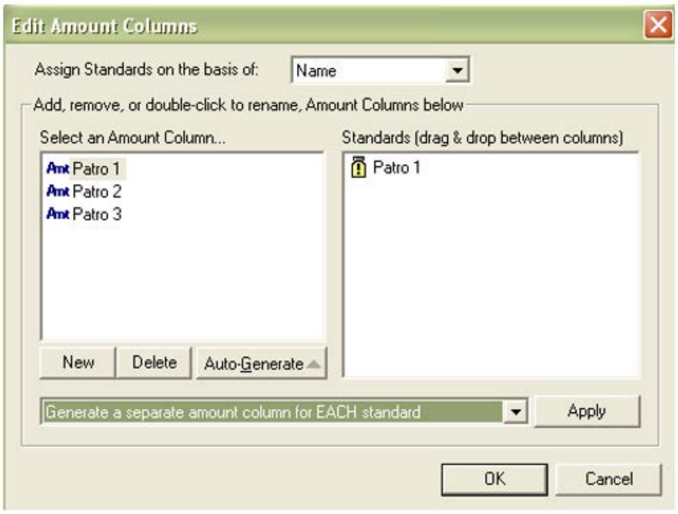
No.	Ret. Time [min]	Param. Name	Param. Value	Channel
1	0,000	Minimum Area	0,2 "[Signal]*min"	All Channels
2	0,000	Inhibit Integration	On	All Channels
3	0,000	Valley to Valley	On	All Channels
4	4,500	Inhibit Integration	Off	All Channels



c. En la pestaña *Peak Table*:
- ○ *Peak Name* introducimos el nombre de nuestros elementos manualmente
- ○ *Ret.Time* doble clic, en la pantalla que sale seleccionamos *Absolute Time.*
- ○ *Standard* doble clic y seleccionamos *External*.
- ○ *Int.Type,* doble clic y seleccionamos *Area*.
- ○ *Cal.Type,* doble clic y seleccionamos *Linear* y *No Weights*.
- ○ *Peak Type,* doble clic y seleccionamos *Autodetected.*

No.	Peak Name	Ret.Time	Window	Standard	Int.Type	Cal.Type	Peak Type	Group	Comment
1	Clorur	7,160 min	5,000 RG	External	Area	LOff	Auto		Autogenerated
2	Nitrit	9,157 min	5,000 RG	External	Area	LOff	Auto		Autogenerated
3	Nitrat	14,653 min	5,000 RG	External	Area	LOff	Auto		Autogenerated
4	Fosfat	19,458 min	5,000 RG	External	Area	LOff	Auto		Autogenerated
5	Sulfat	21,546 min	5,000 RG	External	Area	LOff	Auto		Autogenerated

d. En la pestaña Amount table:
- ○ Vamos a *EDIT → COLUMNS → EDIT AMOUNT COLUMNS*
- ○ Saldrá una ventana nueva
- ○ Clicamos en *Auto-Generate*
- ○ Clicamos en *Apply*
- ○ En el mensaje que sale le damos a **Sí.**
- ○ En las columnas que hemos generado introducimos manualmente la concentración de cada patrón **para cada elemento**. Si por ejemplo tenemos un elemento con otra concentración dentro del patrón, lo cambiamos. (en nuestro ejemplo todos tienen igual concentración).



e. En la pestaña *Peak tracking:*

- Lo dejamos todo igual que en la imagen.

No.	Peak Name	Ret.Time	Window	Reference Spectrum	Match Crit.	Check Deriv.	Min. WL	Max. WL	Threshold	Rel. Max. Dev.	Check Extr.	Comment
1	Clorur	7,160 min	5,000 RG		Least Square	Off	Auto	Auto	950	Off	Off	Autogenera
2	Nitrit	9,157 min	5,000 RG		Least Square	Off	Auto	Auto	950	Off	Off	Autogenera
3	Nitrat	14,653 min	5,000 RG		Least Square	Off	Auto	Auto	950	Off	Off	Autogenera
4	Fosfat	19,458 min	5,000 RG		Least Square	Off	Auto	Auto	950	Off	Off	Autogenera
5	Sulfat	21,546 min	5,000 RG		Least Square	Off	Auto	Auto	950	Off	Off	Autogenera

f. En la pestaña *Calibration*:

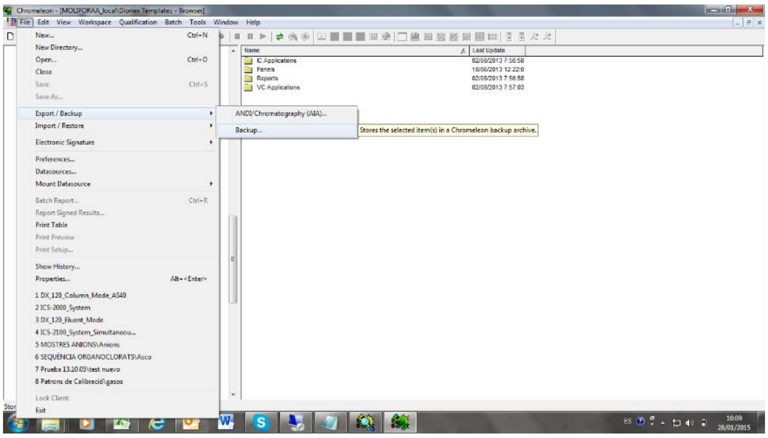
- Nos ponemos encima de la línea, clicamos con el botón derecho.
- Seleccionamos Append Standard.
- Buscamos nuestros patrones uno a uno y los añadimos

g. Finalmente, guardamos nuestro Calibrado

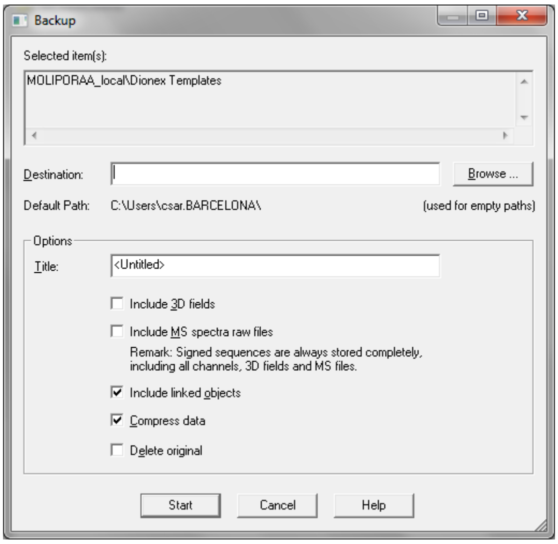
10.4. Backups

<u>Backups Chromeleon 6.8</u>

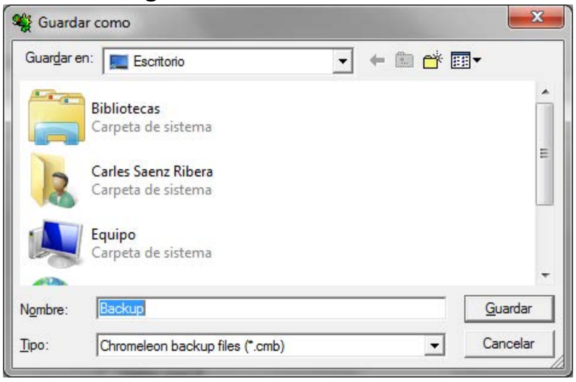
1) File -> Export/Backup -> Backup…



2) Aparece la siguiente ventana:

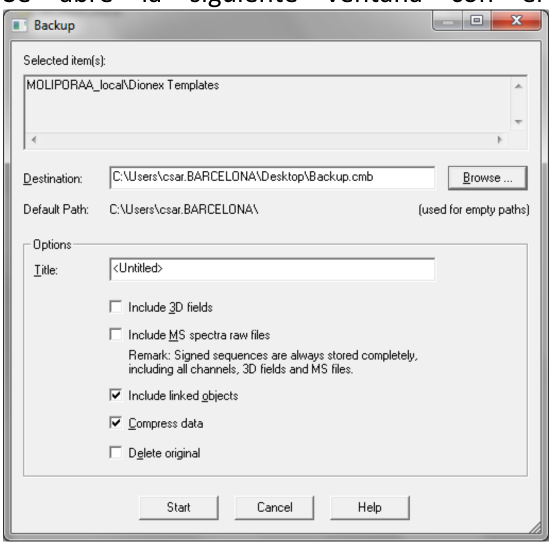


3) En el campo Destination elegir el destino donde queremos guardar el backup. Lo hacemos a través del botón Browse (explorador de las carpetas de windows). Se abre la siguiente ventana donde ubicaremos el archivo de nuestro backup:

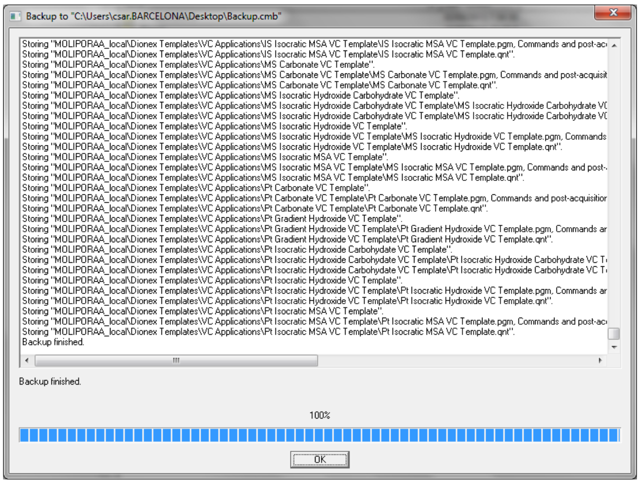


En el campo Nombre escribir el nombre que queremos dar a nuestro archivo de backup y seleccionar el botón Guardar.

4) Se abre la siguiente ventana con el campo Destination completo:



5) Nos aseguramos que en Options esté seleccionado solamente los campos ‘Include linked objects’ y ‘Compress data’. Ahora ya podemos clicar Start para empezar el backup. Empezará a guardar los datos y saldrá una barra de información con el porcentaje de datos guardados, cuanto termine saldrá el mensaje Backup finished:



Pulsar OK y listo, se habrá generado un único archivo con extensión .cmb con los datos comprimidos de nuestro backup.

Para restaurarlo solo habrá que hacer doble-click y elegir el destino.

11. RESIDUOS

Los residuos generados en el funcionamiento del cromatógrafo son los siguientes:

- Eluyente recogido en el recipiente de residuo
- Eluyente sobrante no utilizado
- Soluciones madre obsoletas
- Sobra de muestras y muestras no utilizadas

Estos residuos tienen un riesgo mínimo y pueden desecharse sin problema por el desagüe. No obstante, dado que los dos eluyentes con los que se trabaja son ácidos y básicos se depositarán todos los residuos en un bidón (laboratorio de inorgánica) con tal de neutralizarlos y diluirlos todavía más. Esto reducirá todavía más el mínimo impacto que estos residuos puedan tener en el medio ambiente.

12. CONSIDERACIONES FINALES

12.1. Puntos importantes

- Las burbujas de aire y las partículas pueden dañar el cromatógrafo. Es importante que el eluyente esté siempre filtrado (0,22 µm) y desgasificado, que las muestras estén siempre filtradas y que el agua usada tanto para preparar eluyente como muestras sea MilliQ.

- Para lavar los instrumentos de laboratorio utilizados para las preparaciones así como cualquier parte del cromatógrafo nunca se usará jabón. Se lavará primero con abundante agua (del grifo), después con agua destilada y finalmente con agua MilliQ.
- No debe dejarse el cromatógrafo montado y parado más de 5 días, ya que hay riesgo de precipitaciones y obturaciones. La mejor opción es hacer circular eluyente lo más a menudo posible y, en caso de que no haya que usarlo en varios días, desmontarlo y dejarlo guardado.
- Aniones y cationes deben separarse. Es importante no mezclar componentes de uno y otro en ningún momento y, sobretodo, no aplicar el eluyente equivocado.
- Siempre que inyectemos agua MilliQ o muestra en el cromatógrafo (supresora, celda o válvula de inyección) deberá hacerse con una jeringa de 1 mL para evitar sobrepresiones que dañen el aparato.
- Las posiciones del autosampler del 45 al 50 (incluidos) están destinadas a viales con agua MilliQ para hacer rinse. Es importante no poner muestras en estas posiciones.
- Supresora y columnas deben llevar tape (o conexión estando montadas), ya que si se dejan demasiado tiempo con la conexión libre pueden secarse.
- Para asegurar que no entra aire, es importante realizar una purga básica cuando se ha rellenado la botella de eluyente (o levantado el tubo) y completa cuando se ha montado el cromatógrafo.
- Para asegurar que la muestra que se pasa por el autosampler llene debidamente el Loop, se debe programar para dosificar, como mínimo, 400 µL.
- Hay que estar pendiente de vaciar cuando esté lleno el recipiente de residuo con tal que no se desborde.

12.2. Resolución de problemas

- Cromatógrafo se para por exceso de presión: Es importante para el cromatógrafo tan pronto como detectemos que la presión está llegando a niveles altos, ya que si lo forzamos pueden romperse las membranas de la supresora. Si se continúa poniendo en marcha el cromatógrafo, probablemente se generará alguna fuga, y si persiste saltará la alarma por detección de agua en la bandeja del cromatógrafo.

    - Obturación de la celda de conductividad: Este tipo de obturación lo detectaremos si intentamos inyectar agua en CELL IN con una jeringa de 1 mL y no pasa agua haciendo una presión normal. La causa de esta obturación es no haber circulado suficiente agua MilliQ al cambiar de aniones o cationes o viceversa. La mezcla de eluyentes genera precipitación. La solución es hacer circular agua MilliQ de CELL OUT a CELL IN, conectando el tubo que sale de la válvula de inyección a CELL OUT (habiéndolo desconectado de la Pre columna.

    - Obturación de la supresora: La obturación de la supresora se detecta al observar sobrepresión o al no pasar el agua MilliQ cuando se hidrata aplicando una presión prudente con una jeringa de 1 mL. La causa es haber dejado demasiado tiempo la supresora montada sin circular eluyente. Se debe inyectar 5 mL de agua MilliQ con una jeringa de 1 mL por cada uno de las entradas/salida de la supresora. En caso de no pasar el agua aplicando una presión prudente, no forzar (se pueden romper las membranas), avisar a la empresa suministradora.

- Se ha dejado pasando la secuencia y aparece sin pasar: Para averiguar la causa de la interrupción, en primer lugar habrá que mirar los últimos comandos en la pantalla de comandos del monitor. Las causas más comunes son las siguientes:
    - Se ha acabado el eluyente o no se ha actualizado manualmente el nivel de eluyente en el monitor.
    - No se ha introducido bien el batch o no se han configurado bien las secuencias. Revisar el batch y el estado (*single/finished/interrupted*) de las muestras
    - Ha saltado algún tipo de alarma (como la de detección de agua en la bandeja del cromatógrafo). Detectar el problema y resolverlo antes de volver a pasar otra muestra.
    - No hay archivo .qnt en la secuencia, de forma que aunque se hayan pasado las muestras, aparecerán vacías. No hay que volverlas a pasar, cuando se copie el archivo QNT aparecerán los resultados.
- No se estabiliza la línea base: La causa más probable de que no se estabilice la línea base es una preparación incorrecta del eluyente (concentración superior o inferior a la debida). Volver a preparar eluyente revisando el procedimiento y los cálculos.

Appendix II Supplementary material for Chapter 3

Appendix II.I Inventory of the materials and energy per m of network considered for the comparison of the pipes.

Table A II-1 Inventory of the materials and energy per m of network considered for the comparison of the pipes.

	ecoinvent 2.2 process			Unit per lineal m						
	Material	Processing	Energy requirements (MJ/kg)	HDPE (90 mm)	LDPE (90 mm)	PVC (90 mm)	HDPE (200 mm)	PVC (200 mm)	DI (200 mm)	GFRP (200 mm)
Pressure (bar)	-	-		6	6	6	10	10	10	10
Connections	-	-		W	BP	ER	W	ER	BU-ER	PS
Weight (kg)	-	-		1.0	2.1	1.0	4.7	4.0	36.0	11.4
Life expectancy (years)	-	-		50	50	50	50	50	50	50
HDPE[1] (kg)	Polyethylene, HDPE, granulate, at plant/RER S	Extrusion, plastic pipes/RER S[2] Injection moulding/RER S[3]	85	1.52	0	0	5.50	0	0	0
LDPE[1] (kg)	Polyethylene, LDPE, granulate, at plant/RER S	Extrusion, plastic pipes/RER S[2] Injection moulding/RER S[3]	88	0	2.63	0	0	0	0	0
PVC[1] (kg)	Polyvinylchloride, at regional storage/RER S	Extrusion, plastic pipes/RER S[2] Injection moulding/RER S[3]	69	0	0	1.34	0	4.76	0	0
DI[1] (kg)	Cast iron, at plant/RER S	Metal product manufacturing, average metal working/RER S	58	0	0	0	0	0	38.8	0

GFRP (kg)	Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER S	Injection moulding/RER S	111	0	0	0	0	0	0	4.96
Synthetic rubber (kg)	Synthetic rubber, at plant/RER S		91	0.0147	0.0072	0.121	0.0696	0.101	0.245	0.0105
Sand (kg)	Sand, at mine/CH S		0.058	1,530	1,530	1,530	1,590	1,590	1,590	1,590
Gravel (kg)	Gravel, round, at mine/CH S		0.058	148	148	148	163	163	163	163
Diesel, machinery (MJ)	Diesel, burned in building machine/GLO S		1.4*	92.0	92.0	92.0	99.2	99.2	99.2	99.2
Transport van (tkm)	Transport, van <3.5t/RER S		33**	0.152	0.263	0.135	0.550	0.487	3.91	0.497
Transport lorry (tkm)	Transport, lorry 16-32t, EURO5/RER S		2.8**	50.5	50.5	50.5	52.5	52.5	52.5	52.5

**MJ/MJ diesel, **MJ/tkm, [1]Includes the pipe and its accessories made of the same material, [2]pipe, [3]accessories, HDPE=high density polyethylene, LDPE=low density polyethylene, PVC=poly vinyl chloride, DI=ductile iron, GFRP=glass fibre reinforced polyester, W=Welded, BP=By pressure, ER= Elastomeric ring, BU=Bell union, PS= Polyester sleeve. Source: Metabase Itec, 2010*

Appendix II.II Inventory of the materials and energy considered for hydrants, pumps and shut-off valves.

Table A II-2 Inventory of the materials and energy considered for hydrants, pumps and shut-off valves.

	ecoinvent 2.2 process			kg per unit				
	Material	**Processing**	**Energy requirements (MJ/kg)**	**Hydrant, 100 mm**	**Pump, 35 m^3/h**	**Pump, 60 m^3/h**	**Shut-off valve, 50 mm**	**Shut-off valve, 100 mm**
Steel	Steel, low-alloyed, at plant/RER S	Metal product manufacturing, average metal working/RER S	61	-	3.5	16.5	1.9	4.5
Cast Iron	Cast iron, at plant/RER S	Metal product manufacturing, average metal working/RER S	58	168	31.5	148.5	10.5	25.2
Galvanised steel	Steel, low-alloyed, at plant/RER S	Metal product manufacturing, average metal working/RER S	61	0.2	-	-	-	-
Epoxy resin	Epoxy resin, liquid, at plant/RER S	-	135	0.3	-	-	-	-
Synthetic rubber	Synthetic rubber, at plant/RER S	-	91	-	-	-	0.13	0.3

Source: Metabase Itec, 2010

Appendix III Supplementary material for Chapter 4

Appendix III.I Data of the municipalities considered in the statistical study

Table A III-1 General data of the municipalities considered for the statistical study.

Cases	Inhabitants supply	Density (inhabitants/ km^2)	Seasonality	Location	Climate
A	330	13	1.21	Inland	Mediterranean
B	799	35	1.06	Inland	Mediterranean
C	1,182	68	1.90	Inland	Mediterranean
D	1,507	13	1.00	Inland	Mediterranean
E	594	15	3.37	Inland	Mediterranean
F	1,105	2	1.36	Inland	Mediterranean
G	1357	4	1.33	Inland	Mediterranean
H	1,807	27	1.03	Inland	Oceanic
I	718	8	1.00	Inland	Mediterranean
J	2,146	258	1.00	Inland	Mediterranean
K	2,236	81	1.21	Inland	Mediterranean
L	2181	6	1.28	Inland	Mediterranean
M	2,501	257	1.00	Inland	Mediterranean
N	1724	183	1.19	Inland	Mediterranean
O	1,489	92	2.01	Inland	Mediterranean
P	1,608	4	1.09	Inland	Mediterranean
Q	1,970	20	1.24	Inland	Mediterranean
R	1911	175	1.83	Inland	Mediterranean
S	2316	5	1.38	Inland	Mediterranean
T	720	5	1.53	Cost	Mediterranean
U	2500	19	1.18	Inland	Mediterranean
V	5777	43	1.21	Inland	Mediterranean
W	5,949	88	1.00	Inland	Oceanic
X	7404	58	1.08	Inland	Mediterranean
Y	4,818	72	1.45	Inland	Mediterranean
Z	6,929	39	1.12	Inland	Mediterranean
AA	5941	58	1.68	Cost	Mediterranean
AB	7,407	125	1.35	Inland	Mediterranean
AC	10,601	225	1.23	Cost	Mediterranean
AD	9,918	13	1.11	Inland	Mediterranean
AE	10,000	69	1.90	Inland	Mediterranean

AF	3,500	43	2.00	Cost	Oceanic
AG	10,541	92	1.04	Inland	Mediterranean
AH	13314	135	1.00	Inland	Mediterranean
AI	13,537	560	0.00	Inland	Oceanic
AJ	16,432	348	1.00	Inland	Mediterranean
AK	20,728	2.052	1.00	Inland	Mediterranean
AL	23,683	379	1.06	Inland	Mediterranean
AM	24,373	271	1.00	Cost	Mediterranean
AN	21708	656	1.15	Inland	Mediterranean
AO	19,061	422	1.31	Inland	Mediterranean
AP	26,553	555	1.21	Cost	Mediterranean
AQ	33589	1155	1.12	Inland	Mediterranean
AR	21094	367	1.35	Inland	Mediterranean
AS	16,738	1.909	1.79	Inland	Mediterranean
AT	42,560	121	1.00	Inland	Mediterranean
AU	32733	200	2.43	Cost	Mediterranean
AV	24,984	1.238	1.10	Cost	Mediterranean
AW	23,406	435	5.34	Cost	Mediterranean
AX	29,698	847	5.05	Cost	Mediterranean

Table A III-2 Data on the water supply network for the municipalities considered in the statistical study.

Cases	Length of the transport network (km)	Length of the distribution network (km)	Electricity consumption (kWh)	Water registered (m^3)	Water supplied (m^3)	Gross income per capita (€)
A	5	7	3,680	17,155	25689	ND
B	0	11	3,134	45,735	97,973	15,500
C	0	11	9,498	50,642	76,483	12,219
D	1	9	12,911	58,888	120,391	15,600
E	1.4	6	14,351	61270	151066	ND
F	2	16	4,746	65,884	74,327	10,112
G	18	20.5	46,083	68914	119200	ND
H	19	65	21,836	77,932	112,800	12,017
I	1	17	21,777	84741	150200	5,823
J	3	20	11,274	99,730	154,511	14,400
K	4	23	92,800	101,197	215,987	8,915
L	16	14.9	41,071	121089	174299	11,099
M	4	9	1,885	129,313	219,996	12,747
N	3.1	25.2	6,385	143178	218275	10,198
O	10	21	66,322	144,175	297,322	14,981
P	15	16	7,111	144,756	221,583	ND
Q	1	9	35,240	154,196	284,818	14,500
R	0.7	15	14,702	154674	193929	17,300
S	4	180	8805	165421	435753	14,777
T	18	16	2,247	176,696	295186	18,795
U	1	13.8	61959	186258	316297	9,705
V	3	91	271,469	313202	466591	13,923
W	17	55	15,430	318,494	484,298	17,000
X	18.6	53.4	102	382538	902224	12,913
Y	9	92	62,280	442,506	571,709	16,300
Z	7	42	55,240	446,767	674,535	ND
AA	8	78	40,932	459595	1088442	ND
AB	13	125	13,724	503,460	688,575	6,059
AC	3	40	180	566,618	1,464,059	11,811
AD	30	36	216,119	615,445	958,010	10,185
AE	12	27	1,773,732	617,168	1,183,044	10,971
AF	20	175	51,096	704,427	1,038,757	10,600
AG	5	135	37,998	720,531	940,436	13,728
AH	23.5	85.9	7,601	838427	1503793	ND

AI	5	119	28,555	847,705	1,492,010	12,500
AJ	5	79	168,056	945,857	1,418,692	11,910
AK	2	65	241,086	950,446	1,354,481	8,187
AL	12	166	31,221	1,213,436	1,908,740	ND
AM	19	95	237,937	1,249,001	2,500,900	11,488
AN	7.6	143.6	79,955	1309506	1973056	11,470
AO	13	104	25,242	1,340,187	1,892,982	12,325
AP	0	55	122,473	1,631,940	2,858,630	ND
AQ	3.1	185.9	892,949	1737957	3428909	8,343
AR	6.9	206	16,532	1991875	3009780	9,193
AS	9	129	58,600	2,047,675	3,685,871	11,280
AT	6	183	11,860	2,057,525	2,971,459	13,220
AU	6	151.7	57,952	2167782	2682916	13,700
AV	0	148	115,740	2,246,188	3,610,100	15,600
AW	13	172	303,568	2,545,205	3,892,161	4,813
AX	6	148	551,179	2,901,512	3,943,436	ND

Appendix IV Supplementary material for Chapter 5

Appendix IV.I Inventory of concrete and reinforcing steel for each case examined.

Table A IV-1 Quantity of concrete and reinforcing steel required for the construction of partially buried cases assessed.

	Unit	CP1002	CP1003	CP1004	CP1005	CP1006	CP1007	CP1008	CP5002	CP5003	CP5004
Concrete	m^3	45	39	40	37	38	43	38	187	148	129
Reinforcing steel	kg	11,896	8,198	6,806	5,253	4,626	4,117	3,725	59,899	41,657	31,491

	Unit	CP5005	CP5006	CP5007	CP5008	CP10002	CP10003	CP10004	CP10005	CP10006	CP10007
Concrete	m^3	115	110	107	106	368	267	221	196	191	185
Reinforcing steel	kg	24,384	20,660	18,101	16,424	125,037	81,563	60,045	47,848	42,365	37,571

	Unit	CP10008	CP25002	CP25003	CP25004	CP25005	CP25006	CP25007	CP25008	CP50002	CP50003
Concrete	m^3	178	829	606	506	441	407	373	339	1,638	1,174
Reinforcing steel	kg	33,293	295,966	201,283	155,694	125,526	112,683	99,349	85,434	626,745	408,396

	Unit	CP50004	CP50005	CP50006	CP50007	CP50008	CP75002	CP75003	CP75004	CP75005	CP75006
Concrete	m^3	905	780	700	657	615	2,441	1,692	1,316	1,120	980
Reinforcing steel	kg	296,127	256,293	230,969	217,458	200,938	1,068,255	600,350	446,680	400,480	358,965

	Unit	CP75007	CP75008	CP100002	CP100003	CP100004	CP100005	CP100006	CP100007	CP100008
Concrete	m^3	889	841	3,167	2,239	1,746	1,466	1,307	1,155	1,056
Reinforcing steel	kg	328,672	313,606	1,635,106	820,777	614,685	556,282	520,592	468,804	432,388

Cylindrical (C); Position: superficial (S), buried (B), partially-buried (P); Volume: capacity in cubic meters (100, 500, 1000, etc.); Height: in m and rounded to the lower unit (for example, 2 for 2.5 m of 3 for 3.5 m); Ex: "CS10006" - superficial cylindrical tank with 1,000 m^3 capacity and 6.5 m in height.

Table A IV-2 Quantity of concrete and reinforcing steel required for the construction of superficially placed cases assessed.

	Unit	CS1002	CS1003	CS1004	CS1005	CS1006	CS1007	CS1008	CS5002	CS5003	CS5004
Concrete	m^3	45	39	40	37	38	43	38	187	148	129
Reinforcing steel	kg	11,896	8,198	6,806	5,253	4,626	4,117	3,725	59,899	41,657	31,491

	Unit	CS5005	CS5006	CS5007	CS5008	CS10002	CS10003	CS10004	CS10005	CS10006	CS10007
Concrete	m^3	115	110	107	106	368	267	221	196	191	185
Reinforcing steel	kg	24,384	20,660	18,101	16,424	125,037	81,563	60,045	47,848	42,365	37,571

	Unit	CS10008	CS25002	CS25003	CS25004	CS25005	CS25006	CS25007	CS25008	CS50002	CS50003
Concrete	m^3	178	829	606	506	441	407	373	339	1,638	1,174
Reinforcing steel	kg	33,293	311,389	201,283	155,694	125,526	112,683	99,349	85,434	767,539	461,346

	Unit	CS50004	CS50005	CS50006	CS50007	CS50008	CS75002	CS75003	CS75004	CS75005	CS75006
Concrete	m^3	905	780	700	657	615	2,441	1,692	1,316	1,120	980
Reinforcing steel	kg	308,297	256,293	230,969	217,458	200,938	1,416,384	762,779	512,364	429,506	367,881

	Unit	CS75007	CS75008	CS100002	CS100003	CS100004	CS100005	CS100006	CS100007	CS100008
Concrete	m^3	889	841	3,167	2,239	1,746	1,466	1,307	1,155	1,056
Reinforcing steel	kg	328,672	313,606	2,175,148	1,178,438	772,306	636,168	565,613	488,493	438,050

Cylindrical (C); Position: superficial (S), buried (B), partially-buried (P); Volume: capacity in cubic meters (100, 500, 1000, etc.); Height: in m and rounded to the lower unit (for example, 2 for 2.5 m of 3 for 3.5 m); Ex: "CS10006" - superficial cylindrical tank with 1,000 m^3 capacity and 6.5 m in height.

Table A IV-3 Quantity of concrete and reinforcing steel required for the construction of buried cases assessed.

	Unit	CB1002	CB1003	CB1004	CB1005	CB1006	CB1007	CB1008	CB5002	CB5003	CB5004
Concrete	m^3	45	39	40	37	38	43	38	187	148	129
Reinforcing steel	kg	11,896	8,198	6,806	5,253	4,626	4,117	3,725	59,899	41,657	31,491

	Unit	CB5005	CB5006	CB5007	CB5008	CB10002	CB10003	CB10004	CB10005	CB10006	CB10007
Concrete	m^3	115	110	107	106	368	267	221	196	191	185
Reinforcing steel	kg	24,384	20,660	18,101	16,424	125,037	81,563	60,045	47,848	42,365	37,571

	Unit	CB10008	CB25002	CB25003	CB25004	CB25005	CB25006	CB25007	CB25008	CB50002	CB50003
Concrete	m^3	178	829	606	506	441	407	373	339	1,638	1,174
Reinforcing steel	kg	33,293	295,966	201,283	155,694	125,526	112,683	99,416	87,061	600,303	408,396

	Unit	CB50004	CB50005	CB50006	CB50007	CB50008	CB75002	CB75003	CB75004	CB75005	CB75006
Concrete	m^3	905	780	700	657	615	2,441	1,692	1,316	1,120	980
Reinforcing steel	kg	296,127	256,293	238,922	233,427	221,554	905,050	600,350	446,680	408,299	385,112

	Unit	CB75007	CB75008	CB100002	CB100003	CB100004	CB100005	CB100006	CB100007	CB100008
Concrete	m^3	889	841	3,167	2,239	1,746	1,466	1,307	1,155	1,056
Reinforcing steel	kg	365,675	359,679	1,331,227	804,872	614,685	580,401	576,656	543,024	518,900

Cylindrical (C); Position: superficial (S), buried (B), partially-buried (P); Volume: capacity in cubic meters (100, 500, 1000, etc.); Height: in m and rounded to the lower unit (for example, 2 for 2.5 m of 3 for 3.5 m); Ex: "CS10006" - superficial cylindrical tank with 1,000 m^3 capacity and 6.5 m in height.

Appendix IV.II Absolute environmental impacts of the water tanks assessed

Table A IV-4 Absolute environmental impacts of the construction of storage water tanks partially buried assessed.

Impact category	Units	CP1002	CP1003	CP1004	CP1005	CP1006	CP1007	CP1008	CP5002	CP5003	CP5004
ADP	kg Sb eq	2.02E+02	1.50E+02	1.34E+02	1.11E+02	1.04E+02	1.02E+02	9.09E+01	9.62E+02	7.05E+02	5.62E+02
AP	kg SO_2 eq	1.14E+02	8.95E+01	8.37E+01	7.21E+01	6.93E+01	7.05E+01	6.29E+01	5.14E+02	3.96E+02	3.29E+02
EP	kg PO_4--- eq	4.98E+01	3.69E+01	3.28E+01	2.71E+01	2.52E+01	2.45E+01	2.19E+01	2.37E+02	1.74E+02	1.38E+02
GWP	kg CO_2 eq	3.31E+04	2.58E+04	2.41E+04	2.08E+04	2.01E+04	2.09E+04	1.86E+04	1.51E+05	1.14E+05	9.32E+04
ODP	kg CFC-11 eq	1.53E-03	1.23E-03	1.17E-03	1.02E-03	9.86E-04	1.01E-03	9.04E-04	6.85E-03	5.33E-03	4.49E-03
PHOP	kg C_2H_4 eq	1.12E+01	8.02E+00	6.93E+00	5.56E+00	5.07E+00	4.78E+00	4.30E+00	5.46E+01	3.90E+01	3.03E+01
CED	MJ	3.99E+05	3.01E+05	2.72E+05	2.28E+05	2.15E+05	2.13E+05	1.91E+05	1.88E+06	1.39E+06	1.12E+06

Impact category	Units	CP5005	CP5006	CP5007	CP5008	CP10002	CP10003	CP10004	CP10005	CP10006	CP10007
ADP	kg Sb eq	4.59E+02	4.07E+02	3.72E+02	3.50E+02	1.98E+03	1.35E+03	1.05E+03	8.71E+02	8.04E+02	7.41E+02
AP	kg SO_2 eq	2.80E+02	2.56E+02	2.40E+02	2.30E+02	1.04E+03	7.49E+02	6.03E+02	5.21E+02	4.96E+02	4.68E+02
EP	kg PO_4--- eq	1.13E+02	1.00E+02	9.14E+01	8.58E+01	4.89E+02	3.34E+02	2.58E+02	2.15E+02	1.99E+02	1.83E+02
GWP	kg CO_2 eq	7.83E+04	7.13E+04	6.66E+04	6.38E+04	3.07E+05	2.15E+05	1.70E+05	1.44E+05	1.36E+05	1.27E+05
ODP	kg CFC-11 eq	3.85E-03	3.56E-03	3.36E-03	3.24E-03	1.38E-02	1.00E-02	8.18E-03	7.13E-03	6.83E-03	6.50E-03
PHOP	kg C_2H_4 eq	2.42E+01	2.10E+01	1.89E+01	1.75E+01	1.13E+02	7.56E+01	5.71E+01	4.66E+01	4.22E+01	3.83E+01
CED	MJ	9.22E+05	8.25E+05	7.59E+05	7.18E+05	3.85E+06	2.66E+06	2.07E+06	1.74E+06	1.62E+06	1.50E+06

Impact category	Units	CP10008	CP25002	CP25003	CP25004	CP25005	CP25006	CP25007	CP25008	CP50002	CP50003
ADP	kg Sb eq	6.79E+02	4.63E+03	3.28E+03	2.64E+03	2.22E+03	2.04E+03	1.84E+03	1.62E+03	9.67E+03	6.59E+03
AP	kg SO_2 eq	4.39E+02	2.42E+03	1.79E+03	1.50E+03	1.30E+03	1.22E+03	1.12E+03	1.01E+03	4.98E+03	3.57E+03
EP	kg PO_4--- eq	1.68E+02	1.14E+03	8.12E+02	6.54E+02	5.49E+02	5.05E+02	4.56E+02	4.02E+02	2.39E+03	1.63E+03
GWP	kg CO_2 eq	1.19E+05	7.12E+05	5.12E+05	4.18E+05	3.55E+05	3.28E+05	2.98E+05	2.65E+05	1.47E+06	1.02E+06
ODP	kg CFC-11 eq	6.12E-03	3.19E-02	2.39E-02	2.02E-02	1.76E-02	1.66E-02	1.53E-02	1.38E-02	6.54E-02	4.75E-02
PHOP	kg C_2H_4 eq	3.46E+01	2.66E+02	1.85E+02	1.46E+02	1.20E+02	1.09E+02	9.76E+01	8.51E+01	5.60E+02	3.73E+02
CED	MJ	1.38E+06	8.98E+06	6.41E+06	5.20E+06	4.39E+06	4.05E+06	3.67E+06	3.25E+06	1.87E+07	1.29E+07

Impact category	Units	CP50004	CP50005	CP50006	CP50007	CP50008	CP75002	CP75003	CP75004	CP75005	CP75006
ADP	kg Sb eq	4.97E+03	4.38E+03	4.01E+03	3.83E+03	3.59E+03	1.61E+04	9.66E+03	7.44E+03	6.73E+03	6.10E+03
AP	kg SO_2 eq	2.79E+03	2.51E+03	2.34E+03	2.26E+03	2.15E+03	8.12E+03	5.21E+03	4.16E+03	3.80E+03	3.49E+03
EP	kg PO_4--- eq	1.23E+03	1.09E+03	9.97E+02	9.53E+02	8.94E+02	3.99E+03	2.39E+03	1.85E+03	1.67E+03	1.52E+03
GWP	kg CO_2 eq	7.76E+05	6.84E+05	6.25E+05	5.96E+05	5.60E+05	2.38E+06	1.49E+06	1.15E+06	1.03E+06	9.32E+05
ODP	kg CFC-11 eq	3.75E-02	3.39E-02	3.16E-02	3.06E-02	2.91E-02	1.06E-01	6.92E-02	5.57E-02	5.10E-02	4.69E-02
PHOP	kg C_2H_4 eq	2.76E+02	2.41E+02	2.19E+02	2.08E+02	1.94E+02	9.43E+02	5.48E+02	4.15E+02	3.74E+02	3.37E+02
CED	MJ	9.75E+06	8.63E+06	7.92E+06	7.57E+06	7.12E+06	3.09E+07	1.88E+07	1.46E+07	1.32E+07	1.20E+07

Impact category	Units	CP75007	CP75008	CP100002	CP100003	CP100004	CP100005	CP100006	CP100007	CP100008
ADP	kg Sb eq	5.65E+03	5.44E+03	2.40E+04	1.31E+04	1.02E+04	9.23E+03	8.69E+03	7.90E+03	7.36E+03
AP	kg SO_2 eq	3.28E+03	3.19E+03	1.18E+04	7.03E+03	5.65E+03	5.17E+03	4.91E+03	4.52E+03	4.25E+03
EP	kg PO_4--- eq	1.41E+03	1.36E+03	5.97E+03	3.25E+03	2.52E+03	2.30E+03	2.17E+03	1.97E+03	1.84E+03
GWP	kg CO_2 eq	8.62E+05	8.30E+05	3.46E+06	2.01E+06	1.57E+06	1.40E+06	1.31E+06	1.19E+06	1.10E+06
ODP	kg CFC-11 eq	4.41E-02	4.30E-02	1.53E-01	9.33E-02	7.55E-02	6.91E-02	6.57E-02	6.05E-02	5.71E-02
PHOP	kg C_2H_4 eq	3.11E+02	2.98E+02	1.43E+03	7.46E+02	5.69E+02	5.16E+02	4.84E+02	4.38E+02	4.07E+02
CED	MJ	1.11E+07	1.07E+07	4.59E+07	2.55E+07	1.99E+07	1.81E+07	1.70E+07	1.55E+07	1.45E+07

ADP=Abiotic depletion potential, AP=Acidification potential, EP=Eutrophication potential, GWP=Global warming potential, ODP=Ozone layer depletion potential, PHOP=Photochemical oxidation potential, CED=Cumulative energy demand

Cylindrical (C); Position: superficial (S), buried (B), partially-buried (P); Volume: capacity in cubic meters (100, 500, 1000, etc.); Height: in m and rounded to the lower unit (for example, 2 for 2.5 m of 3 for 3.5 m); Ex: "CS10006" - superficial cylindrical tank with 1,000 m^3 capacity and 6.5 m in height.

Table A IV-5 Absolute environmental impacts of the construction of storage water tanks superficially placed assessed.

Impact category	Units	CS1002	CS1003	CS1004	CS1005	CS1006	CS1007	CS1008	CS5002	CS5003	CS5004
ADP	kg Sb eq	1.86E+02	1.35E+02	1.19E+02	9.70E+01	8.98E+01	8.66E+01	7.80E+01	9.11E+02	6.55E+02	5.13E+02
AP	kg SO_2 eq	9.49E+01	7.21E+01	6.60E+01	5.57E+01	5.31E+01	5.32E+01	4.79E+01	4.55E+02	3.38E+02	2.73E+02
EP	kg PO_4--- eq	4.55E+01	3.29E+01	2.87E+01	2.33E+01	2.15E+01	2.05E+01	1.85E+01	2.24E+02	1.60E+02	1.25E+02
GWP	kg CO_2 eq	3.06E+04	2.35E+04	2.18E+04	1.87E+04	1.80E+04	1.86E+04	1.66E+04	1.43E+05	1.06E+05	8.59E+04
ODP	kg CFC-11 eq	1.26E-03	9.74E-04	9.06E-04	7.75E-04	7.47E-04	7.61E-04	6.84E-04	5.97E-03	4.48E-03	3.67E-03
PHOP	kg C_2H_4 eq	1.07E+01	7.57E+00	6.47E+00	5.14E+00	4.66E+00	4.34E+00	3.91E+00	5.31E+01	3.75E+01	2.89E+01
CED	MJ	3.62E+05	2.67E+05	2.38E+05	1.96E+05	1.83E+05	1.79E+05	1.61E+05	1.76E+06	1.28E+06	1.01E+06

Impact category	Units	CS5005	CS5006	CS5007	CS5008	CS10002	CS10003	CS10004	CS10005	CS10006	CS10007
ADP	kg Sb eq	4.13E+02	3.62E+02	3.28E+02	3.06E+02	1.89E+03	1.27E+03	9.63E+02	7.91E+02	7.21E+02	6.57E+02
AP	kg SO_2 eq	2.27E+02	2.04E+02	1.89E+02	1.79E+02	9.37E+02	6.48E+02	5.07E+02	4.28E+02	3.99E+02	3.72E+02
EP	kg PO_4--- eq	1.01E+02	8.81E+01	7.95E+01	7.40E+01	4.64E+02	3.11E+02	2.36E+02	1.94E+02	1.76E+02	1.60E+02
GWP	kg CO_2 eq	7.14E+04	6.45E+04	5.99E+04	5.72E+04	2.93E+05	2.01E+05	1.57E+05	1.32E+05	1.23E+05	1.14E+05
ODP	kg CFC-11 eq	3.07E-03	2.79E-03	2.60E-03	2.49E-03	1.23E-02	8.56E-03	6.77E-03	5.76E-03	5.42E-03	5.08E-03
PHOP	kg C_2H_4 eq	2.28E+01	1.97E+01	1.76E+01	1.62E+01	1.10E+02	7.30E+01	5.46E+01	4.42E+01	3.98E+01	3.58E+01
CED	MJ	8.18E+05	7.23E+05	6.58E+05	6.18E+05	3.64E+06	2.46E+06	1.88E+06	1.56E+06	1.43E+06	1.31E+06

Impact category	Units	CS10008	CS25002	CS25003	CS25004	CS25005	CS25006	CS25007	CS25008	CS50002	CS50003
ADP	kg Sb eq	5.97E+02	4.63E+03	3.09E+03	2.45E+03	2.03E+03	1.84E+03	1.65E+03	1.44E+03	1.11E+04	6.90E+03
AP	kg SO_2 eq	3.44E+02	2.27E+03	1.57E+03	1.28E+03	1.08E+03	9.96E+02	9.03E+02	8.01E+02	5.30E+03	3.43E+03
EP	kg PO_4--- eq	1.45E+02	1.14E+03	7.61E+02	6.03E+02	4.98E+02	4.53E+02	4.05E+02	3.54E+02	2.74E+03	1.70E+03
GWP	kg CO_2 eq	1.06E+05	7.06E+05	4.83E+05	3.89E+05	3.27E+05	2.99E+05	2.70E+05	2.39E+05	1.62E+06	1.04E+06
ODP	kg CFC-11 eq	4.73E-03	2.96E-02	2.06E-02	1.69E-02	1.44E-02	1.34E-02	1.21E-02	1.08E-02	6.81E-02	4.46E-02
PHOP	kg C_2H_4 eq	3.21E+01	2.73E+02	1.79E+02	1.40E+02	1.15E+02	1.04E+02	9.21E+01	7.99E+01	6.63E+02	4.06E+02
CED	MJ	1.20E+06	8.90E+06	5.98E+06	4.77E+06	3.96E+06	3.62E+06	3.24E+06	2.85E+06	2.11E+07	1.33E+07

Impact category	Units	CS50004	CS50005	CS50006	CS50007	CS50008	CS75002	CS75003	CS75004	CS75005	CS75006
ADP	kg Sb eq	4.78E+03	4.04E+03	3.67E+03	3.47E+03	3.24E+03	2.00E+04	1.12E+04	7.77E+03	6.59E+03	5.72E+03
AP	kg SO_2 eq	2.46E+03	2.11E+03	1.94E+03	1.85E+03	1.74E+03	9.34E+03	5.46E+03	3.92E+03	3.38E+03	2.97E+03
EP	kg PO_4--- eq	1.18E+03	9.96E+02	9.05E+02	8.58E+02	8.00E+02	4.96E+03	2.77E+03	1.92E+03	1.63E+03	1.41E+03
GWP	kg CO_2 eq	7.42E+05	6.32E+05	5.73E+05	5.42E+05	5.07E+05	2.82E+06	1.65E+06	1.18E+06	1.00E+06	8.71E+05
ODP	kg CFC-11 eq	3.24E-02	2.80E-02	2.57E-02	2.46E-02	2.32E-02	1.18E-01	7.06E-02	5.13E-02	4.43E-02	3.91E-02
PHOP	kg C_2H_4 eq	2.76E+02	2.31E+02	2.09E+02	1.98E+02	1.83E+02	1.21E+03	6.64E+02	4.53E+02	3.82E+02	3.30E+02
CED	MJ	9.26E+06	7.85E+06	7.14E+06	6.77E+06	6.32E+06	3.78E+07	2.14E+07	1.50E+07	1.27E+07	1.11E+07

Impact category	Units	CS75007	CS75008	CS100002	CS100003	CS100004	CS100005	CS100006	CS100007	CS100008
ADP	kg Sb eq	5.16E+03	4.94E+03	3.02E+04	1.70E+04	1.15E+04	9.58E+03	8.59E+03	7.50E+03	6.79E+03
AP	kg SO_2 eq	2.71E+03	2.61E+03	1.39E+04	8.13E+03	5.70E+03	4.83E+03	4.37E+03	3.87E+03	3.54E+03
EP	kg PO_4--- eq	1.28E+03	1.22E+03	7.51E+03	4.21E+03	2.85E+03	2.37E+03	2.13E+03	1.86E+03	1.68E+03
GWP	kg CO_2 eq	7.88E+05	7.54E+05	4.16E+06	2.43E+06	1.70E+06	1.42E+06	1.28E+06	1.12E+06	1.02E+06
ODP	kg CFC-11 eq	3.58E-02	3.45E-02	1.75E-01	1.04E-01	7.40E-02	6.29E-02	5.71E-02	5.07E-02	4.65E-02
PHOP	kg C_2H_4 eq	2.96E+02	2.83E+02	1.84E+03	1.02E+03	6.77E+02	5.61E+02	5.01E+02	4.35E+02	3.92E+02
CED	MJ	1.00E+07	9.60E+06	5.69E+07	3.23E+07	2.20E+07	1.84E+07	1.65E+07	1.45E+07	1.31E+07

ADP=Abiotic depletion potential, AP=Acidification potential, EP=Eutrophication potential, GWP=Global warming potential, ODP=Ozone layer depletion potential, PHOP=Photochemical oxidation potential, CED=Cumulative energy demand

Cylindrical (C); Position: superficial (S), buried (B), partially-buried (P); Volume: capacity in cubic meters (100, 500, 1000, etc.); Height: in m and rounded to the lower unit (for example, 2 for 2.5 m of 3 for 3.5 m); Ex: "CS10006" - superficial cylindrical tank with 1,000 m^3 capacity and 6.5 m in height.

Table A IV-6 Absolute environmental impacts of the construction of storage water tanks buried assessed.

Impact category	Units	CB1002	CB1003	CB1004	CB1005	CB1006	CB1007	CB1008	CB5002	CB5003	CB5004
ADP	kg Sb eq	2.09E+02	1.57E+02	1.42E+02	1.19E+02	1.12E+02	1.11E+02	9.86E+01	9.94E+02	7.38E+02	5.95E+02
AP	kg SO_2 eq	1.21E+02	9.77E+01	9.29E+01	8.09E+01	7.86E+01	8.13E+01	7.18E+01	5.51E+02	4.34E+02	3.68E+02
EP	kg PO_4--- eq	5.16E+01	3.88E+01	3.50E+01	2.91E+01	2.74E+01	2.70E+01	2.40E+01	2.46E+02	1.83E+02	1.48E+02
GWP	kg CO_2 eq	3.41E+04	2.69E+04	2.53E+04	2.20E+04	2.13E+04	2.23E+04	1.98E+04	1.56E+05	1.19E+05	9.83E+04
ODP	kg CFC-11 eq	1.65E-03	1.35E-03	1.30E-03	1.15E-03	1.12E-03	1.17E-03	1.04E-03	7.38E-03	5.90E-03	5.07E-03
PHOP	kg C_2H_4 eq	1.14E+01	8.23E+00	7.16E+00	5.79E+00	5.31E+00	5.05E+00	4.52E+00	5.55E+01	4.00E+01	3.13E+01
CED	MJ	4.14E+05	3.17E+05	2.90E+05	2.45E+05	2.33E+05	2.34E+05	2.08E+05	1.95E+06	1.46E+06	1.19E+06

Impact category	Units	CB5005	CB5006	CB5007	CB5008	CB10002	CB10003	CB10004	CB10005	CB10006	CB10007
ADP	kg Sb eq	4.91E+02	4.40E+02	4.05E+02	3.84E+02	2.04E+03	1.42E+03	1.11E+03	9.34E+02	8.71E+02	8.09E+02
AP	kg SO_2 eq	3.17E+02	2.94E+02	2.78E+02	2.69E+02	1.12E+03	8.22E+02	6.76E+02	5.93E+02	5.73E+02	5.47E+02
EP	kg PO_4--- eq	1.22E+02	1.09E+02	1.00E+02	9.49E+01	5.06E+02	3.52E+02	2.75E+02	2.32E+02	2.16E+02	2.01E+02
GWP	kg CO_2 eq	8.33E+04	7.63E+04	7.16E+04	6.89E+04	3.17E+05	2.24E+05	1.79E+05	1.54E+05	1.46E+05	1.37E+05
ODP	kg CFC-11 eq	4.41E-03	4.12E-03	3.92E-03	3.81E-03	1.49E-02	1.11E-02	9.25E-03	8.19E-03	7.96E-03	7.66E-03
PHOP	kg C_2H_4 eq	2.51E+01	2.20E+01	1.99E+01	1.85E+01	1.15E+02	7.75E+01	5.90E+01	4.85E+01	4.42E+01	4.03E+01
CED	MJ	9.96E+05	9.00E+05	8.34E+05	7.94E+05	3.99E+06	2.80E+06	2.21E+06	1.88E+06	1.77E+06	1.65E+06

Impact category	Units	CB10008	CB25002	CB25003	CB25004	CB25005	CB25006	CB25007	CB25008	CB50002	CB50003
ADP	kg Sb eq	7.47E+02	4.78E+03	3.43E+03	2.80E+03	2.38E+03	2.20E+03	2.00E+03	1.79E+03	9.63E+03	6.90E+03
AP	kg SO_2 eq	5.17E+02	2.59E+03	1.97E+03	1.68E+03	1.49E+03	1.41E+03	1.31E+03	1.19E+03	5.19E+03	3.93E+03
EP	kg PO_4--- eq	1.86E+02	1.18E+03	8.53E+02	6.97E+02	5.92E+02	5.49E+02	5.00E+02	4.49E+02	2.39E+03	1.72E+03
GWP	kg CO_2 eq	1.29E+05	7.35E+05	5.35E+05	4.42E+05	3.80E+05	3.53E+05	3.23E+05	2.91E+05	1.47E+06	1.07E+06
ODP	kg CFC-11 eq	7.27E-03	3.44E-02	2.65E-02	2.29E-02	2.04E-02	1.94E-02	1.81E-02	1.66E-02	6.89E-02	5.27E-02
PHOP	kg C_2H_4 eq	3.66E+01	2.71E+02	1.89E+02	1.51E+02	1.25E+02	1.14E+02	1.03E+02	9.10E+01	5.47E+02	3.82E+02
CED	MJ	1.53E+06	9.32E+06	6.76E+06	5.57E+06	4.76E+06	4.43E+06	4.04E+06	3.64E+06	1.88E+07	1.36E+07

Impact category	Units	CB50004	CB50005	CB50006	CB50007	CB50008	CB75002	CB75003	CB75004	CB75005	CB75006
ADP	kg Sb eq	5.27E+03	4.69E+03	4.42E+03	4.35E+03	4.17E+03	1.45E+04	1.01E+04	7.89E+03	7.28E+03	6.88E+03
AP	kg SO_2 eq	3.14E+03	2.87E+03	2.74E+03	2.71E+03	2.62E+03	7.79E+03	5.73E+03	4.68E+03	4.37E+03	4.15E+03
EP	kg PO_4--- eq	1.31E+03	1.17E+03	1.11E+03	1.09E+03	1.05E+03	3.59E+03	2.51E+03	1.97E+03	1.82E+03	1.72E+03
GWP	kg CO_2 eq	8.21E+05	7.30E+05	6.83E+05	6.67E+05	6.38E+05	2.21E+06	1.56E+06	1.22E+06	1.11E+06	1.04E+06
ODP	kg CFC-11 eq	4.26E-02	3.90E-02	3.73E-02	3.70E-02	3.58E-02	1.03E-01	7.69E-02	6.33E-02	5.92E-02	5.62E-02
PHOP	kg C_2H_4 eq	2.85E+02	2.50E+02	2.35E+02	2.30E+02	2.20E+02	8.24E+02	5.61E+02	4.28E+02	3.94E+02	3.72E+02
CED	MJ	1.04E+07	9.33E+06	8.81E+06	8.67E+06	8.32E+06	2.82E+07	1.99E+07	1.56E+07	1.44E+07	1.36E+07

Impact category	Units	CB75007	CB75008	CB100002	CB100003	CB100004	CB100005	CB100006	CB100007	CB100008
ADP	kg Sb eq	6.57E+03	6.49E+03	2.08E+04	1.35E+04	1.08E+04	1.01E+04	1.00E+04	9.45E+03	9.06E+03
AP	kg SO_2 eq	3.99E+03	3.97E+03	1.09E+04	7.65E+03	6.35E+03	6.00E+03	5.93E+03	5.61E+03	5.40E+03
EP	kg PO_4--- eq	1.65E+03	1.63E+03	5.16E+03	3.36E+03	2.68E+03	2.54E+03	2.51E+03	2.37E+03	2.28E+03
GWP	kg CO_2 eq	9.85E+05	9.68E+05	3.10E+06	2.07E+06	1.66E+06	1.53E+06	1.49E+06	1.39E+06	1.32E+06
ODP	kg CFC-11 eq	5.41E-02	5.38E-02	1.44E-01	1.03E-01	8.58E-02	8.09E-02	7.97E-02	7.55E-02	7.27E-02
PHOP	kg C_2H_4 eq	3.54E+02	3.49E+02	1.20E+03	7.51E+02	5.87E+02	5.53E+02	5.48E+02	5.17E+02	4.95E+02
CED	MJ	1.30E+07	1.29E+07	4.02E+07	2.65E+07	2.13E+07	2.00E+07	1.97E+07	1.86E+07	1.78E+07

ADP=Abiotic depletion potential, AP=Acidification potential, EP=Eutrophication potential, GWP=Global warming potential, ODP=Ozone layer depletion potential, PHOP=Photochemical oxidation potential, CED=Cumulative energy demand

Cylindrical (C); Position: superficial (S), buried (B), partially-buried (P); Volume: capacity in cubic meters (100, 500, 1000, etc.); Height: in m and rounded to the lower unit (for example, 2 for 2.5 m of 3 for 3.5 m); Ex: "CS10006" - superficial cylindrical tank with 1,000 m^3 capacity and 6.5 m in height.

Table A IV-7 Absolute environmental impacts per cubic meter of water stored for superficial cylindrical tanks of 8.5 m in height.

	Units	100	500	1,000	2,500	5,000	7,500	10,000
Abiotic depletion	kg Sb eq	7.76E-01	6.01E-01	5.63E-01	5.74E-01	6.13E-01	6.42E-01	6.75E-01
Acidification	kg SO_2 eq	4.76E-01	3.52E-01	3.24E-01	3.19E-01	3.29E-01	3.39E-01	3.52E-01
Eutrophication	kg PO_4--- eq	1.84E-01	1.45E-01	1.37E-01	1.41E-01	1.51E-01	1.59E-01	1.67E-01
Global warming	kg CO_2 eq	1.65E+02	1.12E+02	9.99E+01	9.49E+01	9.59E+01	9.80E+01	1.01E+02
Ozone layer depletion	kg CFC-11 eq	6.80E-06	4.89E-06	4.45E-06	4.31E-06	4.38E-06	4.49E-06	4.62E-06
Photochemical oxidation	kg C_2H_4 eq	3.89E-02	3.18E-02	3.03E-02	3.18E-02	3.47E-02	3.68E-02	3.90E-02
Cumulative energy demand	MJ	1.61E+03	1.21E+03	1.13E+03	1.13E+03	1.20E+03	1.25E+03	1.31E+03

Table A IV-8 Appendix III.IV Environmental impacts of the life cycle elements of cylindrical water tanks of 8.5 m in height and of 100 and 10,000 m3 in capacity for superficial, buried and partially buried positions.

	Impact category	Units	CP1008	CP100008	CS1008	CS100008	CB1008	CB100008
Excavation	**Abiotic depletion**	kg Sb eq	2.84E+00	2.21E+02	0.00E+00	0.00E+00	5.68E+00	4.42E+02
		%	3%	3%	0%	0%	6%	5%
	Global warming (GWP100)	kg CO_2 eq	4.30E+02	3.35E+04	0.00E+00	0.00E+00	8.59E+02	6.69E+04
		%	2%	3%	0%	0%	4%	5%
Compaction	**Abiotic depletion**	kg Sb eq	8.89E-03	8.89E-01	8.89E-03	8.89E-01	8.89E-03	8.89E-01
		%	0%	0%	0%	0%	0%	0%
	Global warming (GWP100)	kg CO_2 eq	1.35E+00	1.35E+02	1.35E+00	1.35E+02	1.35E+00	1.35E+02
		%	0%	0%	0%	0%	0%	0%
Transport equipment for retention walls	**Abiotic depletion**	kg Sb eq	1.05E+00	1.05E+00	0.00E+00	0.00E+00	1.05E+00	1.05E+00
		%	1%	0%	0%	0%	1%	0%
	Global warming (GWP100)	kg CO_2 eq	1.58E+02	1.58E+02	0.00E+00	0.00E+00	1.58E+02	1.58E+02
		%	1%	0%	0%	0%	1%	0%
Assembly of retention walls	**Abiotic depletion**	kg Sb eq	4.18E+00	4.18E+01	0.00E+00	0.00E+00	4.18E+00	4.18E+01
		%	5%	1%	0%	0%	4%	0%
	Global warming (GWP100)	kg CO_2 eq	6.33E+02	6.33E+03	0.00E+00	0.00E+00	6.33E+02	6.33E+03
		%	3%	1%	0%	0%	3%	0%
Concrete	**Abiotic depletion**	kg Sb eq	1.87E+01	5.21E+02	1.87E+01	5.21E+02	1.87E+01	5.21E+02
		%	21%	7%	24%	8%	19%	6%
	Global warming (GWP100)	kg CO_2 eq	9.29E+03	2.58E+05	9.29E+03	2.58E+05	9.29E+03	2.58E+05
		%	50%	23%	56%	25%	47%	20%
Steel	**Abiotic depletion**	kg Sb eq	4.70E+01	5.46E+03	4.70E+01	5.53E+03	4.70E+01	6.55E+03
		%	52%	74%	60%	81%	48%	72%
	Global warming (GWP100)	kg CO_2 eq	5.49E+03	6.37E+05	5.49E+03	6.45E+05	5.49E+03	7.64E+05
		%	30%	58%	33%	64%	28%	58%

Demolition	**Abiotic depletion**	kg Sb eq	5.36E+00	5.36E+02	5.36E+00	5.36E+02	5.36E+00	5.36E+02
		%	6%	7%	7%	8%	5%	6%
	Global warming (GWP100)	kg CO_2 eq	8.11E+02	8.11E+04	8.11E+02	8.11E+04	8.11E+02	8.11E+04
		%	4%	7%	5%	8%	4%	6%
Transport	**Abiotic depletion**	kg Sb eq	1.18E+01	5.82E+02	6.89E+00	2.03E+02	1.66E+01	9.64E+02
		%	13%	8%	9%	3%	17%	11%
	Global warming (GWP100)	kg CO_2 eq	1.78E+03	8.81E+04	1.04E+03	3.07E+04	2.52E+03	1.46E+05
		%	10%	8%	6%	3%	13%	11%
		Total kg Sb eq	**9.09E+01**	**7.36E+03**	**7.80E+01**	**6.79E+03**	**9.86E+01**	**9.06E+03**
		Total kg CO_2 eq	**1.86E+04**	**1.10E+06**	**1.66E+04**	**1.02E+06**	**1.98E+04**	**1.32E+06**

Cylindrical (C); Position: superficial (S), buried (B), partially-buried (P); Volume: capacity in cubic meters (100, 500, 1000, etc.); Height: in m and rounded to the lower unit (for example, 2 for 2.5 m of 3 for 3.5 m); Ex: "CS10006" - superficial cylindrical tank with 1,000 m^3 capacity and 6.5 m in height.

Table A IV-9 Environmental impacts of the case assessed based on realistic conditions and using defined environmental standards.

		Water tank 1 (400 m^3)		Water tank 2 (2,000 m^3)		Water tank 3 (8,000 m^3)	
		Realistic	Optimized	Realistic	Optimised	Realistic	Optimised
Abiotic depletion	kg Sb eq	4.03E+02	2.65E+02	1.79E+03	1.17E+03	6.98E+03	5.87E+03
Acidification	kg SO_2 eq	2.60E+02	1.60E+02	1.13E+03	6.64E+02	4.23E+03	3.04E+03
Eutrophication	kg PO_4--- eq	9.97E+01	6.42E+01	4.47E+02	2.86E+02	1.75E+03	1.46E+03
Global warming	kg CO_2 eq	6.85E+04	4.93E+04	2.88E+05	1.95E+05	1.04E+06	8.69E+05
Ozone layer depletion	kg CFC-11 eq	3.61E-03	2.23E-03	1.55E-02	9.03E-03	5.72E-02	3.99E-02
Photochemical oxidation	kg C_2H_4 eq	2.06E+01	1.38E+01	9.41E+01	6.37E+01	3.78E+02	3.40E+02
Cumulative energy demand	MJ	8.17E+05	5.37E+05	3.60E+06	2.31E+06	1.38E+07	1.13E+07

Appendix V Supplementary information for Chapter 6

Table A V-1 Rainwater and drinking water from the conventional supply network used for irrigation in the ICTA-ICP building from 21/05/2015 to 15/04/2016.

	m^3		
	Total	**Rainwater**	**Drinking water**
Irrigation ornamental plants[1]	76.6	60.2	16.4
Irrigation crops[2]			
Crop 1	46.1	29.6	16.4
Crop 2	44.0	39.8	4.2
Crop 3	6.3	6.3	
Total irrigation crops	96.3	75.7	20.7
Leachates	34.8		

[1]The distribution of the water demand into rainwater and drinking water was done in accordance with the periods of rainwater availability.
[2]The volume of water used for the irrigation of crops was measured with a flow meter.

Table A V-2 Detailed breakdown of the water demand in the building from 21/05/2015 to 15/04/2016 (shaded cells indicate estimated flow).

	Total water used (m^3)	Reclaimed greywater (m^3)		m^3 of drinking water
Toilet flushing - NW[1]	636.2	36.2		600.0
Toilet flushing - SE	406.0	34.0		372.0
	Total water used (m^3)	Rainwater (m^3)		
Irrigation crops	96.3	75.7		20.7
Irrigation ornamental plants[1]	76.6	60.2		16.4
	Rainwater (m^3)			
Washbasins - SE[1]	23.1			
Washbasins - NW[1]	36.2			
	showers/week	N weeks	m^3/shower	
Shower[2]	14	39	0.02	10.9
	m^3/week	N weeks		
Labs[2]	0.25	39		9.8
	m^3/week	N weeks		
Kitchen[2]	0.25	39		9.8
	Times/year	m^3		
Cleaning AQUATRON tank[2]	2	3		6.0
Cleaning yellow water tank[2]	2	2		4.0
	%	total m^3		
Inefficiency decalcifier[3]	0.002	1,054		2.3
	m^3/week	N weeks		
Drinking fountains[2]	0.05	39		2.0
	Services/week	mL/service	N weeks	
Coffee machine[2]	396	115	39	1.8
Total estimated				**1,056**
Total measured				**1,054**

[1]*Reliable estimation (methodology in section 2.2).*
[2]*Estimation with low reliability: observation, interviews to the staff and surveys to users. These flows were adjusted to approach the total 1,054 m^3 of water measured.*
[3]*Estimated from data provided by the manufacturer: 0.023 L for each cycle of decalcification (10.4 L)*

Appendix VI Supplementary information for Chapter 7

Appendix VI.I Results of the analysis of the nutrient solution and the leachates in crop S2.

Table A VI-1 Results of the analysis of the integrated samples of nutrient solution during crop S2 (08/03/2016-20/07/2016)

	Ion chromatography	Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)							
Date	**N (mg/l)**	**P (mg/l)**	**K (mg/l)**	**Ca (mg/l)**	**Mg (mg/l)**	**Na (mg/l)**	**S (mg/l)**	**Fe (mg/l)**	**Zn (mg/l)**
2016-03-12	88.16	35.6	226.1	98.3	16.8	8.3	58.6	0.6	0.4
2016-03-19	88.16	35.8	246.9	106.1	16.6	10.3	65.1	1.0	0.5
2016-03-26	87.35	33.3	242.1	118.9	21.1	9.2	58.4	1.0	0.5
2016-04-02	105.30	30.8	219.0	97.7	17.6	7.5	54.9	0.6	0.4
2016-04-09	77.73	32.1	226.1	113.0	20.3	8.0	56.9	0.8	0.4
2016-04-16	82.11	42.2	222.0	107.4	19.4	7.4	51.9	0.6	0.3
2016-04-23	89.24	29.3	239.1	121.7	21.7	7.6	60.7	0.9	0.4
2016-04-30	98.63	30.3	208.7	117.3	19.9	7.4	42.0	0.9	0.5
2016-05-07	90.22	29.1	198.0	114.8	19.8	7.3	36.1	0.6	0.5
2016-05-14	86.55	27.5	181.5	116.0	19.8	6.3	34.5	0.6	0.5
2016-05-21	94.74	32.0	213.3	109.3	18.6	6.9	45.2	0.6	0.5
2016-05-28	88.81	24.8	209.1	102.3	16.9	6.8	46.8	0.6	0.5
2016-06-04	84.31	28.7	221.6	117.4	19.9	7.7	49.5	0.7	0.6
2016-06-11	92.98	27.7	223.5	107.4	18.1	7.8	51.1	0.6	0.6
2016-06-18	86.82	28.1	234.3	129.6	22.4	8.1	52.0	0.9	0.6
2016-06-25	103.69	27.8	226.3	139.2	24.9	15.5	55.8	0.8	0.6
2016-07-02	103.30	20.4	215.0	160.6	32.5	56.4	68.7	0.9	0.3
2016-07-09	102.06	69.4	316.0	170.3	34.5	66.9	88.5	1.0	0.3

ICP-OES			Flow meter
Mn (mg/l)	Cu (mg/l)	B (mg/l)	Water demand of the crop
0,3	0	0	830
0,3	0	0	582
0,3	0	0	1201
0,3	0	0	1344
0,3	0	0	1858
0,3	0	0	3396
0,4	0	0	3608
0,3	0	0	2688
0,3	0	0	1766
0,3	0	0	2175
0,3	0	0	2082
0,3	0	0	3184
0,3	0	0	2892
0,3	0	0	2578
0,3	0	0	2476
0,3	0	0	2755
0,3	0	0	2422
0,3	0	0	2498

Table A VI-2 Results of the analysis of the integrated samples of leachates during crop S2 (08/03/2016-20/07/2016).

	Ion chromatography	Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)							
Date	**N (mg/l)**	**P (mg/l)**	**K (mg/l)**	**Ca (mg/l)**	**Mg (mg/l)**	**Na (mg/l)**	**S (mg/l)**	**Fe (mg/l)**	**Zn (mg/l)**
2016-03-12	53,68	7,0	269,4	75,0	16,6	26,8	72,8	0,3	0,3
2016-03-19	53,68	4,9	408,0	97,8	25,2	50,0	112,7	0,6	0,3
2016-03-26	90,74	7,5	261,3	95,0	21,0	23,0	75,3	1,0	0,3
2016-04-02	63,29	15,4	219,1	98,5	19,2	12,5	60,0	0,8	0,3
2016-04-09	65,57	8,3	218,6	73,7	16,8	14,6	66,1	0,7	0,3
2016-04-16	37,01	15,6	250,5	67,6	18,8	19,7	61,3	0,5	0,3
2016-04-23	37,42	5,4	263,4	83,9	21,0	16,4	71,6	0,7	0,3
2016-04-30	58,55	14,7	245,6	106,0	24,5	17,2	65,2	1,3	0,3
2016-05-07	73,44	14,6	186,8	103,6	25,3	16,8	41,8	1,3	0,3
2016-05-14	70,14	23,6	155,2	156,6	38,2	19,6	50,7	1,0	0,4
2016-05-21	101,93	32,6	201,5	175,8	39,5	17,9	60,1	1,3	0,4
2016-05-28	122,89	36,2	242,3	146,0	30,5	16,4	77,2	1,1	0,5
2016-06-04	102,49	20,1	182,7	78,7	15,4	9,8	46,3	0,5	0,3
2016-06-11	57,45	32,8	299,5	175,4	34,8	18,8	86,2	1,2	0,5
2016-06-18	138,92	26,1	327,1	186,7	38,2	22,0	91,1	1,7	0,5
2016-06-25	147,57	21,6	376,9	218,2	44,2	26,8	106,0	1,5	0,5
2016-07-02	178,31	9,5	444,2	278,6	68,4	88,3	148,1	2,0	0,4
2016-07-09	197,41	16,9	362,4	228,1	57,6	112,7	124,9	1,3	0,3

ICP-OES			Flow meter
Mn (mg/l)	**Cu (mg/l)**	**B (mg/l)**	**Water demand of the crop**
0	0	0	531
0	0	0	274
0	0	0	447
0	0	0	550
0	0	0	383
0	0	0	1188
0	0	0	2652
0	0	0	1280
0	0	0	840
0	0	0	744
0	0	0	880
0	0	0	1481
0	0	0	992
0,1	0	0	1162
0,1	0	0	826
0,1	0	0	1146
0	0	0	762
0	0	0	1641

Appendix VI.II Results of the analysis of perlite samples from the crops.

Table A VI-3 Results for the analysis of the concentration of nutrients and carbon of unused perlite bags (blanks).

Perlite bag code	N (mg/g)	%rsd	P (mg/g)	%rsd	K (mg/g)	%rsd	Ca (mg/g)	%rsd	Mg (mg/g)	%rsd	Na (mg/g)	%rsd	S (mg/g)	%rsd
L1775921S1M1	0,00	0,00	0,00	--	3,5	13	0,46	10	0,51	50	16	6,0	0,00	--
L1775921S1M2	0,00	0,00	0,00	--	4,4	1,3	0,46	25	0,34	1,4	19	2,1	0,00	--
L1775921S2M1	0,00	0,00	0,00	--	4,6	1,5	1,5	89	0,82	63	18	0,4	0,00	--
L1775921S2M2	0,00	0,00	0,00	--	4,4	5,0	0,48	2,3	0,46	1,3	18	2,5	0,00	--
L1591448S1M1	0,00	0,00	0,00	--	4,3	7,0	1,2	23	0,64	47	18	1,8	0,16	124
L1591448S1M2	0,00	0,00	0,00	--	4,3	9,6	0,80	85	0,72	75	17	5,4	0,00	--
L1591448S2M1	0,00	0,00	0,00	--	3,2	14	0,75	3,2	0,47	11	15	8,3	0,00	--
L1591448S2M2	0,00	0,00	0,00	--	3,6	0,7	0,39	11	0,26	9,3	16	2,7	0,00	--
L1804719S1M1	0,00	0,00	0,00	--	4,5	7,1	0,25	2,2	0,25	21	18	2,7	0,00	--
L1804719S1M2	0,00	0,00	0,00	--	5,3	7,3	0,22	7,0	0,43	62	20	2,3	0,00	--
L1604719S1M1	0,00	0,00	0,00	--	5,1	20	0,29	5,1	0,20	3,8	20	5,6	0,00	--
L1604719S1M2	0,00	0,00	0,00	--	4,9	10	0,21	0,8	0,16	3,4	20	4,4	0,00	--

Perlite bag code	Fe (mg/g)	%rsd	Zn (mg/g)	%rsd	Mn (mg/g)	%rsd	Cu (mg/g)	%rsd	B (mg/g)	%rsd	C (%)
L1775921S1M1	1,6	19	0,000	--	0,031	18	0,00	--	0,00	--	0,00
L1775921S1M2	1,5	2,1	0,000	--	0,029	0,9	0,00	--	0,00	--	0,00
L1775921S2M1	1,7	3,4	0,000	--	0,056	33	0,00	--	0,00	--	0,00
L1775921S2M2	1,5	2,0	0,000	--	0,030	1,4	0,00	--	0,00	--	0,00
L1591448S1M1	1,4	25	0,000	--	0,027	22	0,00	--	0,00	--	0,00
L1591448S1M2	1,7	32	0,000	--	0,050	18	0,00	--	0,00	--	0,00
L1591448S2M1	1,1	3,2	0,000	--	0,024	7,2	0,00	--	0,00	--	0,00
L1591448S2M2	0,5	131	0,000	--	0,009	131	0,00	--	0,00	--	0,00
L1804719S1M1	1,0	20	0,000	--	0,021	12	0,00	--	0,00	--	0,00
L1804719S1M2	1,2	19	0,000	--	0,026	22	0,00	--	0,00	--	0,00
L1604719S1M1	1,1	4,8	0,000	--	0,022	2,4	0,00	--	0,00	--	0,00
L1604719S1M2	0,9	12	0,000	--	0,019	3,7	0,00	--	0,00	--	0,00

N,P,S: <0.1 = 0; B: <0.05 = 0; Cu,Zn: <0.01 = 0

Table A VI-4 Results for the analysis of the concentration of nutrients and carbon in perlite bags used in the crops. N,P,S: <0.1 = 0; B: <0.05 = 0; Cu, Zn: <0.01 = 0

Perlite bag code	Used in crops	N (mg/g)	%rsd	P (mg/g)	%rsd	K (mg/g)	%rsd	Ca (mg/g)	%rsd	Mg (mg/g)	%rsd	Na (mg/g)	%rsd	S (mg/g)	%rsd
F4S2 – S1		0	0	0,4	1,3	6,8	5,7	2,1	0,5	0,5	1,2	20	3,5	0,8	20
F4S2 – S2		0	0	0,4	0,8	7,0	6,0	2,0	0,1	0,5	3,0	20	5,3	0,7	1,6
F4S2 – S3		0	0	0,4	1,1	6,5	2,3	2,1	0,1	0,5	0,3	19	0,1	0,7	0,0
F10S3 – S1	S3	1,3	1	0,4	1,2	7,0	5,7	2,8	1,4	0,7	2,6	19	3,7	3,7	100
F10S3 – S2		1	0	0,4	2,7	7,4	1,9	2,6	2,0	0,7	0,5	20	1,8	0,9	1,5
F10S3 – S3		1	0	0,4	2,6	6,9	13	2,6	2,5	0,7	0,3	18	7,1	0,9	1,1
C3A		1	0	0,35	0,27	7,65	9,25	2,11	0,28	0,53	0,41	20,28	4,54	0,85	1,33
C1C2B –S1		0	0	0,78	0,6	8,1	11	2,5	3,8	0,41	3,8	20	5,9	0,88	1,7
C1C2B – S2		0	0	0,78	1,5	8,1	2,1	2,4	4,3	0,40	3,5	20	3,2	0,83	3,6
C1C2N – S1	S, W	0	0	0,76	8,7	6,2	20	2,3	8,7	0,36	7,3	17	11	0,74	4,6
C1C2N – S2		0	0	0,66	0,9	5,8	2,0	2,1	2,0	0,39	3,4	17	2,6	0,73	3,5
C1C2A		0	0	0,73	1,1	7,4	11,4	2,0	1,0	0,33	0,5	19	5,7	0,62	1,6
C1C2C3	S1, W, S2	1	0	1,47	0,15	7,73	1,32	4,15	0,14	0,64	0,20	18,71	0,77	1,07	0,40

Perlite bag code	Used in crops	Fe (mg/g)	%rsd	Zn (mg/g)	%rsd	Mn (mg/g)	%rsd	Cu (mg/g)	%rsd	B (mg/g)	%rsd	C (%)
F4S2 – S1		1,1	0,1	0,0	--	0,023	3,4	0,00	--	0,00	--	0,20
F4S2 – S2		1,1	2,6	0,0	--	0,024	4,2	0,00	--	0,00	--	0,18
F4S2 – S3		1,2	0,03	0,0	--	0,024	0,5	0,00	--	0,00	--	0,21
F10S3 – S1	S3	1,5	22	0,0	--	0,028	13	0,00	--	0,00	--	0,18
F10S3 – S2		1,3	9,5	0,0	--	0,025	6,1	0,00	--	0,00	--	0,15
F10S3 – S3		1,3	3,8	0,0	--	0,024	3,5	0,00	--	0,00	--	0,16
C3A		0,81	0,00	0,00	--	0,02	1,49	0,00	--	0,00	--	0,11
C1C2B –S1		1,3	26	0,0	--	0,038	17	0,00	--	0,00	--	0,10
C1C2B – S2		1,3	10	0,0	--	0,038	11	0,00	--	0,00	--	0,10
C1C2N – S1	S, W	1,2	21	0,0	--	0,033	13	0,00	--	0,00	--	0,10
C1C2N – S2		1,1	11	0,0	--	0,030	8,6	0,00	--	0,00	--	0,17
C1C2A		1,1	2	0,0	--	0,032	0,7	0,00	--	0,00	--	0,14
C1C2C3	S1, W, S2	1,52	5,64	0,04	5,36	0,04	1,64	0,02	0,50	0,00	--	0,35

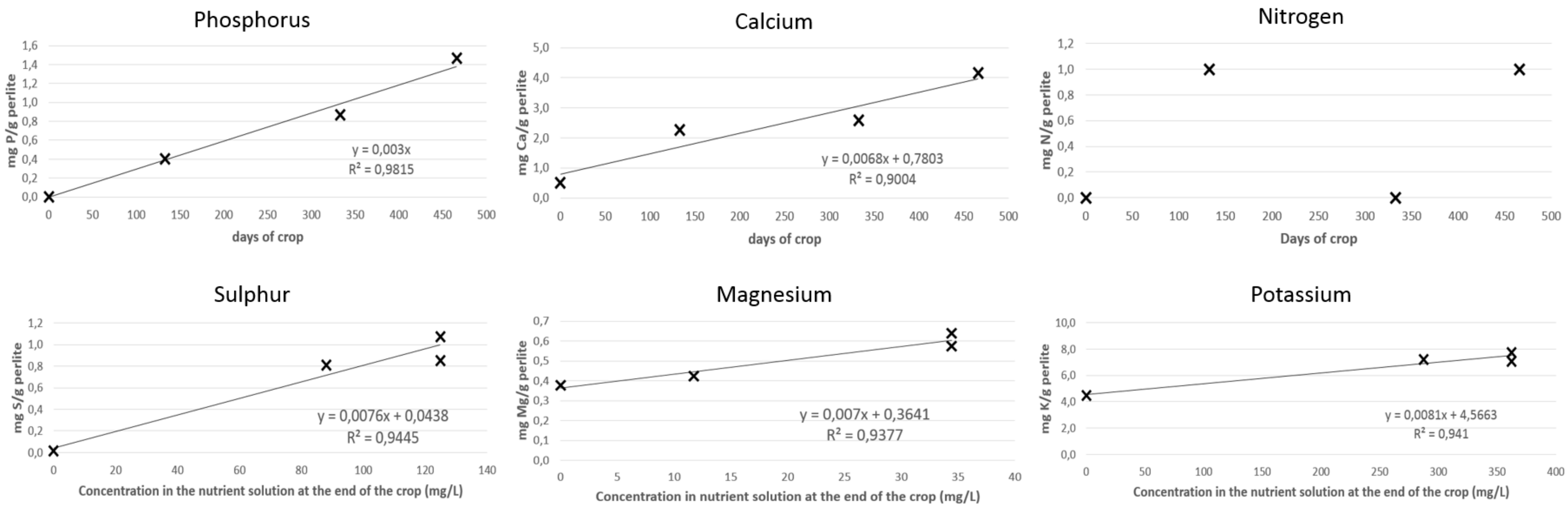


Figure A 1 Scatter plots and linear regressions of the nutrients and the variables related to the crop that provided the higher coefficient of determination.

Appendix VII Supplementary information for Chapter 8

Appendix VII.I Inventory of the i-RTG infrastructure

This section of the supplementary information presents the inventory of the infrastructure of the i-RTG.

Rainwater harvesting system (ICTA-ICP building) - life cycle inventory

The whole infrastructure was considered for the inventory of the rainwater harvesting system of the building. The required information was obtained from the building layouts and interviews with building managers, architects and direct observation of the infrastructure. The inventory was converted to one cubic meter using the estimated rainwater that would fall over the 50 years of lifespan. This value was later used to calculate the reference flow for the i-RTG. Table 1 shows the detailed inventory used for the calculation of the environmental impacts.

The rainwater tank of the system was placed underground, and the excavation during the construction of the building was included in the assessment. However, no transport was considered for the soil extracted because it was used on-site (around the building) for landscaping purposes.

Table A VII-1 Inventory table for the rainwater harvesting system in the ICTA-ICP building.

Element	Material	Lifespan	Units	Quantity	
				System (50 years)	per m^3 rainwater
Water tank	GFRP	50	kg	4051.7	2.28
Pipes	HDPE	10	kg	305.0	0.17
Pump	Cast iron	10	kg	65.8	0.04
	Steel	10	kg	7.7	0.004
Processes					
GFRP	Injection moulding	50	kg	4051.7	2.28
HDPE	Extrusion, plastic pipes	50	kg	305.0	0.17
Cast iron/steel	Metal working manufacturing	50	kg	73.5	0.04
Transport	Lorry 3.5-7.5 metric ton	50	tkm	486.2	0.27
Transport	Light commercial vehicle	50	tkm	45.4	0.03
Installation	Excavation, hydraulic digger	50	m3	100.0	0.06
Deconstruction	Energy for the backfilling	50	m3	12.8	0.01
Transport (end of life)	Lorry 3.5-7.5 metric ton	50	tkm	265.8	0.15
Waste	Municipal solid waste	50	kg	305.0	0.17

GFRP=glass fibre reinforced polyester, HDPE=high density polyethylene

Auxiliary equipment (i-RTG) - life cycle inventory

All the auxiliary equipment of the greenhouse was considered in the inventory, as shown in Table A VII.II. The data was represented for the total quantity required for the installation (with a lifespan of 10 years), for the functional unit (1 kg of tomato) and for one square meter of the greenhouse considering the productive area of the crop (84.34 m^2).

Greenhouse structure (i-RTG) - life cycle inventory

For the structure of the greenhouse, the data for the inventory was obtained from Sanye-Mengual et al. (2015). The following elements of the structure were considered according with the study: anchor (concrete anchor and steel bolt), structure (pillar, pillar complements, bracing tubes, chapel, steel straps), gutters (exterior gutter, interior gutter), walls (LDPE roll wall), covering (polycarbonate, steel frame) and the climate screen. For more information, see Sanye-Mengual et al. (2015).

Appendix VII.II Details and assumptions of the LCA of the reference scenario for tomato production (conventional greenhouse)

This section presents the details and assumptions considered for the definition of the reference scenario, which is based on the production of tomato using conventional agriculture.

- **General description of the reference scenario**

A hypothetical conventional multitunnel greenhouse was considered for the reference scenario. Data for the infrastructure and operation of the greenhouse was obtained from previous literature based on a 5,000 m^2 greenhouse with standard characteristics and functioning. For the calculation of the transport, the greenhouse was assumed to be located in the Mediterranean area of Almeria (Spain), which is a common origin for the tomatoes consumed in Barcelona.

- **Greenhouse structure and auxiliary equipment**

Data for the structure and the auxiliary material in the greenhouse was obtained from Martínez-Blanco et al. (2011), adjusting the impacts to the duration of the hypothetical crops. The greenhouse holds a round arched structure with six spans, a steel frame, concrete foundations and is covered with a low-density polyethylene film. The auxiliary equipment is made up of a fertigation system for the supply of nutrients and water and the necessary tanks, pumps and tools.

- **General management (energy, pesticides, machinery use)**

Data for the general management of the crop, including the energy to pump water, the pesticides and the machinery employed in the greenhouse was also obtained from Martínez-Blanco et al. (2011). Since the article focuses on a soil-based crop, the impacts of the substrate (perlite) were added considering the same lifespan that was accounted for the i-RTG to make a fairer comparison.

Table A VII-2 Inventory of the auxiliary equipment in the i-RTG

Element	Material	Lifespan	Units	Quantity		
				i-RTG (10 years)	per kg tomato*	per m² (10 years)**
Pump + pressure switch	Cast iron	10	kg	8.8	4.41E-04	1.04E-01
	Steel	10	kg	1.0	5.19E-05	1.22E-02
	HDPE	10	kg	0.5	2.60E-05	6.12E-03
Nutrient tanks	PE	10	kg	8.1	4.09E-04	9.64E-02
Water tanks	PE	10	kg	15.0	7.56E-04	1.78E-01
DOSATRON	PP	10	kg	1.6	8.00E-05	1.89E-02
Flow meter	Cast iron	10	kg	4.8	2.39E-04	5.63E-02
	HDPE	10	kg	0.3	1.26E-05	2.96E-03
Digital timer	HDPE	10	kg	0.5	2.58E-05	6.08E-03
	Electronics	10	kg	0.0	1.36E-06	3.20E-04
Pipes and joints - headboard	PVC	10	kg	8.2	4.12E-04	9.71E-02
Pipes - distribution	LDPE	10	kg	5.5	2.76E-04	6.50E-02
Joints and stoppers - distribution	PE	10	kg	0.3	1.70E-05	4.00E-03
Drippers + tubes	PVC	10	kg	1.5	7.74E-05	1.82E-02
Leachate trays	LDPE	5	kg	3.5	1.75E-04	4.12E-02
	EPS	5	kg	48.2	2.43E-03	5.72E-01
Support for staking (clips, wires)	HDPE	5	kg	4.0	2.01E-04	4.74E-02
	Steel	5	kg	3.9	1.96E-04	4.62E-02
	Polypropylene	5	kg	3.8	1.91E-04	4.51E-02
Adhesive	Adhesive	10	mL	0.2	7.86E-06	1.85E-03
Solvent	Solvent	10	mL	0.4	2.01E-05	4.74E-03
Processes						
Cast iron/steel	Metal working manufacturing	10	kg	9.8	4.93E-04	1.16E-01
Steel	Wire drawing	5	kg	3.9	1.96E-04	4.62E-02
HDPE	Injection moulding	10	kg	1.0	5.18E-05	1.22E-02
		5	kg	4.0	2.01E-04	4.74E-02
PE		10	kg	23.5	1.18E-03	2.79E-01
PP		10	kg	1.6	8.00E-05	1.89E-02
		5	kg	3.8	1.91E-04	4.51E-02
PVC	Extrusion, plastic pipes	10	kg	4.9	2.46E-04	5.80E-02
LDPE	Extrusion, plastic pipes	11	kg	5.5	2.76E-04	6.50E-02
PVC	Injection moulding	10	kg	4.8	2.43E-04	5.73E-02
LDPE	Extrusion, plastic film	5	kg	3.5	1.75E-04	4.12E-02
EPS	Injection moulding	5	kg	48.2	2.43E-03	5.72E-01
Transport	Light commercial vehicle	10	tkm	7.6	3.82E-04	9.00E-02
Transport (end of life)	Light commercial vehicle	10	tkm	6.5	3.27E-04	7.71E-02
End of life	Sanitary landfill	10	kg	75.4	3.79E-03	8.94E-01

**The total production for the three crops conducted (S1, S2, W) was considered, **Considering the productive area of the greenhouse (84.34 m2), GFRP=glass fibre reinforced polyester, HDPE=high density polyethylene, PE=polyethylene, PP=polypropylene, PVC=poly vinyl chloride, LDPE=low density polyethylene, EPS=polystyrene*

The composting of the biomass from the crop was not included in the previously mentioned study. The same amount of biomass generated per functional unit measured in the i-RTG was considered in this scenario. The biomass was assumed to be composted in an industrial composting plant according to (Colón et al. 2012).

- **Productivity, water use and fertilisers**

The data for the productivity, the use of water for irrigation and the duration of the crops was obtained from Muñoz et al. (2015). This study presents a spring and a winter crop for the same varieties of tomato used in the i-RTG (Arawak® for spring and Tomawak® for winter) and with the same culture techniques (soil-less hydroponic). These crops were conducted in the same greenhouse used in Martínez-Blanco et al. (2011), a 5,000 m^2-standard multitunnel. The fertilisers used were calculated using standard nutrient concentrations in conventional greenhouses according to Muñoz et al. (2008).

- **Packaging and distribution**

The impacts of the packaging and distribution of production were estimated in accordance with the model proposed by Sanye-Mengual et al. (2015), considering a transportation from Almeria to Barcelona with a 6% loss during the transport and a 10% loss in the retail (16% loss in total). Moreover, the transport from the greenhouse in Almeria and from the retail point until the consumer's house was considered based on data from the same study.

Table 3 shows the data sources taken into account for the definition of the reference scenario, including both the sources for the inventory (quantity of inputs and outputs in the crops) and the calculation of the environmental impacts (data for the calculation of the impacts from the inventory).

Table A VII-3 Summary of the data sources considered for the definition of the reference scenario.

Category	Source for the inventory	Environmental information
Infrastructure		Ecoinvent 3
Greenhouse structure	AL (a)	
Auxiliary equipment	AL (a)	
Operation		
General management (energy, pesticides, etc.)	AL (a)	
Productivity, water use and duration	AL (b)	
Fertilizers	AL (b,c)	
Substrate	i-RTG	
Biomass composting	i-RTG, AL (d)	
Commercialization		
Packaging	AL (e)	
Transport to retail point	AL (e)	
Transport to consumer house	AL (e)	

(a) Martínez-Blanco et al. (2011), (b) Muñoz et al. (2015), (c) Muñoz et al. (2008), (d) (Colón et al. 2012), (e) Sanye-Mengual et al. (2015), AL=adapted from literatura, i-RTG=considered the experimental value observed in the i-RTG

Appendix VII.III Environmental impacts of crops S1, W and S2.

This section of the supplementary information presents all the information regarding the environmental impacts of the crops conducted. The produce of the crops was consider to adapt the environmental impacts obtained to the functional unit.

Environmental impacts of conventional production in spring and winter crops

Table 4 shows the absolute environmental impacts of the production of tomato in theoretical scenario with conventional greenhouse (reference scenario). Tables 5, 6 and 7 show the environmental impacts of the three crops conducted during the study.

Table A VII-4 Environmental impacts of conventional greenhouse tomato production for spring and winter crops.

	CC	ET	TA	FE	ME	FD
	kg CO_2 eq	kg 1,4-DB eq	kg SO_2 eq	kg P eq	kg N eq	kg oil eq
Spring	1.72E+00	3.55E-02	7.45E-03	2.00E-04	1.90E-03	6.00E-01
Winter	2.03E+00	4.60E-02	9.25E-03	3.02E-04	3.33E-03	6.87E-01

CC=climate change, ET=ecotoxicity, TA=terrestrial acidification, FE=freshwater eutrophication, ME=marine eutrophication, FD=fossil fuel depletion

Table A VII-5 Environmental impacts of spring crop 1 in the i-RTG (S1).

		SPRING CROP 1 (S1)					
		CC	**ET**	**TA**	**FE**	**ME**	**FD**
		kg CO_2 eq	kg 1,4-DB eq	kg SO_2 eq	kg P eq	kg N eq	kg oil eq
Infrastructure	Greenhouse structure	9.43E-02	2.64E-03	3.26E-04	1.18E-05	9.29E-06	3.12E-02
	Rainwater harvesting	1.14E-01	2.01E-03	5.45E-04	2.36E-05	1.39E-04	3.85E-02
	Auxiliary equipment	2.22E-02	5.55E-04	8.90E-05	5.66E-06	2.69E-05	1.13E-02
Total infrastructure		2.31E-01	2.31E-01	5.20E-03	9.60E-04	4.11E-05	1.75E-04
Operation	Substrate	4.56E-02	8.53E-04	2.34E-04	4.52E-06	3.80E-05	1.97E-02
	Fertilizers	2.55E-01	7.06E-03	1.21E-03	5.67E-05	1.88E-03	3.97E-02
	Pesticides	4.43E-04	1.88E-05	3.70E-06	1.55E-07	4.84E-07	2.04E-04
	Energy	8.56E-03	1.06E-04	4.51E-05	1.44E-06	2.78E-05	2.64E-03
	Water	4.71E-06	9.35E-07	2.09E-08	2.66E-09	2.99E-08	1.25E-06
	Nursery plants	8.15E-03	3.93E-04	4.89E-05	1.58E-06	1.26E-04	6.77E-03
	Wastewater	0.00E+00	0.00E+00	0.00E+00	5.59E-04	4.24E-03	0.00E+00
	Composting	6.12E-02	3.47E-05	6.15E-04	1.10E-07	2.31E-05	6.36E-05
Total operation		5.85E-01	3.79E-01	8.46E-03	2.15E-03	6.24E-04	6.34E-03
Environmental impacts crop S1		8.16E-01	6.10E-01	1.37E-02	3.11E-03	6.65E-04	6.52E-03

Table A VII-6 Environmental impacts of spring crop 2 in the i-RTG (S2).

		SPRING CROP 2 (S2)					
		CC	**ET**	**TA**	**FE**	**ME**	**FD**
		kg CO_2 eq	kg 1,4-DB eq	kg SO_2 eq	kg P eq	kg N eq	kg oil eq
Infrastructure	Greenhouse structure	1.11E-01	3.12E-03	3.86E-04	1.40E-05	1.10E-05	3.69E-02
	Rainwater harvesting	9.07E-02	1.59E-03	4.32E-04	1.87E-05	1.10E-04	3.06E-02
	Auxiliary equipment	2.62E-02	6.56E-04	1.05E-04	6.69E-06	3.18E-05	1.34E-02
Total infrastructure		2.28E-01	5.37E-03	9.23E-04	3.94E-05	1.53E-04	8.09E-02
Operation	Substrate	6.83E-02	1.28E-03	3.51E-04	6.78E-06	5.69E-05	2.95E-02
	Fertilizers	1.69E-01	4.64E-03	8.04E-04	3.83E-05	1.38E-03	2.66E-02
	Pesticides	4.75E-03	1.52E-04	4.15E-05	2.04E-06	8.34E-06	2.46E-03
	Energy	7.52E-03	9.30E-05	3.97E-05	1.27E-06	2.45E-05	2.32E-03
	Water	2.40E-06	4.76E-07	1.06E-08	1.35E-09	1.52E-08	6.37E-07
	Nursery plants	1.19E-02	5.73E-04	7.13E-05	2.31E-06	1.84E-04	9.87E-03
	Wastewater	0.00E+00	0.00E+00	0.00E+00	3.70E-04	1.91E-03	0.00E+00
	Composting	6.99E-02	3.96E-05	7.02E-04	1.26E-07	2.64E-05	7.26E-05
Total operation		3.31E-01	6.78E-03	2.01E-03	4.21E-04	3.60E-03	7.08E-02
Environmental impacts crop S2		5.60E-01	1.22E-02	2.93E-03	4.60E-04	3.75E-03	1.52E-01

Table A VII-7 Environmental impacts of the winter crop in the i-RTG (W).

		WINTER CROP (W)					
		CC	**ET**	**TA**	**FE**	**ME**	**FD**
		kg CO_2 eq	kg 1,4-DB eq	kg SO_2 eq	kg P eq	kg N eq	kg oil eq
Infrastructure	Greenhouse structure	3.41E-01	9.55E-03	1.18E-03	4.28E-05	3.36E-05	1.13E-01
	Rainwater harvesting	2.28E-01	3.99E-03	1.08E-03	4.70E-05	2.77E-04	7.67E-02
	Auxiliary equipment	8.02E-02	2.00E-03	3.22E-04	2.04E-05	9.73E-05	4.08E-02
Total infrastructure		6.49E-01	1.55E-02	2.59E-03	1.10E-04	4.08E-04	2.30E-01
Operation	Substrate	1.30E-01	2.43E-03	6.69E-04	1.29E-05	1.08E-04	5.62E-02
	Fertilizers	3.80E-01	1.02E-02	1.77E-03	8.40E-05	3.04E-03	5.84E-02
	Pesticides	5.92E-03	2.16E-04	5.06E-05	2.31E-06	8.52E-06	2.99E-03
	Energy	1.91E-02	2.37E-04	1.01E-04	3.23E-06	6.22E-05	5.91E-03
	Water	4.67E-06	9.26E-07	2.07E-08	2.63E-09	2.97E-08	1.24E-06
	Nursery plants	2.86E-02	1.38E-03	1.72E-04	5.56E-06	4.43E-04	2.37E-02
	Wastewater	0.00E+00	0.00E+00	0.00E+00	2.83E-03	7.83E-03	0.00E+00
	Composting	1.94E-01	1.10E-04	1.94E-03	3.48E-07	7.31E-05	2.01E-04
Total operation		7.57E-01	1.46E-02	4.70E-03	2.94E-03	1.16E-02	1.47E-01
Environmental impacts crop W		1.41E+00	3.01E-02	7.29E-03	3.05E-03	1.20E-02	3.78E-01